Additive Manufacturing Investigation and Demonstration for Hydropower Applications

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14. ABSTRACT

Additive manufacturing can provide an advantage over traditional manufacturing methods in situations where production of parts is limited (custom fabrication), or where parts are complex and/or challenging to manufacture using traditional methods. Engineers at Reclamation's Technical Service Center evaluated material properties of the printed test parts to compare with published data for a wrought or cast part of similar composition. In addition, three case studies involving parts of various sizes and functions were undertaken. Powder bed fusion processes using either 316L or AlSi10Mg produced a high-quality finish with acceptable mechanical properties. The case study phase of this project yielded mixed results; printed log boom anchors were deemed successful whereas the governor parts and slinger rings provided an opportunity for lessons learned. The results of this project suggest that 3D metal printing is viable and, in very specific situations, may be appropriate for producing small parts for use at Reclamation facilities. Part selection is a significant determinant of a successful and economically sound project.

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Cover Photograph: A photograph showing additively manufactured aluminum log boom anchor parts and wall (Oak Ridge National Laboratory).

Mission Statements

Disclaimer

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Acronyms and Abbreviations

3D	three-dimensional
ABS	acrylonitrile butadiene styrene
AM	additive manufacturing
ASTM	American Society for Testing and Materials
ASME	American Society of Mechanical Engineers
BAAM	Big Area Additive Manufacturing
CAD	computer aided drafting
CNC	computer numerical control
DED	direct (or directed) energy deposition
DLP	Digital Light Processing
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FRP	fiber-reinforced polymer
GMAW	gas metal arc welding
LENS	Laser Engineered Net Shaping
LWAM	Laser Wire Additive Manufacturing
L-PBF	Laser Powder Bed Fusion
MDF	Oak Ridge National Laboratory's Manufacturing Demonstration Facility
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PBF	Powder Bed Fusion
PLA	polylactic acid
Reclamation	Bureau of Reclamation
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TSC	Technical Service Center
UAM	Ultrasonic Additive Manufacturing
VP	Vat Photopolymerization
WAAM	Wire and Arc Additive Manufacturing

Symbols and Measurements

GPa	gigapascals
kg/hr	kilogram(s) per hour
lb/hr	pound(s) per hour
mm	millimeters
MPa	megapascals
psi	pounds per square inch

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Executive Summary

The Bureau of Reclamation (Reclamation) faces the challenge of maintaining aging hydraulic infrastructure across the Western United States. Additive manufacturing (AM), a broad term which encompasses technology such as three-dimensional (3D) printing, is experiencing a period of rapid innovation. Production rates, technology, and economics are improving, which may allow AM to become practical for a variety of applications. In general, AM can provide an advantage over traditional manufacturing methods in situations where production of parts is limited (custom fabrication), or where parts are complex and/or challenging to manufacture using traditional methods. While this technology offers promise, there are still challenges to adoption that present a need for additional research. This project sought to examine the current state-of-the-art in AM technology and determine how this technology can be applied within Reclamation and the hydropower industry as a whole. In particular, the project focused on identifying where Reclamation should leverage the inherent advantages of AM to solve challenges which are unique to maintaining aging infrastructure. These challenges include rehabilitation of large structures such as gates and replacement of parts which are no longer manufactured or readily available for purchase. The ultimate, long-term vision for use of AM at Reclamation is to develop a streamlined, AM-based approach for repair or replacement of legacy components on existing equipment and structures in lieu of the traditional process that includes design, procurement of materials, custom fabrication, and assembly. To satisfy the project objectives, a technology review was performed followed by a two-phased experimental approach.

Phase 1 utilized several commercially available processes (laser direct energy deposition, laser powder bed fusion, and cold spray) to print test parts with straight sides for destructive material properties testing. Engineers at Reclamation's Technical Service Center (TSC) evaluated the material properties of the printed test parts to compare with published data for a wrought or cast part of similar composition.

For Phase 2, the Materials and Corrosion Laboratory in Reclamation's TSC partnered with field offices across Reclamation who are interested in exploring AM processes as a tool for operations and maintenance. Three case studies involving parts of various sizes and functions were pursued in coordination with Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF). The process for each case study was selected by subject matter experts at ORNL based on the application. Researchers also performed laboratory testing for material properties, as well as an economic analysis for each use case using data obtained during part production.

PBF processes using either 316L, AlSi10Mg, and aluminum bronze (UNS C95300) produced a high-quality finish with acceptable mechanical properties. The case study phase of this project yielded mixed results; the log boom anchors were deemed successful whereas the governor parts and slinger rings provided an opportunity for lessons learned. The results of this project suggest that 3D metal printing is viable and, in very specific situations, may be appropriate for producing small parts for use at Reclamation facilities. Part selection is a significant determinant of a successful and economically sound project. The likelihood of success can be maximized by selecting parts and materials as follows:

- Select or design parts that do not require extensive post-processing such as machining to obtain a required surface finish.

- Select or design smaller parts (less than 10 inches on the largest dimension) to fit within commonly used PBF equipment.

- Select familiar materials such as aluminum or stainless steel, both of which are common materials used in AM with well-established print parameters for PBF. Additionally, the powder feedstock is widely available.

- Select parts that can be redesigned and optimized for the AM process. For example, the log boom anchor was optimized for strength and weight. Also, the part was comprised of multiple components that could be combined into a single piece allowing for strengthening and cost savings.

- Select parts with designs that present an opportunity for significant machine time reduction and material savings.

AM can be a useful tool to create patterns for making casting molds, but the parts can experience warping if not properly designed. Select parts and patterns that are already designed for casting to minimize risk. Determination of the economic viability of additive manufacturing must be done on a case-by-case basis considering factors such as material costs; post-processing and labor cost; part size; assembly costs; engineering, setup, and development costs.

Future work should build upon the current investment made by Reclamation in the field of AM. Results from the current work have revealed areas where additional research would be beneficial for widespread implementation of AM across Reclamation, including:

- use of AM techniques to repair an original damaged part.

- printing the same original part fully with AM, allowing for continued learning about new part development and to evaluate when AM is best used as a repair method and when it's best suited for complete part replacement.

- continued investigation of the AM case study parts from the current project, including performance in field installation where applicable.

1 Introduction

The Bureau of Reclamation (Reclamation) faces the challenge of maintaining aging hydraulic infrastructure across the Western United States. Many Reclamation facilities now exceed 70 years in age and some replacement parts have become increasingly difficult to find or are no longer available. If a part must be custom-fabricated, costs can quickly escalate and agency resources, including craft labor, are already stretched in many cases. And outsourcing a critical part with a long lead time risks costly outages at a facility.

1.1 Background

Additive manufacturing (AM), a broad term that encompasses technology such as three-dimensional (3D) printing, is experiencing a period of rapid innovation. Production rates, technology, and economics are improving, which may allow AM to become practical for a variety of applications. In general, AM can provide an advantage over traditional manufacturing methods in situations where production of parts is limited (custom fabrication), or where parts are complex and/or challenging to manufacture using traditional methods.

While this technology offers promise, there are still challenges to adoption that present a need for additional research:

- There are a multitude of AM processes to fabricate parts from metal, ceramic, and composites; mechanical properties are highly dependent on the process and parameters. Work is needed to identify optimal processes for each part.

- Existing material and fabrication standards by the American Society for Testing and Materials (ASTM) and American Society of Mechanical Engineers (ASME) require evaluation for applicability.

