THE BENEFITS OF ADDITIVE MANUFACTURING AND ITS USE BY GENERAL ELECTRIC FOR AEROENGINE APPLICATIONS

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Abstract—*Additive manufacturing (AM), more commonly known as 3D printing, is the future of manufacturing, repair, and maintenance and has even been described as "the Third Industrial Revolution" by the Journal of Minerals, Metals, and the Material Society (JOM). This is due to the undeniable benefits of AM in speed, efficiency, material waste reduction, and the ability to produce intricate structures. The AM process gets its name from the fact that it adds material, unlike traditional machining and lathing, which involve material removal. In AM, layers of metal powder are successively added to a build table and laser melted in a controlled and localized manner—using a method known as selective laser melting (SLM)—until a 3D object is formed. The remarkable precision of this process allows manufacturers to build parts within stringent tolerances, no matter how complex the structure.*

The benefits of AM are of direct relevance to sustainability—an increasingly important aspect of engineering. A focus of sustainability is to develop technologies that maintain long-term service capabilities without long-term consequences. AM's ability for advanced design and efficiency (and thus a decreased environmental footprint) clearly makes it a sustainable technology with significant potential.

Aside from its potential and sustainability, AM is already exploited in a number of industrial applications. The aviation industry has taken an active interest in the technology in efforts to reduce aircraft weight and increase fuel efficiency—which means money saved for companies and consumers alike, together with a decrease in greenhouse gas emissions. One major company doing so is General Electric (GE), which has developed additive manufactured products such as the LEAP engine fuel nozzle and an advanced turboprop. GE has successfully translated the benefits of AM into components of their jet engines and there is no doubt that other manufacturing companies will follow its lead.

Key Words—3D printing, Additive manufacturing, Advanced turboprop, Aerospace, General Electric, Jet Engines, LEAP engine fuel nozzle.

ADDITIVE MANUFACTURING: A YOUNG AND PROMISING TECHNOLOGY

Every so often, a technology comes around that changes the shape of society and ushers the way for further advancements. The industrial revolution gave people an extensive supply of clothes, furniture, and other goods at a reasonable cost, sparking a culture of consumerism that has been growing for centuries. The internet revolution connected everyone and everywhere and we live in an age of unlimited information because of it. Today, one technology has engineers of all industries and backgrounds excited, and holds the potential to fundamentally change how parts are built and repaired. That technology is additive manufacturing (AM).

AM—more commonly known as 3D printing—involves a continuous build; it successively adds material until an object is made. This is compared to the more traditional cutting and drilling of subtractive manufacturing, where a block of material is machined away until an object is formed.

AM technology is relatively young; the early prototypes of 3D printers were developed just over 30 years ago. In 1987, the company 3D Systems released the first commercially available 3D printer, the SLA 1 [1]. In 1990, the first use of 3D printing for a metal part was a copper gear comprised of just 72 layers of laser-sintered powder [1]. Since these landmark foundations for AM, there have been decades of great interest, research, and investment into the technology. Today, due to very recent advancements in capabilities, there are far superior and more powerful machines and dozens of new AM processes. As a result, AM has become a credible alternative and sometimes even the preferred manufacturing method across a wide range of industries. Indeed, the past few years have seen the greatest growth in AM history. According to the Wohlers Report 2016, the AM industry grew 25.9% to a total of $5.165 billion in 2015 and the sales of AM systems for manufacturing metal parts grew at a year-on-year rate of 46.9% [3]. This clearly reflects a greater interest and acceptance of the manufacturing community for AM as a viable technique.

This rising interest in AM is due to its compelling benefits. According to Suman Das of Georgia Tech, "Immediate near-term impacts [of AM] include dramatic reductions in cost and lead time, the ability to produce small-lot or 'one-of-a-kind' components on demand, and the ability to prototype and produce advanced, high performance, and more efficient components that cannot be manufactured through conventional methods due to inherent limitations on geometry, material, microstructure, and properties" [1].

Another key aspect of AM is its direct relevance to sustainability. In recent years, an emphasis on responsible innovation has steadily increased; engineers must consider the long-term consequences when developing new technologies. For AM, its growth and impacts establish it not only as a technology for the future, but also a technology for sustainability. As defined by the United Nations World Commission on Environment and Development, sustainability is the act of "satisfying the needs of the present generation without compromising the ability of future generations to meet their own needs" [2]. This means that a sustainable technology is one that remains affordable, functional, and beneficial for decades to come, without being a detriment to society and the environment. AM meets all of these constraints.

