



Comparison of 3D Printed Aluminium Additive Manufacturing in Aviation, As Opposed to Solid Aluminium and Environmental Impacts:

MSc Industry 4.0 and Advanced Manufacturing

An evaluation of Aluminium Additive Manufacture of fully functional aluminium components used in commercial aircraft seating for proof of concept, test and development, along with consideration of beneficial environmental impacts.

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Final Report

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Abstract

The utilisation of additive manufacturing technologies, particularly 3D printing, has gained considerable attention in various industries due to its potential to revolutionise traditional manufacturing processes for fabricating complex and customised parts. This paper researches the potential use of 3D aluminium printing, compared to conventional manufacturing methods. Aluminium, known for its favourable mechanical properties and is widely used in both traditional manufacturing and 3D printing processes. (Katz-Demaynetz, 2019).

This dissertation aims to provide a comprehensive analysis of the strength comparison between 3D printed and solid aluminium components. Utilising quantitative and qualitative examination of existing literature, case studies, and industry practices.

Exploring the validity of use, cost comparisons, demonstrating potential reductions in material waste, energy consumption, carbon emissions, and overall environmental impact associated with 3D aluminium printing as opposed to conventional manufacture. Researching the mechanical properties and performance of 3D printed aluminium, offering valuable insights for the potential of this technology in various engineering applications. At this point in time it is not fully accepted as practical solution for every situation. Nevertheless, the findings will contribute to a better understanding of the mechanical properties and environmental sustainability of additive manufacturing technologies, facilitating informed decision-making in industrial usage and applications where appropriate. (Rajesh. S, 2020).

Acknowledgement

There are many people in my life who have contributed, guided and encourage me to aspire to greater levels than I believed personally achievable. Sadly not all of them are here now to share in my demonstration and celebration of the capabilities that they knew I was able to portray. They would be as proud as those that still challenge me to grow.

It is with tremendous gratitude that I offer my thanks to everyone involved in my progression and achievements, family, friends and colleagues old and new. It is your support that has assisted me throughout the many years to hone my skill sets, develop professionally, to continue my learning, gaining experience and knowledge that served me well and for giving me a hunger to further academic goals.

Author's Declaration

I declare that the work in this dissertation was carried out in accordance with the regulations of UWTSD. The work is original except where indicated by special references in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the UWTSD.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

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A handwritten signature in black ink, consisting of a stylized 'N' followed by a flourish.

Date: 22 January 2024

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1. Introduction

Additive Manufacturing (AM), including 3D printing has emerged as a disruptive force reshaping conventional manufacturing. Renowned for lightweight and high strength ratios finds widespread use across industries (Hannibal, 2018).

This study aims to comprehensively assess and compare the strength attributes of 3D-printed aluminium against solid aluminium components, offering insights into the potential design and use of 3D-printed aluminium applications through modern advanced manufacturing (JCM 2020 Members, 2021).

Within aviation, stringent Airworthiness Regulations emphasize safety and apply universally, irrespective of aircraft type or purpose Meeting these exacting standards is mandatory for all components, regardless of size, material, or function. Aviation's rigors and demands addressing diverse challenges (Blakey-Milner, 2021). Once the criteria are established, a design team employs; testing, computer-aided design (CAD), dynamic and static stress assessments, and other methods to evaluate safety. Cost, performance and driving innovative solutions are paramount within the manufacturing sectors such as aviation, automotive, and other transportation whether it be pleasure, commercial or sports. The potential savings for a company such as SAFRAN Seats GB particularly during design and development as it provides bespoke luxury seating for all major airlines and work closely with aircraft industries to meet customer requirements.

2. Research

2.1 Aims

This research will be governed by the properties of 7075 T6 grade aluminium that is broadly used in the manufacture of frame components to build commercial aircraft that is supplied globally since introduction in 1945 (Clinton Aluminium Innovative Alloys, 2019) to air framers and airlines utilising CAM and CNC. It will examine the properties of both conventionally supplied 7075 T6 compared to Al7075 material. Additive Manufacturing Process relating Direct Metal Laser Sintering (DMLS) which is common methods used, providing insight as to the potential for commercial use. At best the results subtracted from current technology for additive manufacturing processes and aluminium powder used for this study could affirm its suitability.

2.2 Objectives

Consider practicalities for potential supply of aftermarket or new components and their conformity to regulations. Taking into consideration the composition structure from 3D printing. Comparing test pieces printed, using generative design artificial intelligence (AI) construction compared to conventional subtractive manufacturing from solid material. Comparing the tensile properties providing evidence of the decreases in development time, manufacturing cost and carbon footprint reductions through Additive Manufacturing. To emphasise the viability of use of modern additive manufacturing methods using aluminium powder material deployed during and throughout the development phases of design and prototyping of new aircraft components for concept design, functionality prove out and suitability or not for legacy parts.