Mechanical properties are directly controlled by the microstructure, and for AM processes that use heat to melt and fuse material together, the solidified microstructure will differ from a part made with a subtractive process. This means there is potential for these properties to vary substantially between a traditional part and an AM part. In addition, depending on the AM process parameters, there could also be variation between two AM parts produced using the same technique, or even variation within a single part. Surface finish of an AM part is also highly dependent on the AM technique and the post-processing that occurs thereafter. Material properties, mechanical properties, and surface finish are all critical to obtaining an acceptable service life, so selecting the optimal process and material is important. A thorough evaluation of material properties is needed to identify the limits of AM with respect to its potential use across a range of hydropower-related applications.

1.2 Research Objectives and Approach

This project seeks to examine the current state-of-the-art in AM technology and how this technology can be applied within Reclamation and the hydropower industry as a whole. This objective was pursued by posing the following three questions:

1. Can AM be used to lower operations and maintenance (O&M) lifecycle costs for unique/custom parts and equipment?
2. What are the limitations of current AM technology and materials (both technical and practical) as they relate to hydropower applications?
3. Which materials and types of parts are good candidates for AM?

In particular, the project focused on identifying where Reclamation should leverage the inherent advantages of AM to solve challenges which are unique to maintaining aging infrastructure. These challenges include rehabilitation of large structures such as gates and replacement of parts which are no longer manufactured or readily available for purchase. To use AM for this purpose, designers must first either produce a computer aided drafting (CAD) file of the part or use a 3D scanning device to obtain a model. A separate research project has investigated use of 3D scanning technology to reverse engineer existing legacy parts (Science and Technology Program, Project ID 19146).

To satisfy the project objectives, a two-phased research approach was taken. Phase 1 utilized several commercially available processes to print a test part with straight sides for destructive material properties testing. Engineers at Reclamation's Technical Service Center (TSC) evaluated the material properties of the printed test parts to compare with published data for a wrought or cast part of similar composition.

For Phase 2, the Materials and Corrosion Laboratory in Reclamation's TSC partnered with field offices across Reclamation who are interested in exploring AM processes as a tool for O&M. Three case studies involving parts of various sizes and functions were pursued in coordination with Oak Ridge National Laboratory's (ORNL) Manufacturing Demonstration Facility (MDF). The process for each case study was selected by subject matter experts at ORNL based on the application. Researchers also performed laboratory testing for material properties, as well as an economic analysis for each use case using data obtained during part production.

The ultimate, long-term vision for use of AM at Reclamation is to develop a streamlined, AM-based approach for repair or replacement of legacy components on existing equipment and structures in lieu of the traditional process that includes design, procurement of materials, custom fabrication, and assembly.

2 Technology Review

Until recently, AM has only been economically viable for small, high value parts due to the high cost of feedstock and low production rates. Therefore, its adoption had been limited to industries such as biomedical and aerospace. However, advancements in the technology are expanding its potential to broader and larger scale applications, including hydropower. As a potential future step, Reclamation facilities could purchase a 3D printing machine, gaining the capability to quickly fabricate parts onsite. However, with the numerous AM machines on the market, the first task for this project was to survey the existing literature to determine what commercially available processes and technologies are best suited for hydropower applications.

The following subsections include the review of past work to obtain background knowledge and to determine the state-of-the-art for AM technologies applicable to Reclamation, with a focus on large-scale AM processes, hydropower applications, and mechanical properties of additively manufactured materials.

The review is broken into three sections:

- Metal Additive Manufacturing Processes
- Fiber-Reinforced Polymer Additive Manufacturing Processes
- Post-Processing (Metals and Composites)

Processes and materials included in the technology review were based on those of interest in the study.

2.1 Metal Additive Manufacturing Processes

Metal AM involves fusing metal powder or filament to form a 3D shape. The feedstock can be joined by a variety of heat sources such as lasers, electron beams, and plasma arc. With the vast majority of current technologies utilizing powder in their processes, powder feedstocks are more commonly used versus wire feedstock. Note that powder feedstock can pose safety and health hazards; precautions including appropriate personal protective equipment and engineering controls are needed to avoid inhalation exposure. The most commonly printed metals are stainless steels, tool steels, titanium, and high strength nickel alloys. Table 1 summarizes the commonly used metal AM processes. These processes will be described in greater detail in the sections that follow.

Table 1.—Summary of Common AM Processes

Category	Process	Power/ Joining Source	Feedstock	Commonly Printed Metals
Direct (or directed) Energy Deposition (DED)	General	Laser or electron beam	Powder or Wire	Many—Steels, aluminum, titanium, etc.
DED	Wire and Arc Additive Manufacturing (WAAM)	Electric arc	Wire	Titanium, steel, aluminum, nickel
DED	Cold Spray	Particle impaction, kinetic energy	Powder	Aluminum, nickel, steel, titanium
Binder Jetting	N/A	Liquid binder followed by sintering to achieve full density	Powder	Steels, copper, bronze, nickel, titanium, etc.
Powder Bed Fusion (PBF)	N/A	Laser or Electron Beam Melting (EBM)	Powder	Many

One of the earliest precursors to AM-like processes utilizing metals is the common practice of welding. Whereas welding typically involves deposition of a single layer of molten metal, a patent from 1925 describes the process of achieving three-dimensional "decorative articles" by stacking multiple layers of the deposited molten metal [1]. A modern descendant of that welding-like AM process is Wire and Arc Additive Manufacturing (WAAM), which utilizes the same power sources, torches, and wire feeding equipment as welding. Parts are built as wire feedstock (of typically titanium, steel alloys, aluminum, or nickel) is melted by the heat source and deposited as a bead onto the build plate or onto previous layers [2]. Since material is deposited precisely where needed, there is little waste, and the process is very cost-effective. Coupled with a high deposition rate, WAAM is garnering increased interest, particularly for the fabrication of large-scale, mild steel components [3].

One of the first applications of metal AM was through selective laser sintering in the late 1980s to early 1990s, when metal alloy powders of copper, tin, and lead-tin solder were sintered together to form a three-dimensional part [4]. Shortly after, researchers from the Massachusetts Institute of Technology developed the binder jetting process [5]. Early versions of Laser Engineered Net Shaping (LENS), Ultrasonic Additive Manufacturing (UAM), and Electron Beam Melting (EBM) were introduced in the late 1990s and early 2000s [6] [7] [8].

Although metal AM has been in development for nearly two decades, the effect of process parameters on the mechanical properties and microstructure of a part is not yet adequately established. One complicating factor is that parts produced via the same process but on different machines have been found to possess varying microstructures—from columnar to equiaxed grains [9]. One of the biggest challenges facing metals AM is for the printed part to have the same mechanical properties as their wrought counterparts. AM process parameters such as build plate chemistry, gas flow, recoater blade condition, time between laser passes, and part orientation can affect the mechanical properties of a part [10]. Jelis et al. successfully optimized process parameters and fabricated dense, homogeneous AISI 4340 steel parts using laser powder bed fusion (L-PBF) with the same mechanical properties as wrought 4340 steel; however, cost and time were major limiting factors [10]. In further work, the researchers reduced the cost by using thicker powder layers of larger powder sizes; resultant mechanical properties were not substantially compromised [11].

For certain metals and AM processes, some mechanical properties of the printed part exceed those of the wrought versions. When EBM was used to print 316L stainless steel, tensile testing showed an increase in yield strength of over 75 percent [12]. In addition, ultimate tensile strength increased by nearly 30 percent and there was a marked increase in ductility. The improved properties were attributed to the formation of highly textured long, columnar grains within the resultant microstructure. A separate study found long, columnar grains to result in unfavorable anisotropic properties—this microstructure is typically avoided for most applications [13]. Hierarchical sub-grain boundaries with stacking faults and high dislocation densities were also noted. Hierarchical grain boundaries are characterized by microstructural features at multiple length scales, i.e., micron-sized features/grains containing much smaller grains. Another powder bed fusion process, Selective Laser Melting (SLM), has provided similar results, with yield strengths of 316L stainless steel measured at two to three times higher than conventional 316L steel [14]. Additional research has suggested SLM could be used to produce stainless steel parts with higher strength to weight ratios than wrought parts [15].

