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The uses of Additive Manufacturing technology in aviation

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Abstract:
Additive manufacturing refers to the process when a component is manufactured by the contentious addition of material on a substrate. It offers high geometric freedom in manufacturing without sacrifice in structural strength and allows reduction in weight by using material more efficiently. These unique abilities that conventional manufacturing do not have offers new opportunities for aviation industries. The used of additive manufacturing in aviation started in the 2010s, however, because it is still a relatively new technology in aviation, its use has been limited. In recent years more additive manufacturing started to appear in aero-engines, in the cabin and new experimental projects conducted gives new insights on how we may make use this technology. This review will discuss the current usages of different additive manufacturing technologies in different sections of aviation, repairing technology using additive manufacturing, the detection and removal defects of additive manufactured components and the future prospects of additive manufacturing in aviation.

Keywords: Additive manufacturing; Aviation; Hybrid manufacturing.

1. Introduction

As air traveler number reaches a new height in 2024 (10.4% increase compared to 2023, 3.8% above pre-COVID-19 levels), more environmentally friendly and economical flights has become a common goal for airliners[1]. Members of the IATA has committed to achieve net zero carbon by 2050, new aircraft technology to achieve sustainable air travel is to be found, additive manufacturing as a innovated production method have started gain attention in the field of aviation[2].

Additive manufacturing (AM) as stated in its name, is a method of production in which material is added layer be layer to produce the final product, major characteristic of additive manufactured materials includes lower weight and geometry flexibility. AM have proven it self in manufacturing of propeller blade of ships and train structural pivot, showcasing its ability in providing light-weighted and high strength products in relevant industries[3].

Existing thesis and application revealed huge potentials for the application of AM in aviation industry. Weight reduction, more efficient propulsion and improvement in maintainability as some of the diverse routes towards greener flights that may be achieved by the used of additive manufacturing[4]. Despite

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such advantages, AM faces barriers such as certifications, quality control and lack of methods of fatigue evaluation[5].

2. Usages of additive manufacturing in aviation

2.1 Usage in aero-engines

The usage of AM in aero-engines have already revolutionized the propulsion system of aircraft. In the general electric GE90, GEnx and GE9X engine. The GE90's T25 sensor housing was the first FAA certified additive part (2015), the GE9X engine uses roughly 300 AM made component, setting a record for the use of different AM technology in aero-engines[6].

The GE90's T25 sensor housing uses Selective Laser Melting technology (SLM), and made SLM the first applicable AM method in the aero-engines industry. Selective Laser Melting is a high accuracy additive manufacturing technology that uses high-energy laser beams to melt and solidify metal powders layer by layer to produce high precision and complex structured metal parts. In a sealed, inert gas-protected forming chamber, the metal powder is evenly laid out on the forming platform. A high-power-density fiber laser, controlled by a directing system, scans the laser beam to melt the cross-sectional outline of the current powder layer, the melted metal then forms an integral metallic structure after solidification. Use of SLM in T25 sensor housing combine 10 individual parts into a single complex structural part, thereby increasing the accuracy by 30%[6].

In 2020, FAA certified the first flight crucial engine component, the #4/5 bearing housing on the Honeywell ATF3-6 engines. "We were able to use our expertise in additive manufacturing to produce the qualified part much faster, reducing our lead time from approximately two years to two weeks.", said Jon Hobgood, vice president of manufacturing engineering, Honeywell Aerospace. The success paved the path for future applications of AM on aero-engines[7].

The TAPS III (twin-annular pre-mixing swirler) combustor on GE9X uses fuel nozzle made of Cobalt-Chromium Alloy using SLM technology[6]. The use of SLM turned what used to be 20 individual parts into a single component, achieving 25% weight reduction, 500% increase in durability and 95% reduction in spare parts[6]. SLM gave higher freedom in designs, such as internal flow channels in the fuel nozzle and complex structure of combustion mixer. Allowing air to mix thoroughly with vaporized fuel ahead of combustion, creating a initial lean burn environment. As the fuel combust the burn only becomes leaner and avoids the peak flame temperature happening at the stoichiometric fuel-air ratio in between rich burn (excess fuel) and lean burn (excess air) region. On the GEnx, the TAPS II system achieved a 60% cut down in NOx emission.