This paper will discuss the different AM processes, the materials used, and the benefits resulting from them. The current technical challenges of AM and the research addressing those challenges will also be considered. Finally, this paper will look at the commercial use of AM by describing the products of AM from one of the largest engineering companies, General Electric.

ADDITIVE MANUFACTURING: HOW IT WORKS

The Process

There are many methods by which AM is done, ranging from processes that involve heating wires covered in metallic powder to those involving the focusing of electron beams to weld metals. However, the most common of these methods is laser-based 3D printing. The three variations of laser-based 3D printing are selective laser sintering (SLS), selective laser melting (SLM), and laser metal deposition (LMD).

SLS starts with an extremely thin (about 20 micrometers, which is roughly one third of the thickness of human hair) and a level layer of metallic powder set on a flat table [4]. A precise laser is programmed to scan over the layer of powder in order to partially melt it in a directed and localized manner. Different types of lasers are used, including CO_2 and Nd:YAG—gas state and solid state lasers, respectively [1]. The different lasers vary in temperature and help control the solidification of the metal. The partially melted metal is held together using a binding polymer. After a given pass, the table is lowered and another layer of powder is set on top and is again partially melted. The process is repeated, layer by layer, until a desired three-dimensional object is created. Next, because binding material is added through each step, the object has to go through post processing to remove the unwanted binder. However, the use of binders in the process allows parts to be made without support structures, so SLS is often used to make parts with hanging components [1]. But because the powder is only partially melted, the final product is not fully dense and is therefore weak. Thus, more post processing is required, specifically Hot Isostatic Pressing (HIP), in which a non-reactive gas is uniformly pressurized around the object, reducing porosity and thereby increasing density.

Selective laser melting is an AM process derived from SLS and is currently the predominantly used AM method. SLM follows the same equipment setup, configuration, and principle as SLS: layers of metallic powder are successively stacked and scanned over with a laser in a pre-determined path. However, in SLM, the powder is fully melted instead of partially melted, thus the metallic parts are close to being fully dense to the extent that they do not require a post HIP treatment [5]. This results in greater strength and microstructural homogeneity [1]. The latter is an important characteristic that determines whether a part is reliable or not, which will be discussed later in this paper. SLM was once a difficult process to achieve because although it uses the same lasers and equipment as SLS, the energy density of the lasers in SLM are much higher and thus harder to control. However, after over two decades of research in the field, lasers today are far more powerful and precise than their predecessors of the 1990s. As shown in the table below, modern day lasers are five times more precise, 100 times more powerful, and 500 times faster. Moreover, the layers of metallic powder are far thinner, so builds can be much more precise [4]. Just as it has during the past 30 years, SLM will continue to improve and remain a sustainable process for the foreseeable future.

	1993	**2015**
Laser Power	7.5 W	200-1000 W
Spot size	0.5 mm	0.1 mm
Scan speed	2 mm/s	1000 mm/s
Layer thickness	100 µm	20-50 µm

FIGURE 1 [4]
Comparison of process parameters for laser powder bed fusion

Figure 2 below is a schematic representation of the SLM process. In this example, a burner tip for a gas turbine is being replaced. The maker of the burner tip, Siemens (Europe's largest industrial manufacturing company), reports that SLM makes their repair process 10 times quicker because it avoids "quite a few manufacturing and inspection processes" [6].

