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An Overview of Ni Base Additive Fabrication Technologies for Aerospace Applications

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Abstract

The cost of aerospace components is often significantly increased due to the amount of material over and above the finished geometry that must be removed during manufacturing. This results in a substantial conversion cost needed to generate the final component. It is not uncommon to machine away 90% or more of the initial input shape, thereby increasing cost, cycle time and other overhead costs. Additive manufacturing includes an umbrella of technologies that can be used to dramatically reduce the input forging size, resulting in lower cost and manufacturing cycle time. An overview of additive manufacturing technologies and their fit into aero engine manufacturing will be presented. Advantages and disadvantages of the technologies will be discussed. Development work will be presented with commonly used aerospace materials. Preliminary mechanical property results and cost modeling will be presented. Near-term equipment and process development needs will be addressed.

Introduction

Static components in aero engines are often made from wrought products, including plate, bar and forgings. However, wrought shapes usually do not closely follow the shape of the final part, thereby resulting in an excessive amount of material that must be removed to get to the final part configuration. Therefore, the conversion cost is often substantial due to the amount of machining needed to remove the excess material. For many parts, features such as flanges, bosses, ports, pads, tubes, and clevises can result in input material that is substantially thicker than desired. The ratio of the input material weight to the final part weight is often referred to as buy to fly ratio (BTF or B2F). A BTF of 10 or higher is not uncommon in the aero engine industry. BTF ratios of 20+ are possible in the airframe industry. Also, some aero engine components have fine, intricate details that make part manufacturing difficult and costly either due to machining or complex fabrication operations that are needed to make the parts.

While BTF ratios are an important consideration in the development of additive manufacturing, other factors are important in driving a need for additive manufacturing technologies. For new engines, cost attainment is an essential part of new product introduction. Historically, it has been common to gradually drive part cost down over the first 1-3 years after product introduction into service. Manufacturing shops typically work down a ‘learning curve’ and can produce the 250th part more cost effectively than the first part. But, due to the challenges of today’s economic environment, the need to reach the 250th part cost in a much earlier timeframe is critical. The use of additive manufacturing can allow the designer to build low cost options into the initial design, thereby helping to achieve 'entitlement' cost much earlier in the life cycle of the engine.

Another consideration in the development of additive manufacturing is the opportunity for rapid prototype applications. The processes discussed in this paper are essentially a new generation of technologies who's ancestors are rapid prototyping processes of decades past, such as stereolithography. In fact, some of these processes are often referred to as "stereolithography with metal". Design and development of a new engine often requires significant design and manufacturing iterations as well as component, module or engine testing. The use of additive manufacturing has the potential to reduce cost and/or cycle time for design and manufacturing iterations and can support the desire for more cost-efficient and timely testing of components and engines. Even if a given application is not suitable for long-term production with additive manufacturing, the ability to use the technology for development hardware is, in itself, a driving force for technology development.

Lastly, in an age of eco-awareness, both in terms of the impact of manufacturing on the environment and the cost associated with high energy consuming manufacturing processes, additive manufacturing offers the potential for 'green' manufacturing by reducing input material weight and reducing the energy needed to convert input material into a final product. Less raw material combined with more efficient conversion can reduce the overall carbon footprint of aero engine components.

Technology Overviews

Additive manufacturing technologies are often categorized as either Feature Deposition or Bulk Deposition. Feature Deposition processes utilize near net shape (NNS) input material and a deposition process using wire or powder filler material. Bulk Deposition processes use a heat source that melts layers of a powder bed to build up 3D shapes. In some applications, processes used for feature deposition can also be used in bulk deposition mode to build up entire parts.

Feature Deposition Processes

Most fusion welding processes that have the ability to add filler material can be used as additive manufacturing processes. The majority of the work in the aerospace industry has focused on deposition processes that are variations of the laser, electron beam, plasma transferred arc and gas tungsten arc processes. This paper will focus on Laser Additive Manufacturing and Electron Beam Additive Manufacturing, although others in the industry have made significant developments in Plasma Transferred Arc Solid Free Form Fabrication (PTA-SFF) and Gas Tungsten Arc-based Shaped Metal Deposition (SMD).

<u>Laser Additive Manufacturing (LAM)</u>

The LAM process uses a conventional laser welding heat source (CO_2 or solid state laser) combined with a filler material feed system (normally powder based) to deposit multi-layer features on a substrate (Figure 1). The laser path and overall build approach is programmed from the solid model part file such that near-net shaped features can be added. As previously discussed, the substrate would be expected to be thinner than otherwise used for a part with features such as flanges, bosses and ports protruding from the outer diameter.