GE9X uses Electron Beam Powder Bed Fusion technology on Titanium-Aluminium alloy to manufacture its low pressure turbine blades. The Electron Beam Powder Bed Fusion (EB-PBF) technology uses a high-speed electron beam controlled by magnetic coils in a vacuum environment as its heat source to melt metal powder layer by layer to create parts. The electron beam first scans the entire powder bed surface at high speed, heating the metal powders to temperatures of several thousand degrees. After the preheating, the electron beam switches to higher energy density and scans the surface according to the cross-sectional outline of the current layer, melting and solidifying the metal powder in the designated area. After one layer is completed, the platform will descend by a layer thickness. This process is then repeated until the part is complete. The high-temperature environment made it free of residual stress problems, making it suitable for the manufacturing of large, uni-body structural components, the parts made from EB-PBF are less prone to deformation and internal defects[8]. The GE9X uses 228 of such blades as shown in Fig.1 in stage 5 and stage 6 of its low pressure turbine, the use of EBPBF achieved a weight reduction of 50%(about 400 pound per engine)[6].

Fig.1 GE9X's TiAl low pressure turbine blade[8].

2.2 Usage in cabin

The first usage of AM in cabin also dates back to 2015, when Airbus uses SLM in the manufacturing of decorative panels between the cabin and the kitchen of the A320 aircraft[9]. In 2017, Boeing manufactured titanium alloy structural component for the Boeing 787's kitchen using

Rapid Plasma Deposition technology from Norsk Titanium and became the first FAA certified AM component in the cabin[9].
AM together with topological optimization can be used to manufacture structural parts with far less weight. Topological optimization is a method which reduces unnecessary materials to achieve lighter weigh while maintaining the structural performance. The process involves removing materials in regions withstanding minimal structural load and increasing of strength of material (changing density or the material) in high stress regions. However, after topological optimization the structure often have non-regular shape and non-uniform density or strength requirement, hence made it difficult or even impossible to be manufactured by conventional method of injection modeling. Addition manufacturing methods such as Laser-Directed Energy Deposition (L-DED) allows complex geometries to be manufactured and made them the perfect choice in manufacturing topological optimized products. Unlike SLM, in which each layer is formed by selectively melting power in desired regions on a power bed, L-DED uses a nozzle to feed power to the melt pool. By changing the proportion of the powder components during the printing process, smooth gradient transition of different materials can be achieved within a single part. It can be used in the production of seat frames, overhead luggage racks frame and other furnishings to reduce weight.
If we classify the consequence of component failure according to its function into three categories: mild (failure will not significantly impact the safety of the aircraft or affect the work of the crew), sever (failure may affect safety of aircraft, cause discomfort to passengers or interfere with the work of the crew) and catastrophic (failure disables the plane to fly and land safely)[9]. The failure cabin components such as chairs and decorative panels largely belongs to mild class of failure, which means that it is less relevant to the safety to the whole aircraft. Hence the regulations and certifications of AM part used in cabin is less complex than AM used in structural and functional parts. Simpler certification is faced by AM parts in the cabin, allowing a wider usage of AM parts in cabin.

2.3 Usage in structure

A team led by Professor Huang Weidong and Professor Lin Xin from Northwestern Polytechnical University used L-DED technology to manufacture the 3100mm long rib chord of the COMAC C919 and passed COMAC's examinations upon defect and mechanical property[9]. It proves that AM is capable of manufacturing large-scale, load-bearing aircraft components.

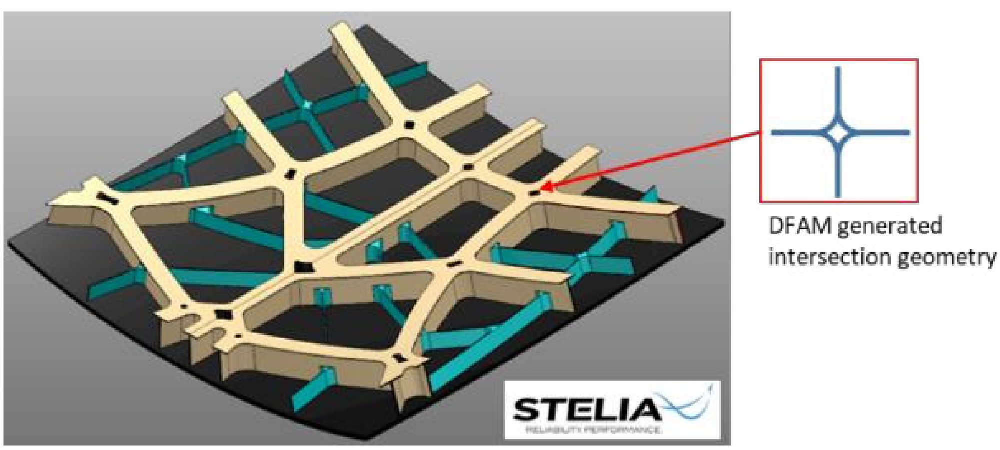

Fig.2 Structural panel designed for AM[10].