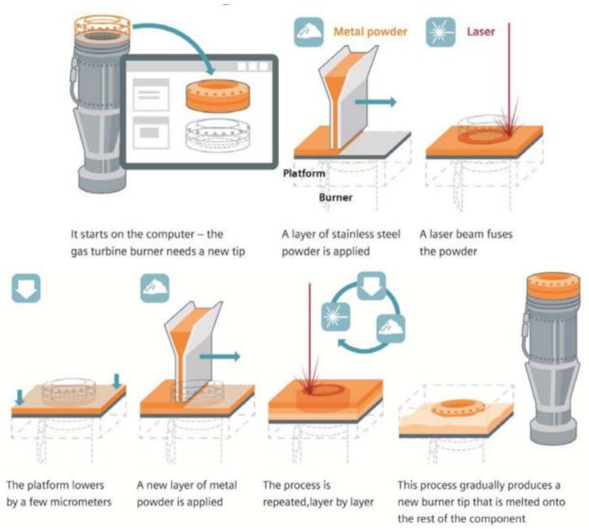

FIGURE 2 [6]
Gas turbine burner SLM repair procedure

Laser metal deposition is the third laser method used in AM, but the process is very different than the others. Like SLM, LMD completely melts powder to create fully dense metals. However, the metallic powder is not set layer by layer. Instead, and as discussed by Leu, “the powder is conveyed by a pressurized-gas-delivery system through a nozzle or multiple nozzles into a melt pool created by a laser beam on a substrate” [5]. This means that the laser and powder are combined to give a directed jet of liquid metal. The major advantage with this method is that manufacturers can do builds in a specific area. Though this does not matter in building parts from scratch, this advantage makes LMD the preferred choice in repairing parts, because manufacturers do not need to use thousands of layers to build up to a region to apply AM.

The Materials

The similarity between all of these processes is the fact that metallic powder is heated through the use of a laser. But what are these powders made of? There is a wide range of different types of metals that have been used for 3-D printing. As reported by Das, "These include pure metals (gold, copper, niobium, tantalum, titanium), alloy powders (aluminum-based, cobalt-based, copper-based, iron-based, nickel-based, and titanium-based), and powder mixtures (copper-based, iron-based, and graded compositions such as Ni-Al, Ti-Ni, Ti-Mo, and Ti-V)" [1]. This range of materials shows that AM can build objects out of many widely used metals, so the process is a viable option for any industry involving manufacturing. Furthermore, with increased research, more materials will become available for AM (i.e. stronger superalloys), which will serve to expand AM’s functionality and sustainability in manufacturing industries.

The Benefits

The advantages of AM are numerous. Firstly, AM builds objects based on computer-aided design (CAD) models. Plus, all of AM uses similar equipment supplied by companies such as EOS, 3D Systems, or Stratasys [5]. So, any 3D-printed part can be built in any AM-capable factory in any part of the world just by digitally sharing CAD models. Hypothetically, if an American-owned aircraft was in China and needed a particular part for repair, that part could be quickly printed in China instead of needing to be shipped over from the U.S. There is also no longer a need for factories to specialize in specific parts, only the need for a 3D printer. In fact, this advantage is already being utilized today. The *Economist* reports that “Caterpillar and John Deere, two American producers of construction and agricultural equipment, are working… on moving their warehouses, in effect, to the online cloud, whence digital designs can be downloaded to different locations for parts to be printed to order” [7]. This will greatly reduce real estate costs, shipping costs and time, and also build and repair times.

Secondly, by the very nature of its process, AM is more material efficient than subtractive manufacturing. With the power and ability to create a product in layers, and add to it rather than subtract, the amount of material wasted is greatly reduced. Over time this reduction of material waste can translate to substantial savings for both manufacturers and consumers. Adding to this efficient use of materials is the fact that a 3D printer is a machine and can be considered as “something that simply works, without much need for human intervention” [6]. Machines and computers make far fewer mistakes than humans, and using computers always makes a process more efficient. It reduces errors, build failures, and the need to redo a build, thus saving time, materials, and money.

Thirdly, and probably most importantly, is AM’s ability to create complex structures. Using conventional subtractive manufacturing, there are certain designs and structures that are impossible to create. These include parts with internal cavities, lattice-like shapes, and other intricate geometries. Since AM prints in layers, more complex shapes become possible. Recalling back to Figure 1, powder beds today are only about 20 µm thick and the size of the lasers used to melt the powder have a spot size of only 0.5 mm. Therefore, any shape, design, or detail, no matter how small or intricate, is possible to build through AM. The reason this is so exciting is that it gives manufacturers the freedom to build anything, to design parts previously thought to be impossible to create. With further utilization of AM, like the applications discussed later in this paper, the endless possibilities create an exciting future for building and designing across all industries.