Two major factors impacting metals AM are internal residual stresses and thermal distortion. Residual stresses occur within a printed part due to many factors unique to AM, including sharp temperature gradients due to application of high temperatures across small areas, high cooling rates, and re-melting of previously solidified material [16]. These residual stresses then contribute heavily to part distortion, particularly for thin-walled builds, as thermal expansion of hot material forces expansion and contraction of nearby material [17]. Distortion also scales with part size. Some mitigation methods such as pre-heating the build platform or heating the build chamber can reduce thermal gradients. Additionally, post-build stress relief heat treatments are ubiquitous before most metal AM parts are utilized; these heat treatments occur at relatively low temperatures and for long soak times [18]. Other methods to reducing part distortion involve modelling the anticipated thermal activity using finite element analysis and redesigning the part geometry to reduce or mitigate thermal gradients. Additionally, support structures can also be placed strategically to draw heat away from the bulk part to reduce stresses and/or inhibit distortion [19].

2.1.1 Direct (or Directed) Energy Deposition

One AM category that is commonly used for producing large parts with loose tolerances is direct (or directed) energy deposition (DED), which includes: Laser Wire Additive Manufacturing (LWAM), Laser Engineered Net Shaping (LENS), Electron Beam Additive Manufacturing (EBAM), Wire and Arc Additive Manufacturing (WAAM), or Direct Metal Deposition (DMD). These processes generally use an energy source to melt metal from a powder or wire feedstock and deposit the material onto a build platform or existing part [20]. In addition to metal, this process can create polymers, ceramics, and metal matrix composite parts, but the primary material used is metal powder [20]. The feedstock material is melted as it is deposited onto the surface, in contrast to other methods which melt material that is pre-set on the surface [20].

2.1.2 Wire and Arc Additive Manufacturing

An example of DED technology, WAAM, uses a gas metal arc welding torch (GMAW) to melt metallic wire that is continuously fed into the weld zone. Placement of the wire feedstock and movement of the arc is controlled by a programmable robotic arm.

WAAM is increasing in popularity because of its cost [21], unrestricted build envelope, and moderate deposition rate [22], as shown in Table 2. WAAM capabilities also include the manufacture of multi-material structures that are achieved by replacing the wire feedstock with a new composition or alloy at any point during the build [23].

WAAM is inherently characterized by lower thermal gradients and solidification velocities, low volumetric energy density [24], and, as a result produces coarser microstructures with lower mechanical properties compared to similar metallic parts manufactured with EBM or L-PBF. For example, Inconel 625 manufactured with L-PBF was 76 HV harder than Inconel manufactured by WAAM due to the smaller grain size of the L-PBF 625 [25]. Another drawback of WAAM is the tendency to form porosity in the final part which can negatively impact mechanical properties [26].

2.1.3 Cold Spray

Cold spray is a solid-state fusion DED process that uses fine powder to build parts. The process is characterized by high particle velocities propelled to the substrate using an inert gas at temperatures below the melting point and can achieve high deposition rates.

Cold spray involves spraying a stream of powder at high velocities onto a substrate using a supersonic flow of gas. The process utilizes carrier gasses of helium, nitrogen, or air at pressures from 0.5 to 6.0 megapascals (MPa). High pressure (greater than 1 MPa) cold spray, is the most widely used cold spray process for AM. High pressure cold spray can utilize a wide variety of powders and metals, but the system is expensive and complex. Low pressure (less than 1 MPa) cold spray is a much simpler, lower-cost alternative to high pressure cold spray, but it is limited to specific powders like aluminum and copper. Powder velocities can reach 550 to 1250 meters per second. While cold spray boasts high deposition rates of greater than 1,000 cubic inches per hour for some metals, the resulting bead profile geometric tolerances are relatively poor. The defense industry has allocated significant resources to developing cold spray as an alternative to a traditional welding process for repairs to aerospace components [27] [28].

Due to the high porosity that results from the cold spray process, mechanical properties are typically inferior to those of conventionally manufactured materials. Despite these drawbacks, this method is commonly used as a repair for non-structural components. Cold spray technology and the resulting mechanical properties of aluminum parts was evaluated in Phase I of this project. Table 2 provides a summary of several DED process available.

Table 2.—Example DED Processes Available

Process	Machine Name	Example Build Envelope inches (mm)			Material(s)	Deposition Rate lb/hr (kg/hr)	Reference
LENS	LENS 850-R	35 (900)	59 (1,500)	35 (900)	Inconel alloys, stainless steels, titanium alloys	1.1 (0.5)	[29]
Large-Scale GMAW/WAAM	Lincoln Electric/ Wolf Robotics	Build size not restricted			Steel and titanium; weldable materials	4.4–6.6 (2–3) (General rate)	[29], [22]
DMD/EBAM	EBAM 300	228 (5,790)	48 (1,220)	48 (1,220)	Metals: Weldable and available in wire feedstock	7–20 (3–9)	[30]
LWAM	Addere III	1,575 (40,005)	310 (7,874)	75 (1,905)	Inconel, titanium, steels, stainless steels	30 (13.5)	[31]
Cold Spray	LightSPEE3D	Build size not restricted			Aluminum, aluminum bronze, copper	13.2 (6)	[32]

2.1.4 Binder Jetting

Binder jetting can be considered to be a combination of a powder bed fusion system and a material jetting system (a process similar to an ink jet printer where material is deposited as liquid droplets). During the process, a jet of binder liquid is applied onto a static bed of powder containing the build material. The binder combines with the powder and adheres the particles together. After each binder pass, a fresh layer of powder is swept onto the build plate, and any un-bound powder is recycled. The resulting parts are a composite of build powder and binder materials, and typically require infiltration with a strengthening agent to achieve full density.

A wide range of materials can be printed with binder jetting, including plaster with a water binder, ceramics, and metals. The most commonly used metals are mainly ferrous and include steels, nickel, and bronze. In metal binder jetting, the binder forms a "green" part with the metal powder. The part must be subsequently de-bound and sintered. Commonly, the metal parts are infiltrated with a second alloy (usually bronze) to fill in the green part's continuous network of voids. Infiltration can yield parts that are nearly 100 percent dense.

Aside from requiring an infiltration step to achieve full part density, one drawback of metal binder jetting is the relatively low resolution of finished parts. This process is sometimes used for fabricating molds, fixtures, and tooling—which can be achieved without needing to create a pattern. In addition, cooling channels can be built into the part to aid in thermal rejection during casting, increasing tool life. Binder jetting does have many benefits; for example, parts can be fabricated at room temperature because the process uses polymer adhesive instead of a heat source to fuse parts, thus eliminating thermal effects such as distortion in this stage of the manufacturing process.

Additionally, binder jetting has one of the largest build envelopes of all AM processes—up to 86.6 x 47.2 x 23.6 inches (2200 x 1200 x 600 mm) [33]. While the build envelope is large, the need for infiltration limits the actual part dimensions to approximately 2 inches.

The mechanical properties of a part fabricated through binder jetting depend on whether the part was infiltrated with a secondary alloy and what that alloy is. The yield strength of a non-infiltrated stainless-steel part is 31,000 pounds per square inch (psi) (214 MPa); yield strength increases to 41,000 psi (283 MPa) after infiltration with bronze [33]. Bronze infiltration decreases the elongation from 34 to 14.5 percent [33]. Additionally, the modulus of elasticity decreases from 2.39 x 10^7 psi (165 gigapascals [GPa]) to 1.96 x 10^7psi (135 GPa) with infiltration [33]. Binder jetting was not pursued in either phase of this project but this technology is rapidly evolving and merits future consideration.

