Additive manufacturing (AM) – also known as '3-D printing' – is the latest process revolutionising parts manufacturing. The concept is now extending into engine production, with several manufacturers emphasising the long-term potential AM has for the industry. The types of AM in use, and the effects they may have on the future of manufacturing, is explored here.

3-D printing & AM of engine parts, & the affects on maintenance

2015 has seen Additive Manufacturing (AM), similar to 3-D printing, become one of the most topical breakthroughs seen in the aviation industry. It is commonly referred to as a 'disruptive technology', since it is changing the way original equipment manufacturers (OEMs) are looking at design and manufacturing.

The focus has predominantly been on the advantages that AM could deliver for engine parts manufacturers and engine parts maintenance. Rolls-Royce (RR) announced earlier in the year that it will test fly an A350 XWB with an AM-manufactured front bearing housing in its Trent XWB-97 engine. At about 1.5 metres (three feet) wide, and half a metre (20 inches) thick, the front bearing housing acts as the main support member for the forward part of the engine, and carries the bulk of the loading inside the engine. It also holds the roller bearings that are responsible for locating the low pressure (LP) and intermediate (IP) compressors and contains almost 50 AM-produced airfoils, so the front bearing housing is likely to be one of the largest engine parts produced using AM to date.

Another example of an OEM making proactive efforts to optimise AM in its processes is General Electric (GE) and Snecma's joint venture CFM International. When its CFM LEAP engine enters service, each engine will have 19 3D-printed fuel nozzles in its combustion system. "These are the fuel nozzles for the advanced LEAP Twin-Annular, Pre-Swirled (TAPS) combustor that will be manufactured via AM," confirms Gareth Richards, LEAP program manager at CFM International. "CFM's parent company GE Aviation began developing the LEAP fuel nozzle in the early 2000s."

The TAPS fuel nozzle, which mixes air and fuel before ignition in the combustion chamber, is a revolutionary concept in itself. Using AM allowed the company to further optimise the design. "Since it was not limited by the use of machine tools, the design is more 'organic'," continues Richards. "The result is a part that is lighter and more durable than the same part manufactured using traditional subtractive techniques. The design has been proven over tens of thousands of component and engine test hours and cycles."

The fuel nozzles do not require a separate certification because they have been manufactured by AM. "Instead, the company followed the normal component qualification process, which included specific component tests and analysis to demonstrate compliance with US Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) requirements," says Richards.

These nozzles are anticipated to be up to 25% lighter than earlier parts, more durable than a conventionally made part, and ultimately simpler to produce. For example, while a conventionally-produced fuel nozzle would have had more than 25 individually brazed parts; an AM fuel nozzle produced by CFM has fewer than five. This has implications for the integrity of engine components.

Other examples of AM advantages include greatly reduced lead times to manufacture, and increased part and design abilities. These benefits will be further explored throughout this article. It is important to note that any materials used throughout the engine modules (most specifically the turbines, compressors and combustor sections) will have to endure, and function over, exceptionally high pressure, temperature and stress environments, and all manufactured components, whether AM-produced or traditionally casted, need to be proven to withstand these conditions.

Traditional machining, also known as casting, requires specific tooling, fixtures and the purchase of large quantities of material that end up as waste after production. Altogether, business processes for casting are time-consuming and not particularly efficient from cost, time and environmental perspectives.

Machining materials can be difficult, particularly when their properties can include low thermal conductivity and high strength. These types of metals – commonly known as 'super alloys' – can damage machining and cutting tools. Turbine blades are, however, an example of a component where complex casting and machining procedures are essential. This is due to the exceptionally high temperatures and pressures experienced (particularly in the HPC and HPT) when the engine is operating. Cooling ventilation ducts are therefore drilled, lasered or casted into the blades.

Types of AM

AM is a generic term that covers a variety of processes, each designed to build up components layer-by-layer. In GKN Aerospace, AM is seen as subtly different to 3-D printing. "Whereas 3-D printing most commonly refers to the use of polymer or plastic materials, we use the term 'additive manufacturing' (AM) more specifically for the use of highly

Additive manufacturing has implications for the production of complex parts, such as fuel nozzles

engineered end-use metallic components," explains Rob Sharman, global head of additive manufacturing at GKN Aerospace.