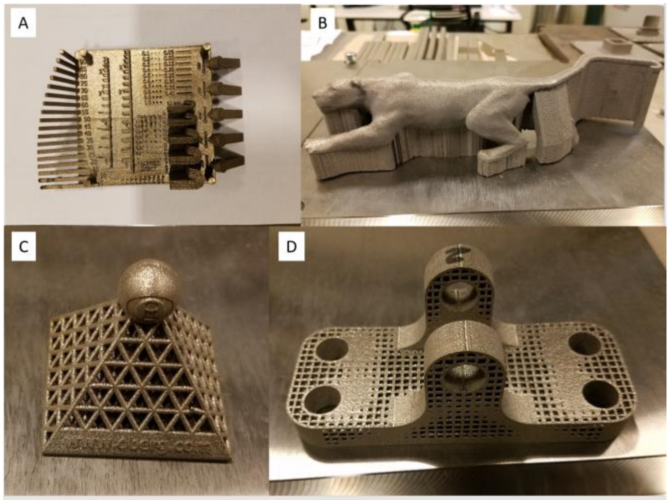

FIGURE 3 [8]
3D printed complex structures

Figure 3 above shows examples of the sorts of complex structures that can be built via AM. By implementing intricate geometries, objects can be lighter, use less material, and can still be even stronger. Image (A) shows just how small holes can be and just how precise the angles of hanging components can be. Image (D) shows how a complex geometry with designed-in density variations can be fabricated. In this latter case, extra support and material are built into regions where mechanical loading (tension) will be highest while other regions have less material. The result is an efficiently constructed part that has the desirable combination of light weight and high strength.

In terms of sustainability, the material efficiency and cost effectiveness of AM makes it affordable and attractive to many manufacturers. Moreover, AM's functionality and precision will grow with continued advancements of computer-related technologies. Altogether, AM will continue to grow in utilization and innovation for many future decades.

The Challenge of Microstructural Properties

Even with all of its benefits, AM is still a young technology with obstacles to overcome before realizing greater commercial use. There are many aspects of AM that researchers are addressing, such as high residual stresses in as-processed parts. According to Dr. Albert To of the University of Pittsburgh, 3D printed parts retain significant internal stresses during processing [8]. Unless properly accounted for, these stresses can result in part distortion and even cracking or fracture [8]. Figure 4 shows what possible distortion can look like; the AM built nickel-based alloy object was intended to be flat and rectangular, but instead came out bent and cracked. For a 3D-printed part in something like a jet engine, having a distorted or cracked part is unacceptable and a clear safety risk. Thus, significant funding and research are being directed towards predicting how materials will behave in AM and how to ensure that a 3D printed part is reliable. Internal stresses in AM parts can stem from a number of sources, including shrinkage during relatively rapid solidification and microstructural heterogeneities [8].

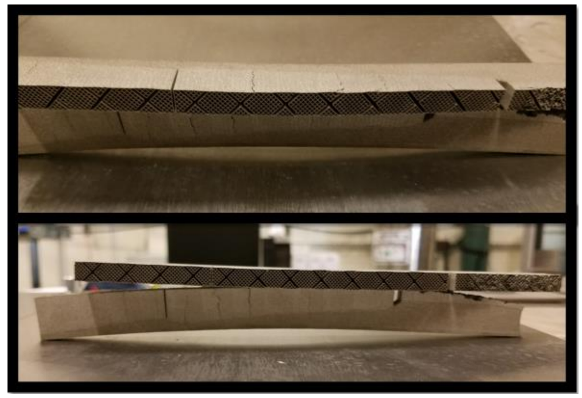

FIGURE 4 [8]
Deformation of AM built nickel-based superalloy object

As described earlier, AM involves high temperature lasers to melt metallic powder. The resulting melt pool is quite small and therefore able to cool rapidly when the laser is removed. Normally, metals in the process of solidifying have a period of relaxation in which the internal stresses have time to equilibrate as the metal takes its final shape. However, the significant temperature drop in AM prevents local relaxation of the surrounding structure to accommodate the rapid liquid to solid volume change which, in turn, leads to internal residual stress or even cracking [8].

Further internal stress can come from microstructural and compositional heterogeneities, which are also a consequence of relatively rapid and localized solidification processes. Microstructural heterogeneities are variations in material properties (e.g., strength, toughness and ductility) across a part on a microscopic level [1]. The presence of microstructural heterogeneities is a major limiting factor when trying to use AM to make parts out of superalloys, which are multicomponent and often multiphase alloys that possess high-temperature strength and environmental resistance to harsh service conditions, such as those found in turbine engines.