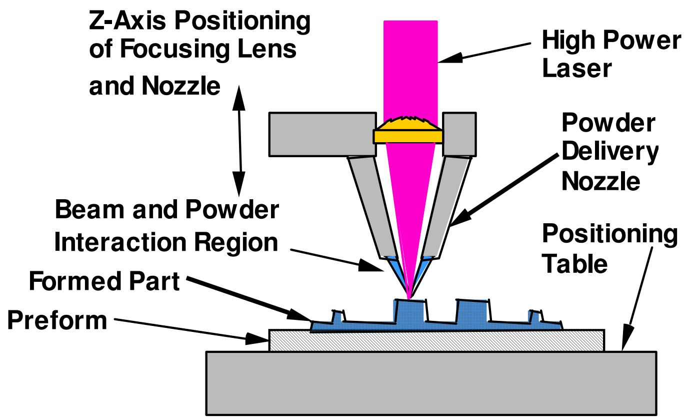


Figure 1. Laser Additive Manufacturing (LAM) Concept

LAM offers several advantages over other Feature Deposition processes, the most noteworthy being the ability to deposit very fine features on relatively thin substrates. LAM mechanical properties have historically been shown to be better than cast+HIP properties and approaching wrought properties. The LAM process typically has a lower deposition rate (0.5 – 10 lbs/hr) compared to EB, PTA or TIG based processes, although as laser power capabilities continue to grow rapidly, this gap can be narrowed. Shielding with an inert gas is typically done locally or in a dry box and is, of course, a key control factor that impacts deposit integrity.

Electron Beam Additive Manufacturing (eBAM)

The eBAM process uses a conventional electron beam welding heat source combined with a wire feed system to deposit multi-layer features on a substrate (Figure 2). As with LAM, the path and overall build approach is programmed from the solid model part file such that near-net shaped features can be added.

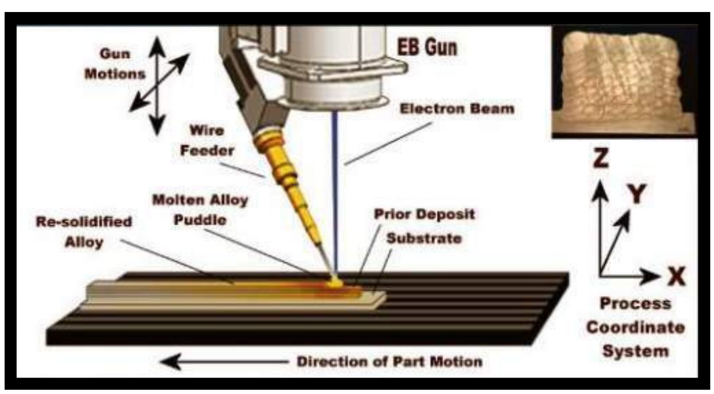


Figure 2. Electron Beam Additive Manufacturing (eBAM) Concept [1]

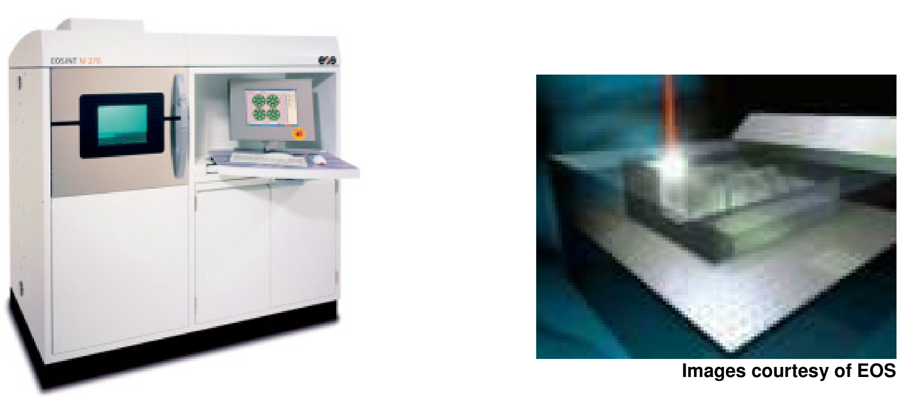
The eBAM process offers two key advantages over other Feature Deposition processes. High deposition rates, up to 20 lbs/hr have been demonstrated with good results. Also, depositing in a vacuum environment is a big advantage in terms of cleanliness. This is certainly an important factor in most aerospace applications. The size of the vacuum chamber can also be a limitation in that some systems might not be big enough for large aero engine components. Also, the initial cost and periodic maintenance cost of an electron beam based system is typically higher than a laser system and substantially higher than a PTA or SMD system.