2.1.5 Powder Bed Fusion

One of the first commercialized and most versatile AM processes is Powder Bed Fusion (PBF), including Selective Laser Sintering (SLS), Direct Laser Metal Sintering (DMLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) [20]. The process creates parts by utilizing a thermal source to fuse together powder particles. Although the process was initially developed for use with plastics, it has been expanded to metallic and ceramic powders, as well as composite materials [20]. As one of the most commonly used AM technologies, PBF has been developed for use with a wide range of metals including stainless steels, nickel alloys, aluminum alloys, titanium alloys, and cobalt-chromium alloys. Additionally, PBF can be used to print precious metals such as gold and silver. Use of a finer particle size will result in improved part resolution and surface finish but will also make the powder more difficult to spread and handle [20].

Because of the reactive nature of the powder feedstock material, PBF processes typically must occur in a closed chamber with a controlled atmosphere to prevent oxidation and warping due to uneven thermal contraction [20]. This requirement inherently limits the size of the build envelope and, consequently, the part sizes. There are a multitude of PBF machines that exist with varying build volume limitations. The ADIRA AC AddCreator reportedly has the largest build envelope of 3.3 x 3.3 x 1.6 feet (1000 x 1000 x 500 millimeters [mm]), but the vast majority of build envelopes are half as large or smaller [34]. Additionally, new technologies enabling adjustable build envelopes are slowly emerging in the industry [35].

One downside of PBF processes is that supports are typically required for metallic materials as means of preventing warping. Additionally, due to the high residual stresses created within the metal during cooling, post-processing is required to achieve the desired mechanical properties like hardness and tensile strength [20]. PBF processes also typically have relatively slow print times, and part quality and integrity depend heavily on the powder quality and type. However, these disadvantages are countered by PBF’s relatively cheap costs-per-part, extensive list of compatible materials, material recyclability, and customizability [36]. Another advantage of PBF parts is the mechanical properties of parts are typically comparable to traditional parts—particularly if parts are post-processed (annealed). While mechanical properties are highly dependent on material system, Phase I of this work evaluated the performance of 316L stainless steel SLM parts. Phase II evaluated select properties of PBF Aluminum 6061 alloys.

2.2 Fiber-Reinforced Polymer Additive Manufacturing Processes

Fiber-reinforced polymers (FRPs) are another important class of engineering materials used in a variety of applications within Reclamation [37]. FRPs offer advantages such as improved corrosion resistance and directional (anisotropic) properties that can be tailored to meet operational needs. Along the direction of the fibers, the material can offer higher strength and stiffness than metallic materials [38]. FRPs can be made very lightweight, offering another advantage over metallic materials. However, to achieve required strength and stiffness in multiple orientations, FRPs may require several different layers of multiaxial fiber reinforcement [38]. For conventionally produced FRPs, this may require a high amount of manual work, leading to variability in quality, high production costs, and greater material waste [38]. AM processes can achieve more automation, providing greater guarantee of uniform quality and a reduction in material waste.

Production of FRPs by AM brings additional complications, such as: 1) how to integrate fibers in the matrix using a layer-by-layer AM process, 2) how to design parts with print and fiber orientation in mind, and 3) how to minimize porosity and void formation. There is currently no single best practice for integrating chopped or continuous fibers into AM parts, so further development is needed before the technology will be ready for creating FRP products for various applications.

Included in the following sections are select FRP AM technologies that are being developed, as well as the advantages, disadvantages, and typical applications of each process.

2.2.1 Material Extrusion

AM by material extrusion, also known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), is widely used in production of thermoplastic parts. A spool of filament is fed through a heated extruder and deposited layer-by-layer. The process is relatively simple, low-cost, high-speed, and allows for easy material change by using multiple nozzles loaded with different materials [39]. On its own, the thermoplastic material may not have sufficient properties for applications beyond prototyping. However, work is being done to determine how reinforcing fibers can be added to the thermoplastic matrix to achieve the desired anisotropic properties [38], [39].

A study found that fiber reinforcement also had the benefit of reducing distortion and warping during printing, which allowed for a high deposition rate [39]. One common issue found in the investigation of the FDM studies was porosity, with the conclusion being reached that these kinds of 3D printed composites require more research before they can be considered commercially available [39].

2.2.2 Big Area Additive Manufacturing

Big Area Additive Manufacturing (BAAM) is a rapid, industrial-scale 3D printing technology developed by Cincinnati Incorporated and ORNL. While BAAM can be used to print metal, another common application is manufacturing composite tooling out of materials like fiber-reinforced acrylonitrile butadiene styrene (ABS). A study investigating the use of BAAM to print FRP tooling found that print time using BAAM was 2.5 hours compared with an estimated 1,372 hours on an industrial FDM system [40]. The more expensive print-time costs of BAAM are offset by the faster print time and lower material costs compared with FDM processes, which use expensive filament feedstock material (in the range of $31 per kilogram), with very slow deposition rates [40]. BAAM has a greater deposition rate and uses pellet feedstock, which can be purchased for less than $10 per kilogram [40]. The study found that the total tool cost to create the FRP tooling with BAAM was roughly $1,500 compared to roughly $93,629 using an industrial FDM process [40].

One challenge associated with BAAM is ridging of the surface [41]. This is an important barrier when manufacturing tooling, which often requires a smooth surface finish. To obtain the desired net shape after post-processing, parts must either be printed smaller to accommodate a coating applied after printing or they must be printed larger and then machined to size. ORNL performed an evaluation of both post-processing methods for durability [41]. Carbon fiber-reinforced ABS molds were printed using BAAM and either given an epoxy coating or milled using a computer numerical control (CNC) router to obtain a smooth surface finish [41]. With the CNC-milled pieces, it was found that the surface finish was still too rough for commercial applications and that after the first casting, the mold would pick up the pattern of the fiberglass mat [41]. These findings show that BAAM requires improvement in surface finish, and that durability of post-processing methods needs to be improved before use in high-volume applications. However, the technology is successful in rapidly creating fiber-reinforced ABS tooling at a quality sufficient for use in low-volume applications.

2.2.3 Vat Photopolymerization

Vat Photopolymerization (VP), also known as Digital Light Processing (DLP) and Stereolithography (SLA), is an AM technique that utilizes a light source to cure liquid monomers or oligomers to create printed parts with high resolution and low feature size [42]. By changing the chemistry of the monomers and oligomers, different physicochemical and mechanical properties can be achieved in the final product [42]. However, due to the inability of the high energy light to penetrate beyond a certain depth, the accessible layer thickness and the print rate are relatively low, and in some cases, extended exposure to the high energy light can also cause side reactions that may degrade the material [42].

Research investigating the use of VP to produce FRP inserts for injection molding found that with short carbon fiber reinforcement of the polymer, Young's modulus increased, standard deviation increased significantly, and break stress and tensile strength decreased [43]. The wide standard deviation and decreased break stress and tensile strength were attributed to defects in the FRPs (e.g., fiber segregation, clustering, and air pockets), which added significant uncertainty to the mechanical properties [43]. These properties are well-suited for lower-stress applications that require minimal deformation [43]. To reduce failures and standard deviation of mechanical properties, improvement in the interface between reinforcing fibers and the polymer matrix is required [43].

2.3 Post-Processing (Metals and Composites)

Additively manufactured parts may not be ready for use in the as-printed state. AM processes may produce excess support material that is not part of the final product. This support material must be machined away from the part [44]. Machining may also be used to achieve final geometries and finishes in metal AM processes with low printing resolution [44]. For example, a part might be produced via AM, and then holes will be drilled into the part as the design requires. Additionally, the part's surface may be too rough and require polishing or chemical etching [45].