A demonstration project held by French DGA/DGAC together with Stelia aerospace, Constelium, Centrale Nantes and CT Ingenierie exploits the use of AM together with traditional manufacturing in on a self-stiffened double curvature structural panel[10]. The panel has a double curvature shape with main radius of 2000 mm and secondary radius of 9500 mm as shown in Fig.2. Different from conventional method of bolting a skin on to pre-manufactured frames, it uses the skin as a substrate and uses AM to print out stiffeners to create a monolithic structure. This gives more geometric freedom in designs, the distribution of stiffeners will not be restricted by conventional standard profiles can be optimally designed according to the actual load, maximizing materials utilization and achieving the goal of weight reduction. In this double curvature structural panel, primary stiffeners with "T" shaped cross section (beige color in Fig.2) and thin secondary stiffeners (blue color in Fig.2) are printed using WAAM technology. Wire Arc Additive Manufacturing (WAAM) is an AM technology that uses an electric arc as a heat source to melt metal wire layer by layer to produce three-dimensional metal components. It has the advantage of bigger, quicker and

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cheaper production, making it particularly suitable for rapid prototyping and small to medium batch production of large or medium-sized complex metal structural parts.

The processes eliminated bolts as well as the corresponding drilling and installation in manufacturing. Resulting in the reduction of manufacturing cost and shortening of the production cycle. At the same time, it eliminates the stress concentration and potential fatigue around the bolt holes. It could potentially be used in the production of wing panels, fuselage sections or door frames.

3. Repairing using hybrid manufacturing

Another advantage of AM is its ability to repair damaged parts, hybrid manufacturing using CNC and L-DED can save repairing time, cost and reduce the amount of spare parts needed in operation. The repairment goes through a four step process: identification, removal, refill and finally surface cleaning as shown in Fig.3[10].

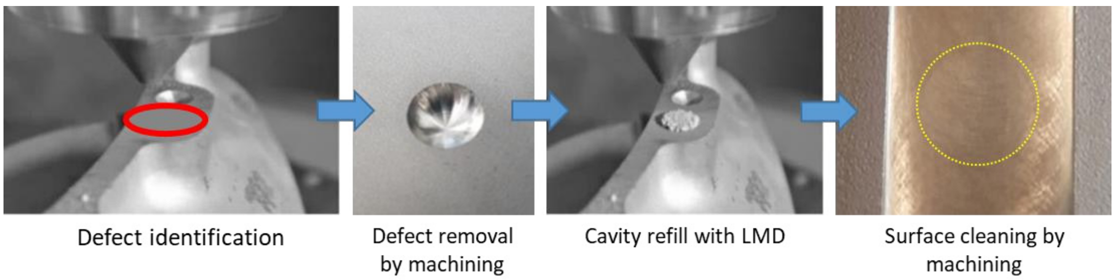

Fig.3 Example of repairing using hybrid manufacturing[10].

Firstly, the 3D data of the component to be repaired is obtained through three-dimensional scanning, the data is compared with the original CAD model to identify the region that need to be repaired. The software generates the processing path for L-DED and the processing path for subtractive manufacturing based on the geometries of the damaged area. The damaged material is removed and the region is cleaned, leaving a cavity with fresh metal surface. Repairing material is then deposited layer by layer on the damaged region to restore the normal shape of the component. This process is carried out under inert gas protection to prevent oxidation of the surface of the cavity. After additive repair, CNC milling was used to process the repaired area to meet the final surface finish requirements. Finally non-destructive testing such as ultrasonic testing and performance evaluation on the repaired components is done to ensure the quality of repair[11]. Compared to traditional repairing methods, the repair layer and the substrate are metallurgically bonded at the atomic level with high strength. Refilling can use the same or different materials as the substrate, and even functional gradient materials to realize performance optimization.