GKN Aerospace has been at the forefront of industry developments using AM. It has established three centres of excellence worldwide in: Bristol, UK (powder bed); Trollhattan, Sweden (mainly fine scale deposition); and St. Louis, Missouri, USA (predominantly large-scale deposition). GKN Aerospace works closely with its sister division centre of excellence in the state of New Jersey, USA that specialises in powder metallurgy. GKN Aerospace began investigating AM in 2012.

In terms of testing the integrity of AM-produced parts, there appears to be little difference from the traditional methods of part testing. "Ultimately, a metal is produced, so the testing is the same as you expect to ensure the integrity of any metallic component," explains Sharman. "What is evolving through the use of AM is our design and material processes and abilities. We are now able to produce parts and design features that were just not possible before."

Ultimately, AM is about designing the whole system around the functions it performs. "AM, like traditional casting, is a generic term," continues Sharman. "There are a variety of different processes that can be applied, each depending on the application of the component in question. We pick each process, depending on the material in question, the function and size of the component, and the rate of production required."

Processes currently most common in AM and 3D printing include:

● Selective Laser Sintering

One of the mainstream technologies in 3D printing and AM is selective laser sintering (SLS). SLS is the process of creating components from powders using atomic diffusion. These powders are typically particles of polymers, ceramic or glass which, via a high-powered laser, get fused together layer-by-layer on a build platform inside an AM apparatus. This apparatus is typically programmed to perform functions via an STL-formatted file, which is a file format that is recognised by the AM apparatus. This file is converted from a computer-aided design (CAD) file that is produced via a computer. This instructs the laser to 'print' various structures in accordance with the required component design.

The term 'sintering' refers to the powder being heated to just below its boiling point, which is just enough to fuse the powder particles into a solid state. Layer-by-layer this process is repeated until the object is completed. Each layer is often less than 0.1mm, usually between 20 to 100 microns.

When the object is fully formed, it is left to cool in the machine before being removed. Once cooled, the object is generally finished, requiring little or no post-production treatment.

Boeing has recently implemented SLS into its manufacturing processes across military and commercial fleets, producing small, polymer parts for environment control system ducts (ECS) in the airframes. Direct metal laser sintering (DMLS) is the metallic version of SLS.

● Selective Layer Melting

Munich-based MTU Aero Engines has begun using selective layer melting (SLM) in its parts production. This process is used to producing borescope bosses for the PurePower PW1100G-JM engine that is the Pratt & Whitney (PW) engine to power the A320neo family.

After creating a 3D CAD model of the component to be manufactured, a laser then builds up the solid equivalent of the model layer by layer from a powdered material. Benefits include the ability to manufacture with only small amounts of material and few tools. This is ultimately both efficient and economical from a business perspective, because it brings down production costs.

As part of Clean Sky, a European technology initiative, MTU is currently manufacturing a seal carrier using additive processes. The inner ring with integral honeycombs will be installed in the high-pressure compressor of the PW1000G and contribute to a weight reduction. Lighter designs are one of the key objectives in engine and aircraft construction.

● Electron beam melting

Much like SLS, electron beam melting (EBM) technology builds up a powder layer-by-layer, melted by a powerful electron beam. Rather than plastics, however, metallic compound powders are used. Once again, each layer is melted to the exact dimensions defined by a CAD file programmed by computer.

The high-power electron beam generates the energy needed for high melting capacity and high productivity, and is controlled via electromagnetic coils, allowing it to be extremely accurate. EBM takes place in a vacuum and at a high temperature, resulting in stress-relieved components with material properties better than cast components and comparable to wrought-produced material.

Each material used in EBM will have specific properties, including an individual ambient temperature. To mitigate against additional and residual stress during the AM process, the electron beam heats the entire powder bed to this optimal temperature, rather than beyond it, which would overheat the material and subject it to unnecessary stresses.