Post-processing of metal printed parts may also change the part's microstructure. Hot isostatic pressing, which uses both high pressures and high temperatures, can remove porosity, change the microstructure, and reduce surface roughness [45]. Another method of changing a part's microstructure is heat treatments [45]. Heat treatment's changes to the microstructure can improve a part's ductility but may reduce yield strength [46]. Heat treatment may also remove defects such as lack-of-fusion or isolated pores improving fatigue resistance [46] [45]. In parts made from certain metal alloys, aging—a term describing long-term heat treatments—is another heat-related post-processing technique that can lead to higher tensile strength, elongation, and hardness [44]. Most post-processing techniques cause the part to shrink [44]. Although post-processing can improve the mechanical properties of an additively manufactured part, needing post-processing may reduce AM's cost effectiveness [46].

Some novel processes exist to remove support structures or improve part finishes. For polymer/composite parts, the body of the part can be printed from non-dissolvable material while the supports are printed from material that readily dissolves in certain solvents. Once the part is printed, it can be submerged into the solvent to easily remove support structures [47]. For stainless steels, a similar process has been developed to sensitize (carburize) the top 100–200 microns of the steel which is then chemically etched/dissolved in acid [48]. If support structures are designed to be less than 200 microns wide, they are completely etched away. This technique can also be used for removing trapped powder, opening internal pathways in a part, and smoothing the part's surface. Another novel surface finishing technique involves applying a processing compound to the part which forms a chemical conversion coating with a portion of the part's surface [49]. The softer material is then mechanically removed, and the process is repeated until the desired surface finish is achieved.

3 Phase 1: Test Printing and Laboratory Testing

This portion of the project focused on printing a test part using commercially available technology and vendors from the private sector with the goal of evaluating the mechanical and microstructural properties of the printed material. The part chosen was a five-faced open-top hollow cube with two different wall thicknesses (shown in Figure 1). After some initial market research into availability, the material selected was stainless steel 316L.

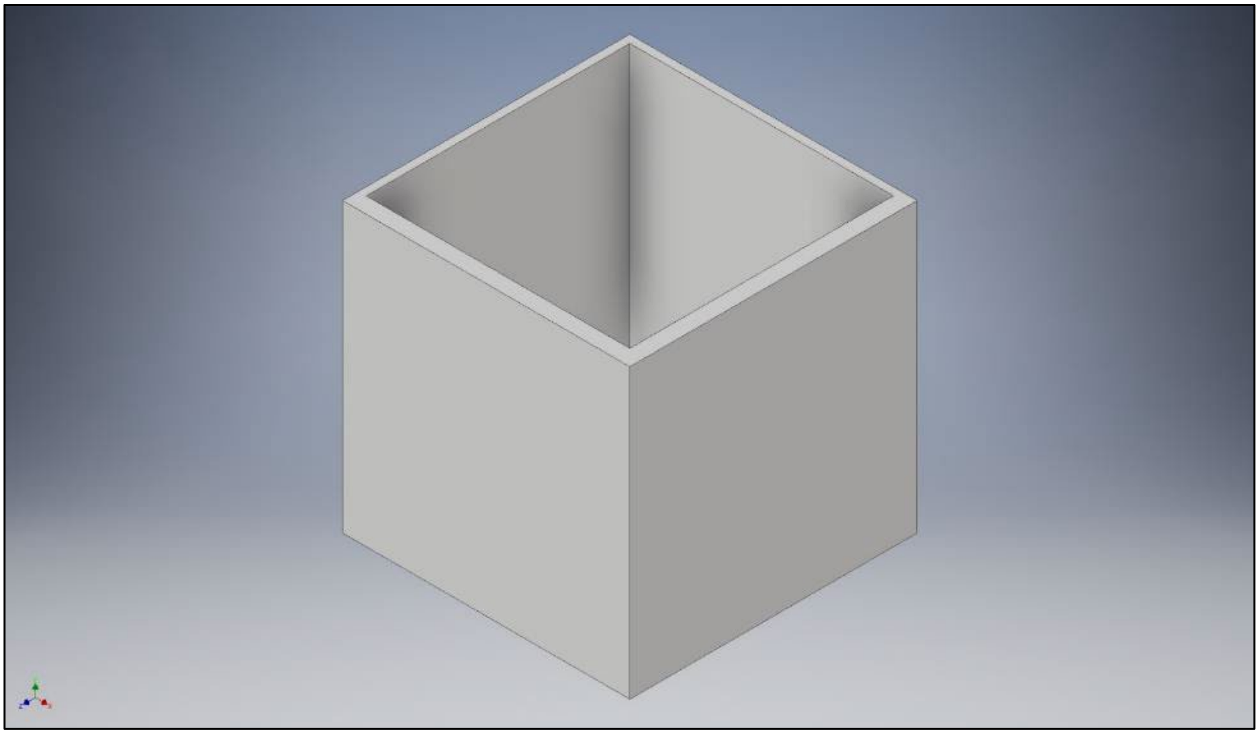

Figure 1.—Model of 9-inch cube geometry selected for the test part.

To understand the viability of the different types of AM processes, the team performed market research on the most popular vendors and processes. Many vendors were contacted over the course of the project to reach a better understanding of the market. The research team selected three individual vendors to provide test parts for evaluation in Phase 1 for DED, L-PBF, and Cold Spray.

3.1 Laser Direct Energy Deposition Test Part

The selected vendor uses a factory standard wire feed laser welding robot, Kuka model KR90HA, coupled with their proprietary software, developed in-house to produce additively manufactured components via the LWAM process. Parts are placed on a 2-axis tilt-rotary table that, when combined with the 6-axis welding robot arm, gives 8-axis of motion control; the machine setup can be seen in Figure 2. As parts are being produced, the weld process is monitored using a laser depth dynamics system as well as thermal and video cameras. In-process adjustments to laser power, wire speed, robot speed, and height can be made to control weld pool width, length, and part height. Control is maintained through proportional-integral-derivative control, machine learning, or fuzzy process control systems, dependent on part complexity and requirements. After the part was printed, samples were machined from the part and tested (tensile, Charpy impact, metallography, and hardness). Results and more information are published in a separate report, Technical Memorandum 8540-2021-016 [50].

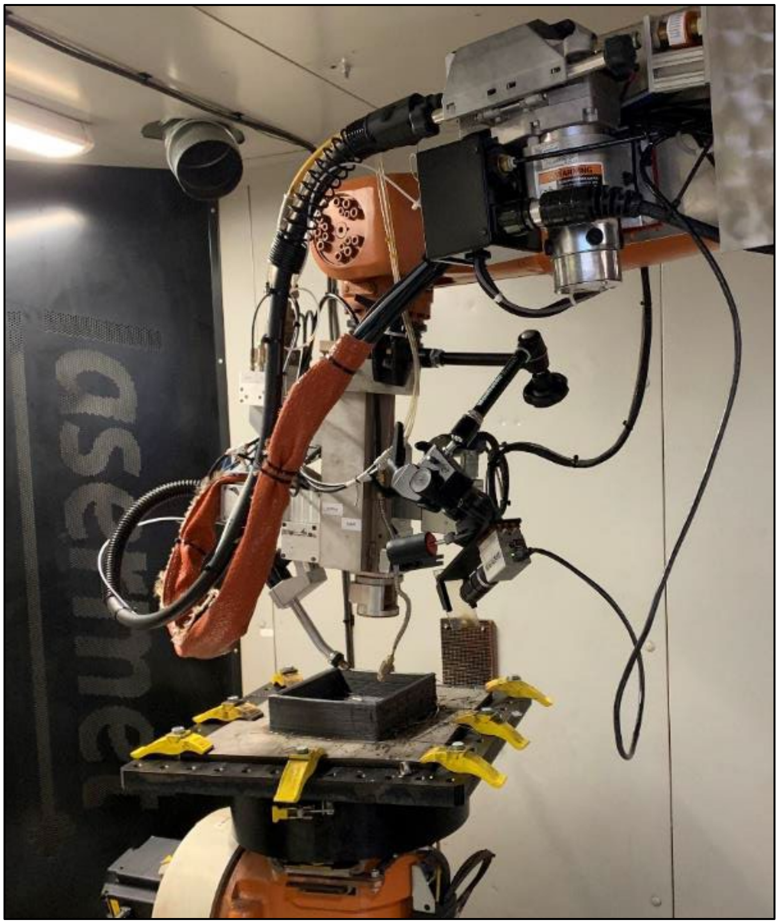

Figure 2.—Welding robot and tilt-rotary table used for DED test part.