Bulk Deposition Processes

Bulk Deposition processes are processes that build an entire 3D part from scratch or on a substrate. As the name implies, these technologies can output an entire part as opposed to just adding features. The as-deposited shape typically needs very little conversion to yield a completed part. Some limited machining or surface finishing is often needed along with heat treatment for most materials, including Ni base materials. This paper will focus on the powder bed processes, Direct Laser Metal Melting and Electron beam Melting, although there are other Additive Manufacturing processes, including Ultrasonic Additive Manufacturing (UAM) that are being developed and are at different Manufacturing Readiness Levels (MRLs). The powder bed processes are novel technologies that use a laser or electron beam heat source to melt very thin layers of powder in a precise path and sequence such that very intricate features and geometries can be built.

<u>Direct Laser Metal Melting (DLMM)</u>

The Direct Laser Metal Melting process, also known by other names such as Direct Metal Laser Sintering (DMLS$_{TM}$) and Selective Laser Melting (SLM), is a powder bed process that is reasonably new to the aerospace industry, but has been used in the medical and dental industry for many years. The powder bed is in an inert atmosphere to provide shielding of the molten metal. The process melts fine layers (typically ~.0008 inches) using a rastered laser beam moving a very high speeds in a preprogrammed path (Figure 3) corresponding to a 2D slice of the 3D CAD model. At the completion of each layer, a new layer of powder is spread across the top and another 2D section is fused. This cycle is repeated over and over again, one layer at a time, until the build is done. Due to the very fine layer thickness, build times are typically long compared to other deposition technologies. A typical build time estimate is 10 hours per inch of build height although this can certainly vary by part, alloy and laser type/power. But, the resulting build is very near net shape and the parts can be completed with little post-deposit processing.



Images courtesy of EOS

Figure 3. EOS M270 DMLS$_{TM}$ System and Process Schematic

In addition to the extremely intricate shapes that can be made, parts can be made in batches such that the volume of the build chamber can be utilized efficiently. Reuse of the unused powder can often be done so that the cost of the input material is not prohibitive. This technology is used most often with cobalt-based alloys, but work with Ni based alloys has progressed well in recent years. An obvious limitation to the process is the chamber size. Original equipment manufacturers (OEMs) offer different sized equipment, but chamber sizes bigger than a 12” cube are typically not offered. This limits the types of components that can be considered for aero engine applications. However, advancements in the technology both in terms of build rate and size capacity are ongoing. Current, the largest capacity commercially available DMLS is limited to 300mm x 350mm x 300mm (x, y, z)[2].

<u>Electron Beam Melting (EBM)</u>
The EBM process operates much the same as the DLMM process except that the heat source is an electron beam and the process is in done a vacuum chamber (Figure 4). Another difference is the ability of the process to use the rastered electron beam to preheat the powder bed and maintain the bed at an elevated temperature throughout the build. This can result in parts with less distortion and less residual stress compared to DLMM. The EBM process also has slow build rate compared to non-powder bed technologies, but is typically 2X faster than DLMM. A build time estimate of 5 hours per inch of build height is often used. The faster build time compared to DLMM often means that the process is less capable than DLMM of building extremely intricate parts. Both powder bed processes have a trade-off between build rate and the ability to deposit intricate details.

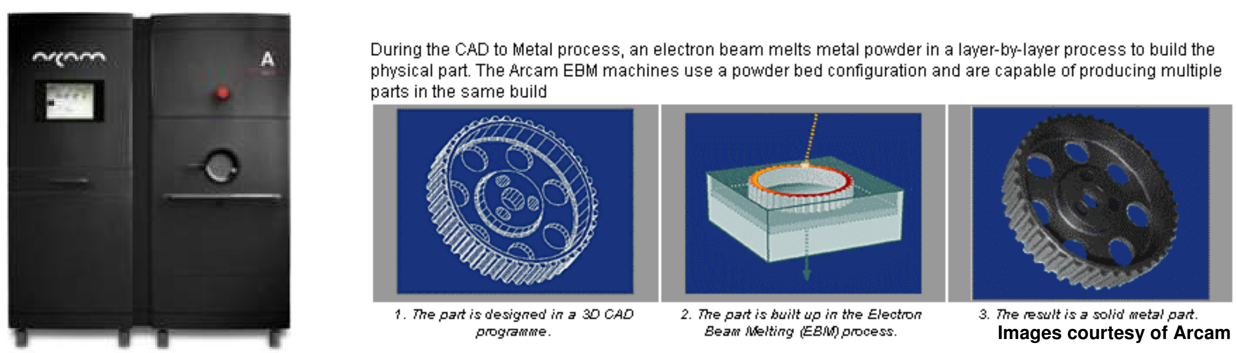


Figure 4. Arcam EBM System and Process Schematic

The EBM process is well suited for titanium due to the build chamber being in vacuum. Cobalt alloys are also common with EBM, but Ni base alloys are just starting to be development and present some challenges with preheat and build stability. As with DLMM, advancements in the technology, especially in the area of build rates are continuing to improve the viability of the process. Current, an EBM system is limited to 200mm x 200mm x 330mm height.