Figure 5 shows a magnified image of a fully and properly heat treated nickel-based superalloy Inconel 718 (IN718). The dark cuboidal spots are γ' precipitates: discrete particles that form in the solid-solution nickel matrix [9]. The γ' precipitates are highly desirable for their potent strengthening abilities, but are only beneficial in a uniform distribution like what is shown in Figure 4. However, if the precipitates are clustered in a nonuniform manner, areas of weakness and fragility are created, which can be detrimental to the mechanical properties of a build [8]. In order to reach a uniform distribution of γ' precipitates, a part has to go through a controlled heat treatment. For parts produced by subtractive manufacturing, the heat treatment is not overly expensive because the parts are typically larger, less complex, and fairly homogeneous even before any treatment. By contrast, AM-built parts currently tend to be small, intricate and heterogeneous, because microscopic material properties is hard to control when building layer by layer. As a consequence, the heat treatment of AM builds may be more time intensive, expensive, and, in many cases, still needs to be developed [8]. This makes the 3D printing of superalloy parts currently very challenging and hence a current deterrent to the more widespread use of AM.

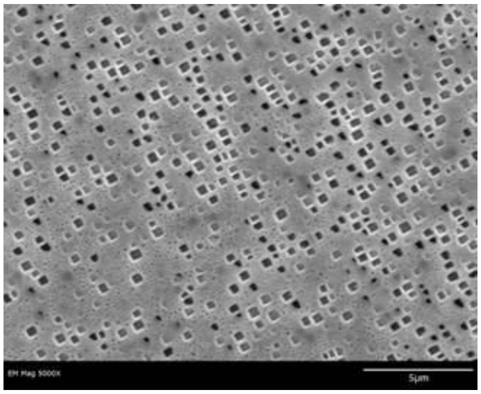

FIGURE 5 [9]
High magnification secondary electron microscope image of a heat-treated nickel-based superalloy (IN718)

In short, the causes of microstructural heterogeneity in AM parts are clear and any consequential effects, such as distortion, are concerning. Therefore, AM can often be a trial-and-error process and may require a lot of post-processing. This can completely nullify the benefits of AM, like reduced costs and build time. For that reason, much of today's research goes into accounting for and removing residual build stresses associated with a given AM process.

As a result, computer simulation and *in situ* monitoring are receiving increased attention [1]. Simulation and *in situ* processes are ways to model what is taking place during an AM build. Images and data are collected with each layer built using devices like high-speed infrared cameras, X-ray imaging, and displacement sensors. The resulting thousands of images are collated to create a 3D model of the part that can show information such as porosity, temperature variation, and microstructural heterogeneity. This model can then be used to simulate future builds and predict when, where, and to what degree deformation might occur. The goal is that simulation can one day be used to further control AM—the temperature, the melt conditions, the rates of solidification—and remove any issues associated with residual stress and distortion.

FIGURE 6 [8]
The Advanced Manufacturing Research Laboratory (AMRL) in Benedum Hall, Pittsburgh, PA

A facility currently conducting AM simulation research is the University of Pittsburgh's very own Advanced Manufacturing Research Laboratory (AMRL), which is pictured above in Figure 6. The AMRL is located in the sub-basement of the Swanson School of Engineering. A key effort within the AMRL is the recently-established MOST-AM Consortium (Modeling and Optimization Simulation Tools for Additive Manufacturing), which is led by Dr. Albert To. The MOST-AM's mission is to develop advanced simulation and modeling techniques in order to take advantage of the full scope of AM. Greater simulation and manufacturing prediction will make AM a more viable option for commercial applications and thus facilitate the increased and sustainable usage of AM.

ADDITIVE MANUFACTURING APPLIED: GENERAL ELECTRIC

AM's largest users are the aerospace and medical industries—fields that often deal with small and intricate parts [1]. However, AM's capabilities of complex structures and efficiency are of greater service to the aerospace industry, which always strives to become more fuel efficient through weight reduction and advanced design. One of the greatest pioneers of AM in aerospace is the company General Electric (GE).