The front bearing housing produced

GKN says additive manufacturing cuts cost, reduces waste and lowers environmental impact

by RR was manufactured via EBM. GKN also uses EBM for titanium components, such as fittings and brackets. "EBM is the preferable AM method for small to medium components, since it builds fast, is economical and has limited residual stress," adds Sharman.

- Powder Bed Fusion

Powder bed fusion (PBF) is used in both SLS and EBM processes. All PBF processes involve spreading the powder material over the preceding layers, often using a roller or a blade. A reservoir below or beside the bed provides fresh material supply. Loose, unfused powder remains in position, but is removed after the process is completed. Once again, PBF is popular with small intricate parts, which need complex and accurate detail.

- Laser-wire deposition (LWD)

Laser-wire deposition is most commonly used for free-form manufacture. It is well suited for such tasks as adding features to engine casings.

Using laser welding and wire filler material, structures are once again built up layer by layer. The deposition process is sensitive to disturbances and is subject to rigorous monitoring and adjustments. Again, a 3-D scanning system is developed and integrated with the robot control system on the apparatus. This allows for automatic in-process control of the deposition. Layer height is monitored and influenced by controlling the wire feed rate on each deposition layer. Laser wire deposition is now being tested through the deposition of engine bosses.

- Blown powder deposition

Once again, blown powder deposition (BPD) is similar to 3-D printing, since material is deposited from a nozzle onto a substrate. The metal powder, however, is blown into the focal point of a high-powered laser with the nozzle positioned so that the powder can be deposited on the substrate, or previously built layers.

The process has very high deposition rates and can repair damaged components, but its dimensional accuracy is poorer than that of the SLM processes. Overall, blown powder deposition is best suited to repair and modification of high-value components.

Titanium 64 (6Al-4V) is the most widely used metal across GKN's production portfolio in AM. "This material responds well to the AM process," explains Sharman, "although we are exploring material options."

Further to MTU's involvement with the PW1000G family and AM, PW has been making AM prototypes (including tooling and development engine hardware) for a number of years. "We have made hundreds of AM parts to support development of the PurePower® Geared Turbofan™ (PW1000G) family of engines, and have flight tested and certified some of the components for our PurePower engine," begins Dr Williams Brindley, manager of advanced manufacturing and aftermarket technology at PW. Some of the AM parts for the PurePower engine family include compressor stators (or airfoils) and sync ring brackets. The first production PurePower® PW1500G engines with AM parts will be delivered in late 2015. This is the exclusive powerplant for the Bombardier C Series.

"We will be the first to use AM technology to produce parts, including compressor stators and sync ring brackets, in new jet engines that will be delivered to customers," continues Brindley. "Some of the benefits we have seen include up to 15 months' lead-time savings compared to conventional manufacturing processes, and up to a 50% weight reduction over produced parts."

The methods that have been applied to developing and introducing AM components for use in the PurePower engine series, include: EBM and PBF which are used for the synch ring brackets; and Laser PBF (including direct metal laser sintering (DMLS), used in the compressor stators. "As important as the build process is, it is worth noting that post-processing is just as critical in completing AM components," continues Brindley. "There may be multiple thermal processes affecting material properties, such as strength, hardness and ductility. Depending on the part, we may need surface-finishing techniques to support aerodynamic performance and mechanical properties, such as fatigue strength. We use five-axis milling to get the tighter tolerances for critical surfaces. Also, 3-D scanning, in addition to several other inspection and testing techniques, ensures the parts being installed in our engines are of the highest quality."

Effects on repair

Traditional repair methods will still exist for any component, whether casted or created by AM. Sharman anticipates that repair techniques will remain the same with AM-produced components. "While there should be no significant difference in repair methods and overhaul of AM-produced parts, AM enables repair, where repair was not previously possible or economic," explains Sharman. "An example is the blown powder deposition process, which is able to repair and modify high-value components. Also, AM is far more efficient for creating one-off or small numbers of parts for legacy portfolios, where regular part production no longer takes place."

Supporting legacy programmes that are out of production is very inefficient via casting processes. This is where efficiency hinges on mass production of parts, but the flexibility and lack of tooling suits AM.