Additive Manufacturing Development Activities

MAI Project – Laser Additive Manufacturing of Superalloys

GE Aviation was a consortium team member of the ‘Additive Manufacturing for Superalloys’ MAI program from 2005-2008[2]. The final summary report out occurred in 2008. The purpose for this effort was to investigate and evaluate additive manufacturing (AM) technologies that could reduce component cost caused by cost disproportionate features on forged rings. Cost analysis of typical aero engine static case parts shows a high material cost component (Figure 5).

While the ratio of material cost to conversion cost will fluctuate with raw material process, the material component will always be significant. This is the main driving force for the development of additive manufacturing. This paper will summarize the LAM work done on Alloy 718 at GE Aviation.

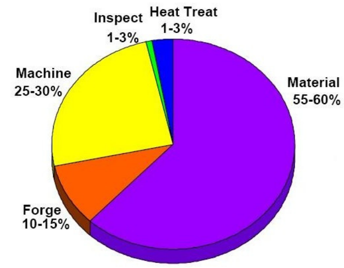


Figure 5. Typical static case cost analysis[3]

Scope of Work

GE Aviation was the technical lead for the LAM development work to demonstrate feasibility of AM to produce Alloy 718 rings with additive features representative of aero engine components. Task 2 of the program included deposition of Alloy 718 and Waspaloy features on flat and curved substrates. Task 3 scope included mechanical property and metallurgical evaluation of Alloy 718 deposits as well as refinement of the cost models and development of a business case with internal rate of return (IRR). Task 4 scope included subscale demonstration of part fabrication, verification of mechanical test results, metallurgical analysis and further refinement of cost models. Task 5 was aimed at the business objectives of scale-up and implementation logistics and rough order of magnitude cost. Note: a fullscale prototype ring was fabricated with EB deposition by P&W as part of the Task 5 workscope, the results of which are beyond the scope of this paper.

Results of LAM

For Tasks 3 property testing, 0.5 inch thick deposits were made on Alloy 718 substrates using Alloy 718 powder. All deposits were solution and age heat treated after deposition and ultrasonic inspected prior to machining. Tensile, creep, stress rupture and LCF testing was performed. Results were above cast minimum, which was established as Task 3 exit criteria.

Task 4 subscale demo exit criteria for tensile and LCF property testing required results within 10% of Task 3 results. In Task 4, representative features were deposited on an Alloy 718 wrought ring. Representative micrographs are shown in Figure 6. Photos of Task 4 deposits used for property testing are shown in Figure 7. As with Task 3, the ring with laser deposits was heat treated with the standard Alloy 718 solution and age cycle after deposition and was ultrasonic

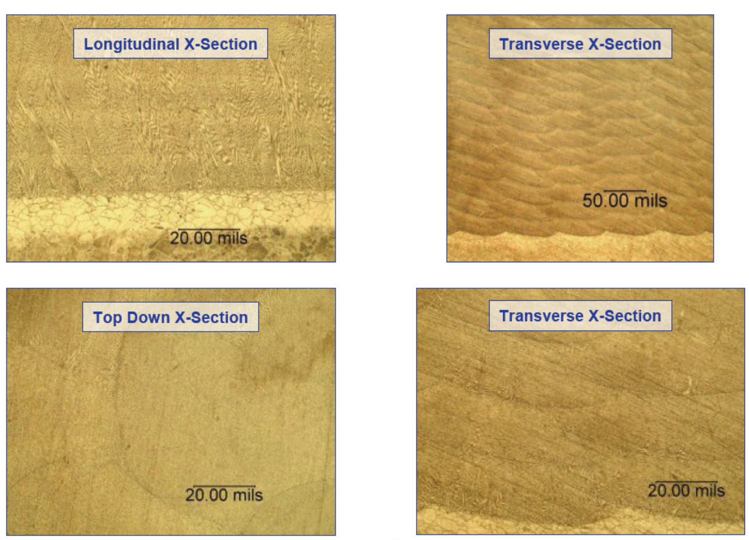


Figure 6. Representative LAM micrographs from GE Task 4 Alloy 718 deposits

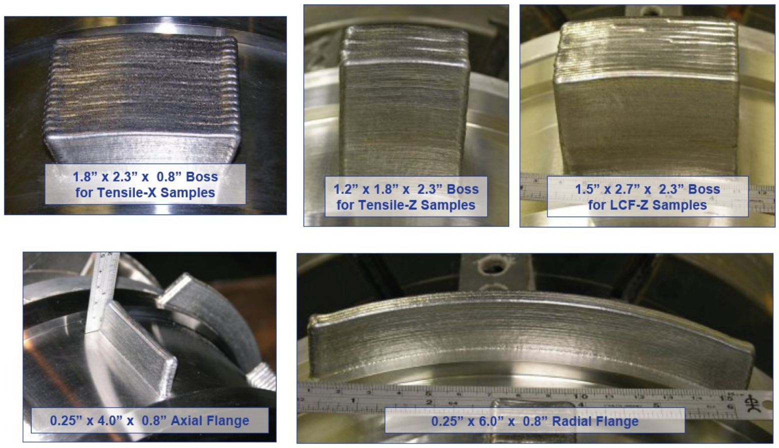


Figure 7. GE Task 4 LAM deposits on Alloy 718 Ring

inspected prior to machining of mechanical test specimens. Results of tensile and LCF testing showed properties above cast minimums (Figure 8). All data was also within 10% of Task 3 data.