3.1.1 Findings and Recommendations

Deviations from specified dimensions were observed in the completed part resulting in excess or lack of material in certain regions as well as rough surface finish. The thermal procedure used also resulted in unacceptable warping in the part. Anisotropic fracture properties related to the orientation of the heat-affected zones were observed, and inconsistencies in the production of the part (e.g., print stoppages) lead to notably different properties in discrete sections of the material (e.g., along print lines). Gas porosity was observed in metallographic and fracture analysis that may affect mechanical properties. On average, the DED 316L stainless steel exhibited higher yield strength but lower ultimate tensile strength and lower elongation than the wrought plate of the same material. Charpy impact energy was also lower than expected for the material when compared with published values. Statistical variability was higher than what would be expected from conventional 316L stainless steel.

Overall, it was found that the DED process, with the parameters used, resulted in a multitude of unfavorable characteristics in the completed part. With consideration of the above findings, the DED process (with the processing parameters and stress relief procedures used) is not acceptable for production of components for use in applications that require consistent material properties that are equivalent to those of wrought 316L stainless steel. Additional development and testing is needed to produce parts with consistent and predictable dimensions and mechanical properties.

3.2 Laser Powder Bed Fusion Test Part

A commercial vendor provided an additively manufactured part for analysis using a powder bed selected laser melt process on an SLM 280HL machine in an argon environment. The part selected was a 5-inch open cube. The part was built using 50-micron build layers and recycled 316L stainless 15- to 45-micron powder with no post-build heat treatment, stress relief, or machining. After the part was printed, samples were machined from the part and tested (tensile, Charpy impact, metallography, and hardness). Results and more information are published in a separate report, Technical Memorandum 8540-2021-017 [51].

3.2.1 Findings and Recommendations

Results indicated that the PBF process achieved high dimensional accuracy to the CAD model. Impurities were not observed within the material, though a small amount of porosity was observed in micrographs. Anisotropy was most notable in the direction transverse to print layer deposition, displaying an overall reduced material performance; however, no significant differences in performance were noted between material from the 1/2-inch and 1/4-inch walls. Overall, the material exhibited a lower toughness than wrought material.

With consideration of the above findings, the PBF process, when used with appropriate starting material and process parameters, may be an acceptable candidate for production of components depending on application. Consideration should be given to the orientation of components in the build process as material performance was observed to be anisotropic and, therefore, the appropriateness for use may require assessment on a case-by-case basis.

3.3 Cold Spray Test Part

A vendor provided cold spray aluminum 6061 blocks for testing and evaluation (Figure 3). One block was printed in the Z-direction (top) and the other was printed in the XY-direction (bottom). The vendor also provided additional test samples that were printed using a slightly different aluminum 6061 alloy. During the printing process, the material is sprayed onto a disposable backing substrate that is easily removed once the build is finished. Five tensile samples were machined from each block for testing. Results and more information are published in a separate report, Technical Memorandum 8540-2021-018 [52].

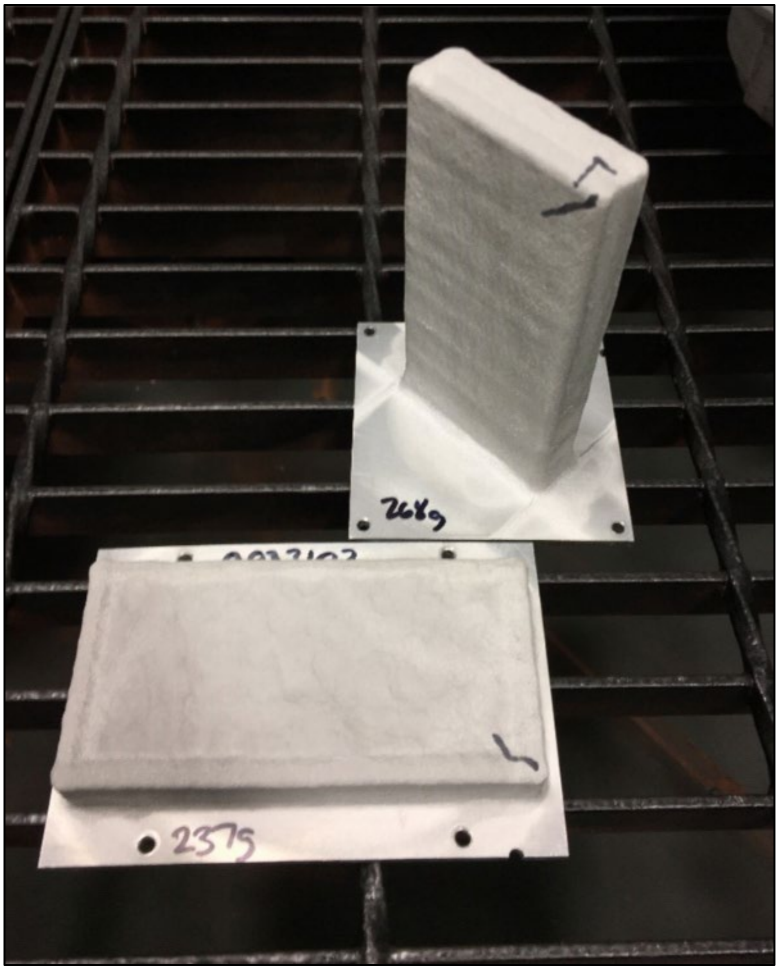

Figure 3.—Cold spray-printed 6061 aluminum blocks printed in the Z- and XY-directions [52].

3.3.1 Findings and Recommendations

It was found that the cold spray Al 6061 had significantly poorer mechanical properties when compared to conventional Al 6061. While aluminum is typically a very ductile material, the cold spray process produced brittle samples with comparatively low elongation and elastic modulus. Aside from the high percentage of porosity noted in the cold spray microstructure, metallographic evaluation found similar microstructures between cold spray and conventional Al 6061, thus indicating porosity as the likely cause of poor mechanical properties. Ultimately, none of the cold spray specimens matched the mechanical properties of the conventional Al 6061. Cold spray parts produced with the current printing process (while the porosity issue remains unsolved) should not be used as substitutes for conventional Al 6061 materials in critical applications.

4 Phase 2: Case Studies

One of the goals of this research project was to gain experience with metal 3D printing to ensure that parts can be produced reliably. For Phase 2 of this project, the Materials and Corrosion Laboratory in Reclamation's TSC partnered with representatives at several regional and area offices to identify opportunities where AM could be deployed to increase the service life of equipment, keep equipment operational while replacements are planned, reduce outage time, or increase the reliability of generating assets. A list of potential parts was generated and three were ultimately selected and pursued as case studies: governor parts for Glen Canyon Dam, log boom anchors for Nimbus Dam, and generator exciter bearing slinger rings for Grand Coulee Dam.