Previous studies have investigated the use of Al-Mg-Sc-Zr alloy powder and L-DED to repair 5083 aluminum-magnesium alloy structure[12]. The study compared the micro structure and mechanical properties of the repaired structure with the original substrate. Testing gives that tensile strength of the repaired sample (197.73 MPa) is not significantly different from an original 5083 sample (190.80 MPa), and is even a slight stronger[12]. Which is caused by Grain Refinement Strengthening and Dispersion Strengthening, effectively compensating the loss caused by gas porosity defects. However, the ductility of the repaired sample significantly decreased[12]. The gas porosity defects becomes concentration of stress during the stretching process, cracks would emerge and propagate from these points, causing the sample to break with less force.

In aviation, it can be used to repair cracks and wearing of metal part such as turbine blades, where the repair cost using hybrid manufacturing is only 1/5 to 1/10 of a replacement. Enabling a large number of previously unrepairable damaged components to be fixed and reused, saving money and the resources to produce new spare parts.

4. Defects and their detection

4.1 Types of possible defects

Porosity is the main sources of fatigue cracks in metal structures[13]. Porosity refer to tiny holes or cavities present within the internal structure of metal AM parts. These holes disrupt the continuity of the material and become stress concentration points, causing metal fatigue and failure of the parts within their designed service life span. Components of the same density may exhibit significantly different performances due to variations in the type, size and distribution of porosity present.

There are two type of possible porosity based to how they are formed, they are porosity due to Lack-of-Fusion (LOF) and Gas Porosity (GP)[13]. LOF porosity is due to improper setting of process parameters, insufficient energy input prevented the complete melting of the metal powder or the adequate fusion between the current molten pool and the previous layer. LOF porosity is mostly presenting large irregular shapes such as sharp corners distributed along the boundaries of the melt channels or between layers. By adjusting the process parameters, LOF porosity can be significantly reduced. Gases may be wrapped around the raw material powder during the manufacturing process, which are released during melting and trapped in the rapidly solidifying molten pool, causing GP. GP are relatively small, near spherical and randomly distributed within the molten pool. As GP originates from the raw material itself, it is hard to remove using optimized manufacturing method. Elimination of porosity can be achieved by Hot Isostatic Pressing (HIP) post-processing[14]. During the HIP process, high temperature (≈0.8 times the melting point) and isotropic high pressure (100~200MPa) via an inert gas is simultaneously applied onto metal parts. Under high temperature and high pressure, the material exhibits a plastic flow, defects such as porosity will be closed and become a rigid metallurgical bond.

Another type of defect present is residual stress[13]. Residual stress is caused by the rapid cooling of material in AM, residual stress generated during AM is inherent and must be released to prevent the part having severe deformation or even cracking when it is cut from the substrate or undergoes subsequent processing. Residual stress can be effectively reduced by post-process heat treatment.

4.2 Defect detection methods

Defects are very common in manufacturing, how to control and reduce defects becomes important in ensuring quality of products. Especially in aviation where parts are expected to serve for decades, a minor defects after years of service may lead to a major problem. Parts such as the frame of the aircraft undergoes periodically varying forces due to cabin pressurization during its service. Hence it is crucial to be able to eliminate defects in production and regularly inspect parts for newly emerging defects during its usage. The detection technologies of metal AM parts can be classified into three main categories: pre-process powder characterization, in-process monitoring, and post-process detection.

Before the manufacturing process begins, it is important to ensure the quality of the raw material. Some pre-process powder characterization methods includes:

l laser diffraction: measure of size of grain

l scanning electron microscope: measure of shape of grain

l hall flowmeter: measure of flow speed of grain

l Inductively Coupled Plasma: inspection of chemical component of power

l Micro-CT: inspection of existence of porosity

In-process monitoring during the printing process detects defects and allow corrective actions to be taken in the process to ensure yield of production. In-process monitoring methods includes:

l melt pool monitoring: monitor the size of melting pool to examine possible defects

l powder bed monitoring: ensure even distribution of powder

l layer-wise monitoring: inspects macroscopic defects such as deformations and bumps

l temperature sensor monitoring: used in indirect assessment of the accumulation of residual stress

After manufacturing is complete, parts still needs to undergo a Non-Destructive Evaluation (NDE) to confirm whether they meet the design and safety specifications. NDEs are also used in routine inspections for potential defects and fatigue formed in service. Some common NDE methods are:

l Neutron Diffraction: measure 3D residual stress distribution deep inside the part

l X-ray Computed Tomography (X-CT): precisely quantify the porosity, distinguish between GP and LOF defects using X-ray imaging from multiple angles

5. Challenges and future developments

Certifications is the most important factor limiting the use of AM, EASA have started work on qualification and certification (Q&C) of AM around 2015 and achieve successful outcome[15]. Part of the problem is the lack of experience and real life data for setting a standard for manufacturing. Like carbon fiber, every new technology needed time to gain trust from regulator, industry and most importantly the public, such accumulation of trust takes considerable time to achieve.