About GE

GE is a global digital industrial company, which designs and manufactures equipment ranging from power generation to aircraft engines to medical diagnosis and treatment equipment [10]. Within the last two years GE has made several investments in AM technology. They purchased over 75% stakes in two large AM companies: Arcam AB and Concept Laser, the latter of which is a leading producer of metal-based SLM machines. [11]. These purchases alongside general funding in AM research summed to a total of over $1.5 billion, make GE a clear leader in AM.

Not only has GE heavily invested into AM, it has also been using internal funding to implement AM into its own designs and products. GE fairly recently developed a jet engine called LEAP, which is an improved version of its previous CFM56 single-aisle aircraft engine. The LEAP engine is currently commercially available and has a 3D printed fuel nozzle. The other product GE is currently developing is called the Advanced Turboprop, which is 3D printed as well, but is still under testing. Both of these products demonstrate the benefits of AM and prove that it is a useful and sustainable process.

LEAP Engine

CFM International is a joint company between GE Aviation (a division of GE) and Safran Aircraft Engines. The company's main product is the single-aisle aircraft engine called the CFM56. The CFM56 is a type of a turbojet reaction engine, and the LEAP engine is the company's latest advancement of the CFM56. The LEAP engine (shown in Figure 7) is very successful and is considered one of the best jet engines on the market, as already 12,500 units have been sold since the product's release in 2016 [12]. But what is most interesting is that a jet engine as advanced as the LEAP contains complex geometries, so it is time consuming and expensive to create without the advanced process of AM. This is one of the reasons why GE has invested heavily into their additive division of the company.

FIGURE 7 [13]
CFM International LEAP Engine

The LEAP engine is a type of turbofan jet engine—an engine that gets its name from its large fan at the front that sucks in air. The goal of any type of jet engine is to create a thrust, or force, that allows the aircraft to fly. Jet engines create this necessary thrust using a gas turbine. Even though jet engines such as the LEAP are complex in design, the principles behind them are quite straightforward. The thermodynamic process exploited by the gas turbine is called the Brayton cycle. In simplistic terms, the Brayton cycle involves the compression of air, thus increasing the air's temperature and pressure [14]. Figure 7 helps visualize how this happens. The fans push the air towards the combustion chamber. The amount of air remains constant while the fans and passageway gradually get smaller, increasing the pressure of the air. The air is then mixed with a small amount of fuel spray and creates a highly flammable solution, which is ignited by a small electric spark [14]. The combustion and expansion of this mixture is what both powers the compressor and propels the aircraft forward. [14].

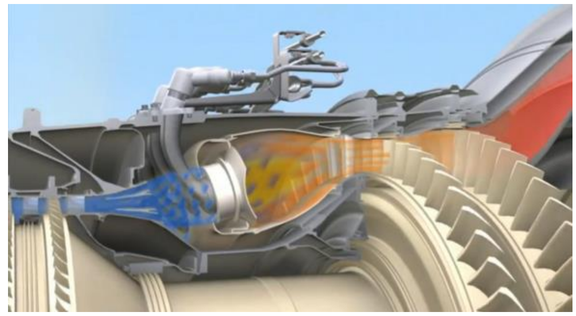

FIGURE 8 [15]
Computer graphic of fuel nozzle at work in a turbofan

High efficiency of a jet engine is dependent on a high ratio of combustion pressure over atmospheric pressure. This ratio is determined in great part by the fuel nozzle. This crucial part is what sprays fuel into the combustion chamber and is what controls the proportions of the mixture inside. Figure 8 shows the fuel nozzle allowing air from the left (blue) and adding fuel in order to create the combustible solution to the right (orange). According to LEAP Engine lead engineer Joshua Mook, "the key to a good fuel nozzle is proper management of air and fuel" [15]. He further explained that if not enough fuel is added, not enough power is generated; however, if too much is added, it is a waste of expensive fuel [15]. In order to reach the optimal levels, complex and intricate geometries are often required to spray precise amounts of fuel into the combustor, making AM the ideal process for the production of fuel nozzles [15].