4.1 Case Study 1—Governor Parts

The primary purpose of a governor for a hydroelectric unit is to control the rotational speed of the turbine and loading of the unit. It accomplishes this by controlling the flow of water through the turbine. The main parts in mechanical governors are a speed sensing system, hydraulic power system, distributing valve assembly, servomotor, pilot valve, and operating controls. A pilot valve and gate limit valve in the governor were selected as the candidates for AM. These parts are currently ordered as custom replacements and undergo a manual machining process to meet the functional requirements of the design. 3D printing still requires a final machining process for these parts but printing a near net shape can reduce the amount of machining required.

Drawings of the components were created by mechanical engineers from physical measurements taken on existing components. An excess thickness of 0.04 inches was added to surfaces on the parts to compensate for the final machining required to achieve desired surface finish, particularly important for the bearing surfaces of the parts. Material selection was also initially based on existing parts; lab testing found that the parts were 316 stainless steel and naval brass. The former material is readily available for the PBF process; however, the latter is not currently viable for the PBF process due to the zinc content of the material. Aluminum bronze was therefore selected as a potential substitute material for compatibility in wear performance to the original components. The stainless-steel components were printed at ORNL while the aluminum bronze components were outsourced to a third party that also developed the powder stock material and heat treatment parameters.

4.1.1 Findings and Recommendations

The AM 316L stainless steel samples had mechanical properties that were considered acceptable for the target application with yield strength and elongation exceeding the literature values for UNS S30300 and average hardness slightly below the measured hardness of the original park.

The AM aluminum samples had greater elongation but slightly lower yield strength than either UNS C95300 (Annealed Aluminum Bronze) or UNS C46400 (Naval Brass H01 temper). Limited testing showed the fatigue performance of the aluminum bronze material compared favorably with literature results for similar materials produced by traditional manufacturing methods. Although hardness was lower than the initial target value, the mechanical properties were considered acceptable for the application.

The AM parts are shown after final machining and assembly side by side with the subtractively manufactured parts in Figure 4.

Figure 4.—Machined aluminum bronze additively manufactured parts compared to original parts removed from service. Left: Gate limit valve (additively manufactured part on right). Right: Section control valve (additively manufactured part on left).

The team encountered several challenges during the final machining process of the different components and ultimately determined that field testing of the parts would present an unacceptable risk to facility equipment. At this time, AM is not a cost-effective alternative for producing intricate parts with tight tolerances since final machining is necessary. The cost of the final machining process for the additively manufactured components likely exceeded the labor cost for traditional machining from stock material. The governor parts were considered unsuccessful due to the following:

- The components were selected for geometric complexity, however, the post-processing requirements of the parts offset any cost saving.

- The lack of additional material to grip the components made post-print machining difficult.
- Reverse engineering of intricate parts increased the risk of producing design errors and non-conforming components.
- Selection of parts made from less common AM materials created additional challenges (development of print parameters and heat treatment, selection of feedstock, etc.) to overcome.
- Selecting a part made of multiple components and materials compounded the issues above.

4.2 Case Study 2—Pier Anchors

A log boom/pier anchor at Nimbus Dam was selected as a second case study to demonstrate AM. A floating log boom prevents floating debris from entering the Nimbus Powerplant unit intakes. The log boom anchor serves as a termination point for the log boom and is fixed to a vertically oriented rail which allows the boom to move vertically as the reservoir surface elevation fluctuates. Figure 5 (left) shows a picture of Nimbus Dam with the log boom visible as a diagonal line stretching from the right bank (top side) to the dam. Figure 5 (right) shows the traditionally fabricated log boom anchors; the anchor on the left is old with corrosion and wear after several years in service; on the right is a replacement anchor.

AM offered the ability to optimize the design for material use and achieve a weight reduction of the part. To achieve this, designers used finite element modeling to map the expected forces on the part and then used topology optimization software to optimize the design by removing unnecessary material from the part. Topology optimization was iterative; the software suggested a possible design which was then used as a guide for a Reclamation engineer to design a more symmetrical part. Finally, the newly designed part was modelled using CAD.

Figure 5.—Left: Aerial view of log boom at Nimbus Dam. Right: Old and new conventionally manufactured pier anchors.

4.2.1 Findings and Recommendations

Figure 6 shows the optimized log boom anchor which was printed from AlSi10Mg. To finish the part, a stainless-steel insert was pressed into the shackle and Delrin rails were attached to the rail portions of the part. While the intent is to install the new parts in the field at Nimbus Dam, as of the time of this writing, limited staff availability have delayed installation plans and field trials are currently pending.

Using a custom-made test fixture and a tensile testing machine, Reclamation staff performed laboratory tensile tests on the printed log boom anchors. While the test design and setup only allowed for the log boom anchors to be pulled vertically (forces in the field would pull the anchors at an approximate 30 degrees off vertical), the anchors withstood the maximum estimated field forces of 4,500 pounds. In fact, the test fixture failed at approximately 16,000 pounds while the log boom anchor showed no sign of deformation.

Until a full set of findings including field results are available, recommendations are pending. However, the successful laboratory tests indicate that the AM optimized log boom anchors may perform as well as or better than the conventional anchors currently utilized in the field. The successful implementation of AM log boom anchors would represent a cost and time savings for Reclamation, as well as a case study motivating the subsequent implementation of the design process and technology to optimize the manufacturability of other important parts needing frequent replacement.

Figure 6.—Printed log boom anchor with stainless steel shackle insert and Delrin rails.

4.3 Case Study 3—Slinger Rings

The slinger ring acts as an oiler device to bring fresh, lubricating and cooling oil to the center top of a horizontal bushing. The ring rests on the shaft by gravity and turns by friction contact with the shaft. The ring supplies oil to the shaft through oil shear; oil is then pulled to areas between the babbitt and shaft journal. As oil is brought onto the shaft, the ring begins to ride on an oil film and the friction decreases. A typical slinger ring will be in service for up to 12–14 years, and they are inspected every 6 years during outages.

Replacement slinger rings are machined from solid plate by the Grand Coulee machine shop. This traditional process results in substantial wasted material and for this reason, the slinger rings were proposed by Grand Coulee as a candidate for AM.

The slinger ring must have predictable, slow wear over time; a uniform cross section and circular inner diameter to remain balanced on the shaft while rotating; and it must meet the critical dimensions and surface finish requirements to provide an appropriate and consistent oil delivery volume across the shaft. As the ring wears, it must not contaminate the oil bath with any suspended particulates that could foul the bearing. Metal particles will sink in the oil bath whereas plastic particles may remain suspended longer and could possibly melt in a tight clearance choking oil flow. Due to these requirements, it is best to use a metal that has a history of long performance, such as the naval brass material that is already installed.

Researchers investigated two potential AM methods to reproduce the Grand Coulee slinger rings. The first method was use of 3D-printed polylactic acid (PLA) patterns to produce castings of the slinger rings. The second method was a PBF process. Due to issues with circularity of the castings, researchers chose the PBF process for final part production. Naval brass is not currently viable for the PBF process due to its zinc content, so aluminum bronze was selected as a substitute material to obtain the necessary wear properties. A third party developed the powder stock material, printing, and heat treatment parameters. Figure 7 shows the casting and direct printing approaches.

Figure 7.—Printed slinger ring PLA casting patterns (left), naval brass castings (center), and printed aluminum bronze slinger rings (right).