"AM components are designed and built to meet the same engineering criteria, safety, and quality as components that are conventionally manufactured.

AM and 3-D printing provide a strong business case not only for the original production of engine parts, but also for their repair during maintenance.

This includes the designed life of the part," confirms Brindley. "We launch appropriate repair programmes parallel to each technology we implement. And as each technology or component matures, the appropriate repair development programmes are launched to achieve high-tech repairs after the component enters service.

"For an AM component, as for a conventionally manufactured one, the developed repair must take into account the service condition of the component, its required capability, and the value to the customer of repairing it," continues Brindley. "Also, as for conventionally-manufactured components, the eventual repair process might not include the original manufacture methods as part of the repair. Ultimately, however, the equipment and tooling required for repair of an AM component follow the same considerations as for a conventionally-manufactured component."

One question AM raises is whether the replacement or repair of engine parts will generally become the norm once AM becomes mainstream for the manufacture of components throughout the engine. This will have implications for the aftermarket, and activity for repair providers. "While the use of AM is tied directly to recognised benefits, the repair-versus-replace decision for these components is made on the same basis as for conventionally-manufactured materials," says Brindley. "Safety and quality, as always, is the first consideration, and the long-term benefit to the customer is the second. AM allows both the manufacturing of new parts, and repair solutions for components in terms of design, speed, flexibility and affordability. AM, therefore, does present a strong business case to both replace and repair engine components."

In the case of GE's and CFM's AM experiences, some changes are expected. "Each new engine technology requires its own unique repair processes," says Richards. "The repairs for the LEAP fuel nozzle were developed along with the technology itself, as were, for example, the repairs for the carbon fibre composite fan blade and the ceramics matrix composites in the high pressure turbine of the LEAP engines." In addition, minimal need for repair is expected. "The focus on the design of the LEAP fuel nozzle was to provide a highly durable, efficient part that would meet the demands of the engine lifecycle consistently, while also achieving dramatic reductions in NOx emissions," confirms Richards.

Overall advantages

While PW's experiences have shown some life cycle improvements, AM has offered other significant benefits focused on the production processes.

- Time

"AM dramatically reduces production time, from design, to prototyping, to the finished product," highlights Brindley.

- Efficiency

AM decreases waste and consumption of raw materials.

- Accuracy

"AM's manufacturing capabilities allow the production of parts with complex geometry, all with reduced tooling," explains Brindley. As seen by CFMI's fuel nozzle developments, it also significantly reduces the number of parts in a component or module.

- Operational benefits

AM reduces inventory, because parts can be made at site of assembly 'just-in-time,' based on demand.

- Environmentally friendly

AM reduces the carbon footprint in the manufacturing process by reducing the amount of raw material used and the number of subsequent operations.

The importance of being able to design parts purely for their eventual function, with fewer parts per component or module, also holds huge implications for manufacturing and assembly lines, as well as the aftermarket for out-of-production engine series.

It also allows OEMs and part manufacturers to become a little more experimental and innovative in their design processes. Because less time is taken during the manufacturing, and resource waste is so much improved, a design team can spend more time designing and developing parts without having to fix a design too early to allow for the long lead time for tooling.

As AM technology develops, manufacturers will increasingly adapt the design of components to take advantage of the specific opportunities the new production processes offer. In future, Sharman anticipates that benefits will include the ability to truly influence the materials and component properties in use during manufacture. "We will be able to functionally 'grade' structures, and create tailored microstructures, and even functionally graded alloys we produce as the part is being built," summarises Sharman. "Alloys being developed for the AM processes do not exist, so we are looking into which alloys are the best to respond to EBM and SLS techniques. By exploiting the benefits of AM and the properties of these alloys, we will be able to even further enhance the performance of parts and materials and create new properties as we manufacture."

AM has clearly been on OEMs' minds for some time, and 2015 has seen the emergence of these revolutionary techniques starting to impact the market. This will inevitably lead to even more competition among OEMs and, to come extent, MRO facilities as they ensure that their ability to perform cutting-edge technology remains above that of rival manufacturers and repair providers. AC