AM gave GE engineers the ability to implement any design they wanted for the LEAP engine, making it a significant improvement over the CFM56. For starters, the LEAP engine is much easier to make, uses less material, and weighs much less. As stated in GE reports, "Within 18 months, the team was able to print much of the machine, reducing 900 separate components to just 16, including one segment that previously had 300 different parts. The printed parts were also 40 percent lighter and 60 percent cheaper" [16]. Moreover, the advanced design of the fuel nozzle greatly improved the performance of the engine. According to GE, the LEAP engine is 15% more fuel efficient, produces 15% less greenhouse gas emission, and generates 10% more thrust [17]. This is a result of weight reduction and complex structures, which is only possible under the use of AM.

The LEAP engine (Figure 7) and LEAP engine fuel nozzle (Figures 8 and 9) are lighter, cheaper, more efficient, and many design aspects can only be achieved using AM. Moreover, their effectiveness and benefit to the environment falls directly in the lines of the definition of sustainability. Plus, the parts are composed of cobalt-chromium and titanium aluminide, single-phase alloys (non-superalloys) that do not run the risk of deforming due to its microstructural properties when being built through AM. Altogether, the LEAP engine and fuel nozzle are superior technologies and living proof for the exciting possibilities of AM.

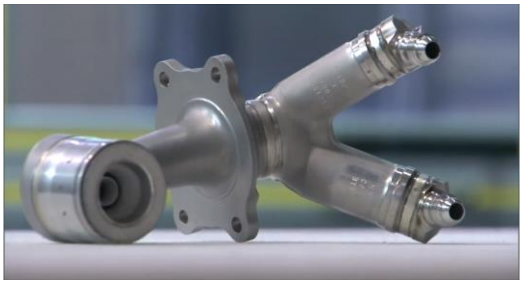

FIGURE 9 [15]
LEAP Engine fuel nozzle

Advanced Turboprop

Another one of GE's products made through AM is its advanced turboprop. A turboprop functions in accordance with the same principle as a turbofan, but uses a much smaller propeller instead of a large fan [18]. This makes the engine lighter and more efficient, but only at low speeds, deeming the turboprop as the preferred engine for small planes [18].

Due to its smaller size, GE decided it would be feasible to revamp the turboprop to the extent that it would mostly be made of AM components. Its new product, the Advanced Turboprop, is still currently under development, but already 35% of the engine's parts are printed, more than any aircraft engine in history [16]. Much like the LEAP engine fuel nozzle, the use of AM allowed GE to consolidate multiple components, reducing the number of components from 855 to only 12 [16]. According to GE, "the simpler design reduced weight, improved fuel burn by as much as 20 percent, and achieved 10 percent more power" [16]. These significant improvements in efficiency translate directly to an environmental benefit and will save the company money, all while increasing the lifespan of a turboprop.

The advanced turboprop began testing in late December 2017, and is planned to power a flight in late 2018 [19]. If all is well, the advanced turboprop would be a milestone for the AM industry, showing that one day AM can be used to build an entire engine, not just a high performance fuel nozzle; a significant mark of sustainability.

ADDITIVE MANUFACTURING: A PROMISING FUTURE

AM has many apparent advantages over subtractive manufacturing. These benefits include faster build times, reduced material waste, and the ability to produce complex structures. When applied to the aerospace industry, these benefits have been able to decrease costs, weight, greenhouse gas emissions, while also increasing fuel efficiency. The consequences of AM are clearly positive, and will only get better over time, confirming it as a sustainable technology. The perks of AM are built upon the foundation of a young history marked by impressive research and technical advancements. If the track continues, one day AM will become the primary means of production for all machines, tools, and products, all of which would possess smarter, more complex designs and considerable financial savings.

AM has rightly been coined a revolution by many engineers and professional societies [3]. Just as any other revolution, we will see AM hold a significant role in our society, remaining functional, beneficial, cost effective, and sustainable for many decades to come. If the internet revolution provided an abundance of information, the additive revolution will bring about an abundance of efficiencies across all fronts. However, we are far from that moment, as AM still has many technical obstacles to overcome. But the idea of fully utilizing the breadth of AM capabilities has spurred considerable interest, research, and investment.

As concluded by AM expert, Edward Herderick of Ohio State University, "The future for additive manufacturing is bright. Today, it is an exciting technology with a relatively limited number of materials and process combinations. It will be up to the community to apply fundamental physical metallurgical principles and materials-intensive processing fundamentals to unlock its full potential and continue to accelerate the additive revolution" [3].

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