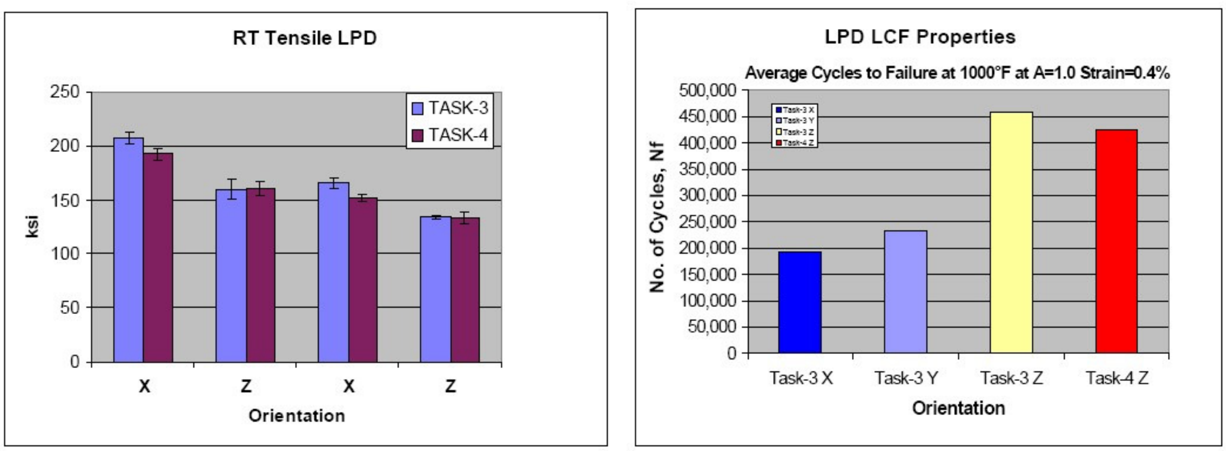


Figure 8. Results of GE LAM Task 4 property tests compared to Task 3 tests

A cost model was developed in Task 3 for LAM and then refined in Task 4. Consideration was given to key cost drivers, including deposition rate, feature complexity, volume and quantity. Plant and equipment costs, overhead costs and filler wire cost were also included. The value of the cost model is that it provides a way to estimate the savings for a specific application based on the key inputs. An estimated cost per deposited pound is the output of the model. For LAM, a range of \$75 - \$200/lb was shown. Of course, the cost per deposited pound needed to show a good business case is not a fixed number, but is dependant on many factors, most notably forging material savings and machining savings. In general, when the cost/deposited pound exceeds \$100/lb, a good business case is difficult to show since the savings will likely not provide a sound IRR.

Summary of MAI LAM Work

The estimated cost savings for an aero engine case, compared to a current forging, was 25-35% using the LAM process to add features to a near-net shape ring. A total development cost estimate of \$1.2 – \$2.0M was made for implementation of a notional aero engine large case component.

GE Case Demonstration – eBAM and PTA
As a demonstration of feature deposition on a simulated aero engine component, a series of deposits were made on an Alloy 718 ring of approximately 610 mm in diameter [4][5]. The features deposited were representative of features commonly encountered in manufacturing of this type of component, including a circumferential flange, split line flanges, embossments and pads. Both the eBAM and PTA processes were used to generate simulated components. For the eBAM process, multiple features were deposited on the ring (Figure 9). For the PTA process, only an ID cone was deposited.