4.3.1 Findings and Recommendations

The mechanical testing and findings for the additively manufactured aluminum bronze material are as described previously in Case Study 1. These mechanical properties were considered acceptable for the slinger ring application, however, only two of the six AM ring halves had all critical dimensions (inside diameter, outside diameter, and thickness) within tolerance. Furthermore, all rings had warpage in the Z-plane, which affects the circularity and prevents them from joining properly. In an attempt to address the warpage, one additional ring half was printed using an Inconel 718 (IN718) build plate. The IN718 build plate was reported to have improved adhesion when printing aluminum bronze than with 1045 mild steel or copper build plates but 3D scans showed no improvement from the first six ring halves. The slinger rings were considered unsuccessful due to the following:

- The PBF ring halves had similar challenges as faced with the aluminum bronze components of the governor parts (print parameters, precise dimensions, and final machining needed to achieve the specified surface finish, heat treatment, feedstock selection, etc.).
- The overall size of the printed parts and aspect ratio caused issues with adhesion to the baseplate and thermal distortion, which made the ring halves unusable.
- Investment casting allowed for use of the original naval brass material, and the PLA test patterns were successful; however, the test castings had warpage issues affecting the ring circularity, which is critical to its function.
- The benefit of material savings was outweighed by the above issues.

5 Economics of Additive Manufacturing

While AM may offer some advantages over traditional fabrication processes in terms of design flexibility and reduction of lead times, economics remains an important consideration. The case study parts can provide some insight into how AM fabrication costs compared with traditional fabrication methods. Economics of individual case studies are discussed in a separate report, Technical Memorandum 8540-2021-019. A primary finding is that careful selection of parts is necessary to maximize the value of AM. The following factors should be considered:

1. **Material costs.—**Materials costs are one factor in determining the overall cost of a part. While AM fabrication can add value by significantly reducing the amount of material waste, powder feedstock used for PBF can cost significantly more than billet, plate, or even wire. Additional powder beyond what is consumed for the actual part is required to fill the chamber. Depending on the situation, the costs for a full load of powder may be passed directly to the purchaser. It may be possible to optimize material use through creative design, but value proposition is likely to be found in part performance—i.e., weight reduction, hydrodynamics, etc.—not in cost savings for most materials.

2. **Post-processing and labor.—**Another potential value proposition for AM is the possibility of reducing fabrication labor costs by printing near net shape parts. To maximize this, it is necessary to select parts that do not have strict requirements for dimensional tolerances and surface finishing. Parts with tight dimensional requirements and/or surface finish requirements are likely to require final machining. In some cases such as the governor parts, the final machining costs can exceed the fabrication costs of a traditional part.

3. **Part size.—**PBF is limited by the build envelope of the machine being used whereas DED parts can be larger. Either way, print times for larger parts can become significant and costs tend to scale directly with part time. Small parts are more likely to be cost competitive with subtractive processes than larger parts.

4. **Assembly costs.—**Replacing a part assembled from many small components with a single AM part has the potential to save costs by eliminating the need to weld or fasten multiple pieces together. The log boom anchor took advantage of this by reducing the number of pieces of machined aluminum required to a single piece.

5. **Engineering, setup, and development costs.—**During this project, a significant amount of time was spent on the engineering phase. These costs can be reduced by gaining experiences, establishing an optimized workflow for part design, and by selecting materials with well-established print and process parameters. Furthermore, the value of AM is increased when a traditionally manufactured part is no longer available for purchase or where the tooling and setup costs are significant.

6. **Risk.—**Thermal distortion and other print failures can occur which can add time and cost to the project. This risk can be minimized through experience and by selecting and designing parts that are less likely to encounter thermal distortion issues. Risk is also lowered by selecting materials with well-established print and process parameters.

6 Conclusions

PBF processes using either 316L or AlSi10Mg produced a high-quality finish with acceptable mechanical properties. The case study phase of this project yielded mixed results; the log boom anchors were deemed successful whereas the governor parts and slinger rings provided an opportunity for lessons learned. The results of this project suggest that 3D metal printing is viable and, in very specific situations, may be appropriate for producing small parts for use at Reclamation facilities. Part selection is a significant determinant of a successful and economically sound project. The likelihood of success can be maximized by selecting parts and materials as follows:

- Select or design parts that do not require extensive post-processing such as machining to obtain a required surface finish.
- Select or design smaller parts (less than 10 inches on the largest dimension) to fit within commonly used PBF equipment.
- Select familiar materials such as aluminum or stainless steel, both of which are common materials used in AM with well-established print parameters for PBF. Additionally, the powder feedstock is widely available.
- Select parts that can be redesigned and optimized for the AM process. For example, the log boom anchor was optimized for strength and weight. Also, the part was comprised of multiple components that could be combined into a single piece allowing for strengthening and cost savings.
- Select parts with designs that present an opportunity for significant machine time reduction and material savings.
- AM can be a useful tool to create patterns for making casting molds, but the parts can experience warping if not properly designed. Select parts and patterns that are already designed for casting to minimize risk.

7 Future Research

Future work should build upon the current investment made by Reclamation in the field of AM. Results from the current work have revealed areas where additional research would be beneficial for widespread implementation of AM across Reclamation, including:

- use of AM techniques to repair an original damaged part.
- printing the same original part fully with AM, allowing for continued learning about new part development and to evaluate when AM is best used as a repair method and when it is best suited for complete part replacement.
- continued investigation of the AM case study parts from the current project, including performance in field installation where applicable.

As in the initial project, the AM repairs or parts should be field tested to assess their performance and feasibility.

7.1 Additive Manufacturing Repairs

Demonstration of AM repairs to existing, damaged parts has many benefits. Printing completely new parts can be applicable in various cases. However, for some critical infrastructure, obtaining drawings of existing parts can be challenging. Additionally, AM restricts parts to certain sizes due to AM technology limitations. Part design must also be optimized for AM while retaining the original part's integrity and performance capability. As such, using AM to print just a repair area can still greatly extend an existing part's service life while eliminating the need for redesigning the part for AM and saving material and time. AM repairs could also be applicable to a wider range of parts and/or large features with fewer dimensional limitations.

Future work should explore techniques for repairs of damaged parts, including using 3D scanning to map the repair area geometry and printing the repair area directly onto the original part using a process such as DED. Additional testing and development is needed to ensure that adequate mechanical properties are achieved for the target application. Additional testing is also needed to investigate the use of other common materials such as mild carbon steel and low alloy steel.

In addition to DED, cold spray technology is a promising method to repair damaged parts because it does not degrade underlying native material. However, the current project has shown that the mechanical properties of the resulting material are inferior to the conventionally manufactured material, and the microstructure (thus mechanical properties) could potentially be improved through post-processing, i.e., post-build heat treatments. A component of the future work should investigate methods to improve the microstructure/mechanical properties of cold spray parts to achieve properties that are similar to those of the conventional material. Results from this evaluation may enable use of cold spray technologies for part repair or full development.

7.2 Complete Part Replacement Versus Additive Manufacturing Repair

Assessing the performance and feasibility of a damaged part repaired via AM versus the feasibility of printing an entirely new part will enable more informed decision-making when parts are damaged. The performance of repaired parts should be directly compared to that of the same parts that will be fully printed with AM. For example, one identified part is a labyrinth seal which could be intentionally damaged (or a damaged part obtained) and repaired via AM. Concurrently, researchers should optimize and print a completely new seal. The goal of future work should be to enable rapid repair (or replacement) of damaged parts to ensure continuity of operations across Reclamation's facilities. To achieve the intended goals, researchers should continue leveraging the existing partnerships developed during the current AM study.

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9 Supporting Datasets

Additional files associated with this project can be accessed via:

- **File Path.—**T:\Jobs\DO_NonFeature\Science and Technology\2018-PRG-Additive Manufacturing Investigation and Demonstration for Hydropower Applications
- **Point of Contact.—**Dave Tordonato, dtordonato@usbr.gov, 303-445-2394
- **Short Description of Data.—**Files primarily include mechanical property test data, part models, photographs of case study parts, project management files, email correspondences, relevant literature, and test standards.
- **Keywords.—**Additive manufacturing, 3D printing, aging infrastructure, corrosion mitigation, remote monitoring, fabrication.
- **Approximate Total File Size.—**3,623 Files, 264 Folders, 28.0 GB