Building a fatigue profile is a very important step toward wider usages of AM[5]. A fatigue profile would include Stress-Number of cycle (S-N) curve, Stress-Number of cycle (ε-N) curve, Crack extension per unit cycle-Load (da/dN-K) curve and other parameters. Crack propagation in AM components exhibit anisotropic behavior. The resistance and speed of crack propagation in a layer and in between layers may be very different, making it impossible to model using previous data from conventionally manufactured parts. Therefore, accurate data of da/dN-K curves for every specific AM material is a precondition for safely applying them in aviation.

In terms of Defect detection, X-CT is currently the most promising non-destructive testing technology for defects of AM products[13]. However, setting a quantitative standard of how to determine whether a defect is "critical"

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based on the CT results remains a major challenge for the industry. X-CT is also very expensive to operate and has limitations due to limited penetration in high-density materials or large parts. Hence it is important in the future development to find a NDE technology that is suitable in examining large component quickly, accurately and also a low cost.

6. Conclusion

AM has a promising but challenging future in the field of aviation, its unique ability to produce light weighted, complex, large uni-body components with high material strength and conduct metallurgic repairing is a perfect match with the industry. However it also faces problems such as high costs, defects, Q&C and lack of industrial experience.

Future developments may focus on gaining more data on AM parts, setting a standard for production and finding more cost effective production, defect inspection and removal methods. With more time, it will become a major tool in future aviation and the key to a sustainable future.

References

[1] International Air Transport Association (IATA). Global Air Passenger Demand Reaches Record High in 2024. Geneva: IATA, 2025.

[2] International Air Transport Association (IATA). Our Commitment to Fly Net Zero by 2050. Geneva: IATA, 2021.

[3] RAMSSES. Propeller blades by additive manufacturing.

[4] DLR – German Aerospace Center. Towards zero-emission aviation: DLR's new aviation strategy. Cologne: DLR, 2021.

[5] Jia Zhenyuan, Lai Yinan, Wang Fuji, Chan Ming, Li Yingguang, Zhan Lihua, Gu Bohong, Xu Chunguang, Lin Li, Duan Yugang, Ye Xin. Key basic scientific questions in composite material parts manufacturing: An academic review of the 248th Shuangqing Forum. Bulletin of National Natural Science Foundation of China, 2021, 35(5): 764–773.

[6] AM Reference. Full details of GE9X additive manufacturing technology are disclosed: What additive technologies were used for which components?

[7] Honeywell Aerospace. Honeywell achieves FAA certification for first flight-critical engine part built from additive manufacturing. Phoenix: Honeywell Aerospace, 2020.

[8] Colibrium Additive. Enabling metal additive production using electron beam melting technology. West Chester (OH): Colibrium Additive, 2024.

[9] 3D Science Valley. What specific airworthiness regulations does the civil aviation authority's review body focus on regarding additive manufacturing?

[10] Rauch M, Hascoet J-Y. Opening new opportunities for aeronautic, naval and train large components realization with hybrid and twin manufacturing. Journal of Machine Engineering, 2022, 22(4): 5–20.

[11] Xu Zifa, Ouyang Wentai, Jia Shaohui, Jiao Junke, Zhang Mina, Zhang Wenwu. Cracks repairing by using laser additive and subtractive hybrid manufacturing technology. Journal of Manufacturing Science and Engineering – Transactions of the ASME, 2020, 142(3): 031006.

[12] Zhu Hongbin, Hua Qian, Li Ruidi, Xu Rong, Lin Zeheng, Niu Pengda, Yuan Tiechui. Microstructures and mechanical properties of 5083 aluminum alloy repaired by laser directed energy deposition. Materials Science and Engineering of Powder Metallurgy, 2022, 27(1): 45–55.

[13] Kim F, Moylan S. Literature review of metal additive manufacturing defects. Advanced Manufacturing Series (NIST AMS 100-16). Gaithersburg: National Institute of Standards and Technology, 2018.

[14] TWI. What is hot isostatic pressing (HIP)? A complete guide.

[15] European Union Aviation Safety Agency (EASA). Joint EASA–FAA Additive Manufacturing Workshop 2023. Cologne: EASA, 2023.