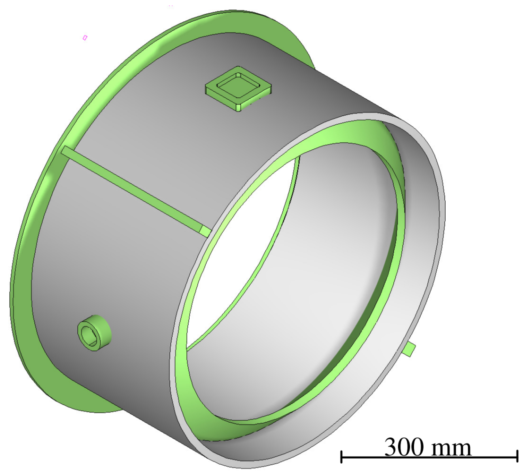


Figure 9. Feature deposition component demonstration

Component Demonstration with eBAM:

The demonstration case was made from rolled and welded 12.7 mm Alloy 718 plate. Prior to deposition, the case was turned to provide clean surfaces and to be round within 0.25 mm. The as-machined wall thickness was ~9.5 mm. The features were deposited using 0.9 mm and 1.6 mm diameter AMS5832 weld wire at deposition rates from 3-8 lbs/hr. Figure 10 shows the as-deposited case. A total of 86 lbs of deposit was made.

Figure 10. As-deposited eBAM demonstration case

Post-weld heat treat is planned, but had not been done at the time of this writing. Metallographic evaluation is also to be performed at a later date. Figures 11 and 12 shows representative photomicrographs from Alloy 718 samples produced with similar parameters.

Figure 11. Representative microstructures from deposition trials with 1.6 mm (.062 in.) wire
Left: Cross section of eBAM deposit of flange
Right: Fusion zone interface of eBAM flange deposit

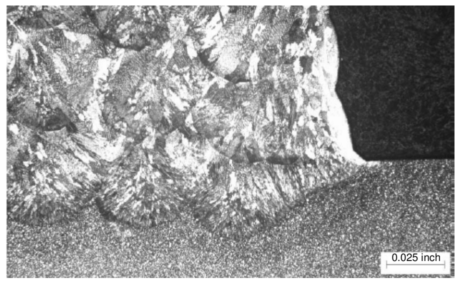


Figure 12. Representative microstructures from deposition trials with 0.9 mm (.035 in.) wire showing fusion zone interface between deposit and substrate.

The eBAM process was successful in deposited features on a simulated engine case. The required dimensions of the features were met, as was the post-deposit roundness of the case. The business case for an actual component would be based on the savings realized through the use of a near-net shaped forging and the reduced machining time compared to the cost to deposit the individual features, including post deposit operations like heat treat and non destructive inspection.

Component Demonstration with PTA:
The same rolled+welded ring configuration was used as the case material for the PTA deposition trials[4]. An ID cone feature was deposited at a deposition rate of approximately 4 lbs/hr. Flanges and other small features were not deposited. Figure 13 shows the two demo cases. The filler material used was both wire and powder Alloy 718. A total of 40 lbs was deposited on each case.

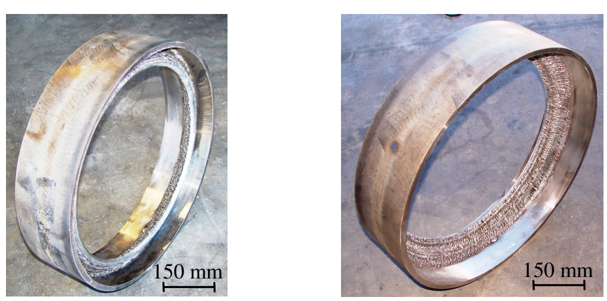


Figure 13. As-deposited PTA demonstration cases

The powder filler gave an extremely rough surface finish compared to wire filler. Post-weld heat treat is planned, but had not been done at the time of this writing. Metallographic evaluation is also to be performed at a later date.

Summary of Component Deposition

For both the eBAM and PTA trials, the amount of stock deposited over the finished features was likely not as near-net shape as possible. It is believed that features can be deposited at 10-15% overstock condition, which should be sufficient to account for distortion, surface roughness and process variability.

The cost to deposit features onto a case is typically a function of many factors, including material type, amount to be deposited, complexity of the features and production parameters. Applications that can be deposited for a cost in the rage of $75-$100/lb are typically more cost-effective than those in the $100-$200/lb range.

Direct Metal Melting

Both Direct Metal Laser Melting and Electron Beam Melting technologies have been part of the GE research and development landscape. With DLMM, the majority of the work has been done CoCr and Ni base superalloys, with limited work done on other alloys. Figure 14 shows a demonstration part made for a compressor blade application.

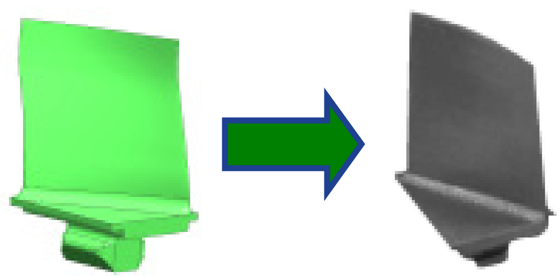


Figure 14. DLMM Blade Demonstration

With EBM, the majority of the work has been done with Ti 6-4. Some limited work has been done on Ni base superalloys. Figure 15 shows a demonstration case component made with EBM.

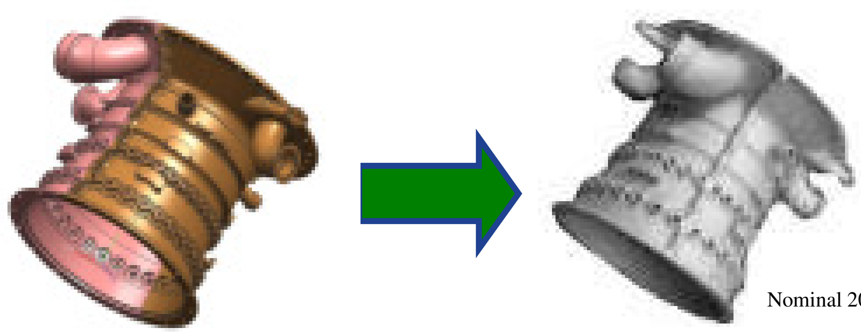


Figure 15. EBM Case Subscale Demonstration

Technology Gaps and Barriers to Implementation

RAM Workshop 2009

The Roadmap for Additive Manufacturing (RAM) Workshop was held in Alexandria VA March 2009. The meeting was attended representatives of academia, industry and the US government and was sponsored by the National Science Foundation and the Office of Naval Research. The objective of the workshop was to develop a roadmap for research in the area of additive manufacturing for the next 10-12 years. The main recommendations from the workshop are summarized below[6]:

Design:
• Exploring design spaces enabled by AM, expand the capabilities of CAD systems in representing AM geometries AM design options

Process Modeling and Control:
• Develop predictive process-structure-property relationship models and create closed-loop and adaptive control systems.

Materials, Processes and Machines:
• Develop a better fundamental understanding of AM processes (including screening methodologies), increase throughput, develop functionally graded materials and embedded components, develop AM for nanomanufacturing and identify/develop sustainable ('green') materials.

Biomedical Applications:
• Create design and modeling methods for customized implants and medical devices, including fabrication of "smart scaffolds" and 3D biological and tissue models using living biologics and create computer-aided modeling for analysis of cell-tissue growth behavior.

Energy and Sustainability Applications:
• Design energy system components to take advantage of AM capabilities and pursue Maintenance, Repair and Overhaul (MRO) for potential AM applications.

Education:
• Develop university courses, education materials, and curricula at both the undergraduate and graduate levels and develop training programs for industry practitioners

Development and Community:
• Reduce machine, material and servicing costs of AM processes and develop internationally recognized standards (ASTM F42 Committee).

National Testbed Center:
• Establish a national testbed center with distributed AM machines and/or expert users

AFRL Additive Manufacturing Workshop

The Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate, along with the Metals Affordability Initiative, hosted an additive manufacturing workshop in October 2009. The purpose of the workshop was to identify technology gaps related to metal additive manufacturing for airframe and aero engine components. Government agencies, OEM airframe and engine manufacturers, suppliers and academia attended the workshop.

Through a brainstorming and prioritization exercise, the top six areas of interest were downselected from a list of 15 issues. These are issues in which the government would be likely to have significant involvement. The top six are listed below.

1. Additive manufacturing material property database
2. Affordable materials for additive manufacturing (alloys, product forms, etc.)
3. Process development (including distortion control)
4. Process modeling
5. Real-time process control
6. Non-Destructive Inspection/Evaluation

The outcome from the list of areas of interest was a commitment to prepare white papers for the purpose of seeking government funding. Six white papers were prepared and submitted to AFRL in November 2009. Two of the six ideas (Non-destructive inspection and affordable materials) were listed in the MAI FY10 Statement of Objectives (SOO) as key areas of interest for MAI funding. Also included in the MAI FY10 SOO was 'Design Rules and Tools for Additive Manufacturing', another idea from the AFRL workshop that was identified as an area of need with the potential for government and industry partnership.

EWI Additive Manufacturing Consortium

Edison Welding Institute (EWI) has recognized the emergence of additive manufacturing technologies in the aerospace and other industries. The benefits of collaboration have been identified in previous workshops and supported by government, industry and academia. What has resulted is the concept of an additive manufacturing consortium (AMC) of companies with an interest in additive manufacturing that could provide pooling of resources, ideas and funding, as well as the potential to secure more external funding.
This differs from other consortia that include AM technologies under their umbrella of activities, but are not focused on them. The AMC's mission is to accelerate the manufacturing readiness of metal AM technologies, especially in the MRL 3-7 range (Figure 16). A scoping meeting was held at EWI in February 2010 for the purpose of identifying technical and business themes important to potential member companies. The prioritized list of business and technical themes are shown below:

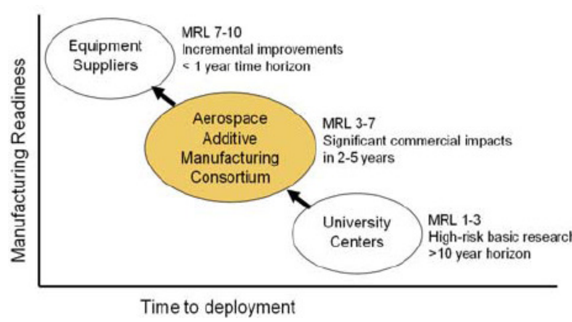


Figure 16. AMC's fit in AM development

Business Themes:
1. Consortium Funding: secure funding for Consortium activities
2. Education & Supplier Development: facilitate AM supply chain development

3. Cost / Business Modeling: develop tools to assess AM business impacts of additive manufacturing technologies
4. AM Solutions Network: establish a National Test-Bed Center with identified solution providers
5. Technology Assessment: assess AM technology landscapes, gaps, and develop approach for accessing IP
6. Collaborative Leadership: coordinate efforts within the Consortium and with regulatory bodies

Technical Themes:
1. Property Database: implement methodology to collect and share AM property data
2. Quality Control: develop technologies to assure AM quality
3. Distortion Control: develop tools to predict and control AM dimensional accuracy
4. Equipment Development: expand the capabilities of commercial AM equipment
5. Feedstock / Input Materials: control AM quality and cost through material selection and specification
6. Design Rules: develop guidelines for AM component designers
7. Standards: support the development of AM process standards and specifications
8. Process Modeling / Optimization: understand AM essential variables for prediction and optimization
9. AM Knowledgebase: compile recommended practices and develop guidelines for implementation of AM processes

The list of themes clearly aligns well with those identified at previous workshops as described above. It is hoped that the AMC will provide a focus that the AM community needs to bring additive manufacturing into the mainstream of aerospace manufacturing.

Moving Forward

<u>The Journey to Implementation</u>

Within GE, like many others in the industry, there are ongoing efforts to develop and evaluate the AM technologies described in the paper. However, the driving force to continue this work beyond MRL 1-3 needs to be actual aero engine applications as opposed to notional ideas. Therefore, identifying applications for which AM technologies can provide true long term cost savings and meet engineering requirements is essential. Rapid prototyping and low rate production applications will likely be areas where AM can provide a short term benefit, but the goal is to find long term, high volume production applications that can have a significant positive impact on cost and delivery cycles.

Currently, there are limited aerospace activities aimed at long term production, so AM appears to be viable in only niche applications. While engineering requirements, mainly mechanical properties, are a significant barrier to implementation, the biggest barrier today seems to be cost. Feature deposition technologies are, most often, too costly to the point that material savings is negated by deposition costs. Bulk deposition applications often have slow build times that result in a per part cost that exceeds conventional manufacturing methods. For both feature and bulk deposition, input material (powder or wire) can be a significant part of the total cost, especially with uncommon alloys. As a result, it is the niche applications, e.g. where the design is extremely complex or the material has low producibility with conventional processes, which can show a long-term savings.

Implementing Additive Manufacturing Technologies

In addition to the technical and business case challenges that present steep barriers to implementation, the process by which a new technology and new material is introduced into an aero engine is very challenging in its own right. The need for process specifications, material specifications, process control methodologies, capable supply chain sources and source approvals are all activities that require significant funding and resource commitment. To complete these activities for one specific part is not as cost-effective as targeting a family of parts. Yet, most development work to date is focused on individual parts. A period of 2-4 years is not uncommon when implementing a new additive manufacturing technology on an individual part.

Summary

The challenges of developing and implementing AM technologies are certainly of considerable magnitude. However, it must be remembered that many technologies that are commonplace in today's aero engines were looked upon much the same way during their infancy. The learning curve for AM technologies is steep and great strides are being made everyday. The capabilities of today's processes are very limited compared to where they will be in five years. The key to moving forward is the commitment of all involved in the industry. Equipment manufacturers can evolve their capabilities by maximizing build/deposition rates and increasing size capacity, material suppliers can drive cost out of wire/powder input stock, service providers can expand their capabilities and materials expertise, academia can develop a better theoretical understanding through fundamental research and development and government can collaborate with industry to provide funding to close technology gaps. And of course, end users, such as GE, can continue to support the AM initiative by identifying candidate applications and providing resources to drive manufacturing readiness to MRL 10. The collaboration of all involved, such as with the AMC, should be viewed as enabling, by providing the industry with a more efficient use of funding and pooling of resources.

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5. GE Aviation funded workscope with Materials & Electrochemical Research Corporation, Oct '09 – Dec '09.

6. D. Bourell, M. Leu and D. Rosen, "Roadmap for Additive Manufacturing - Identifying the Future of Freeform Processing", March 2009.