2.3 Justification

Aviation industry projects that passenger numbers will continue rising and increase by an anticipated 70% projection growth. The United Kingdom aircraft industry is committed to significantly make changes and improvements, promising to cut carbon emissions from 30 million tonnes of CO₂ to Zero by 2050 aiming for a carbon neutral industry (Adams, 2020). Likewise aircraft manufactures and component manufactures have also made similar commitments to tackle global emissions. With respect to reducing carbon footprint, by using more sustainable materials, more energy efficient processes and production of less waste materials to that it benefits economies, social aspects and global issues improve the business reputation.

2.4 Methodology

Additive Manufacturing 3D printing methods are explored in the research along with Selective Laser Melting (SLM) is commonly used for producing functional prototypes and end-use parts. It creates parts additively by sintering fine metal powder particles. A high-power laser melts and fuses the metal powder into solid surfaces. One major difference with SLM technology process, is a high-power laser selectively fuses powdered materials, such as plastics or metals, layer by layer. The unfused powder surrounding the solidified layers acts as a support structure during printing. Direct Metal Laser Sintering (DMLS) is a metal additive manufacturing process that uses a high-power laser to

selectively melt and fuse metal powders together, layer by layer. The process takes place in a high-vacuum environment to prevent oxidation. DMLS can produce fully dense and functional metal parts with complex geometries. These are two of the most commonly employed methods with metals, however, there are others that could be used. In additive manufacturing, finding an exact equivalent aluminium powder can be challenging due to differences in manufacturing processes and the unique properties of the alloy. However, there are aluminium powders available that can provide comparable mechanical properties and characteristics to 7075-T6. Aluminium alloy powders such as Al7075 is quite close to 7075 T6 and often used in additive manufacturing processes, including selective laser melting (SLM) or direct metal laser sintering (DMLS) research method. These powders offer good strength, high hardness, and excellent corrosion resistance, making them suitable alternatives to 7075-T6. It's important to note that the properties of the printed parts can still be influenced by the specific process parameters, including laser power, scanning strategy, and heat treatment conditions. Therefore, it is recommended to consult with powder suppliers or additive manufacturing experts to identify the most suitable aluminium powder for your specific application and desired mechanical properties. **(RESEARCH, n.d.)**

2.5 Limitations

If the results have a negative outcome, this process could still be used to prove design intent. There is the competitiveness of being first to market. Advances in emerging technologies, continuous development and improvements of Additive Manufacturing machines compliment Just in Time (JIT) manufacture. The advancements in materials, applications, along with design and manufacturing engagements harnessing the power of cloud computing and AI are allowing development of products and release to market at unprecedented rates. There are many explorations taking place simultaneously across all sectors of aircraft manufacturing experimenting with biomaterials, analysing the feasibility for their potential applications of certain aircraft parts, however for now they are limited in application.

2.6 Ethics

The aircraft industry's carbon footprint poses a serious environmental threat. This sector is one of the leading emitters of carbon dioxide in the world, reducing emissions is essential for combating climate change. Fortunately, significant progress has been made in recent years in this area through the adoption of innovative technologies, operational changes, and the use of alternative fuels. Technological innovations play major roles in reducing the carbon footprints of aircraft manufacturers and airlines. Increased use of additive manufacture, lighter materials such as composites has helped reduce the environmental effects. All efforts to reduce aircraft industry carbon emissions have been aided in part by changes in technology and manufacturing practices.

2.7 Abbreviations.

3D	Three Dimensional
AI	Artificial Intelligence
AOG	Aircraft on
AM	Additive Manufacture
B-Rep	Boundary representation
BJP	Binder Jet Printing
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
DfAM	Design for Additive Manufacture
DLP	Direct Light Processing
EASA	European Aviation Safety Agency
EBM	Electron Beam Melting
EBW	Electron Beam Welding
FAA	Federal Aviation Administration
GD	Generative Design
ICAMT	International Conference on Advances in Manufacturing Technology
JAA	Joint Aircraft Associations
JIT	Just in Time
PB-AM	Powder Bed Additive Manufacturing
PBF	Powder Bed Fusion
RP	Rapid Prototyping
SLA	Stereolithography Printing
SLM	Selective Laser Melting
*.STL	Model Data export format
TAT	Turnaround Time
TPMS	Triply Period Minimal Surface
TO	Topology optimisation
Units	
Kg	Kilogram
nm	nanometer
µm	Micrometer

3. Background.

The aviation travel industry reports year on year increases in air the numbers of passengers. While passenger number are still below what they were pre-COVID they are rapidly returning to previous levels and from historical data and trend forecasting it will continue to grow year on year. Between 2009 and 2019 the air passenger industry revenue growth has risen from, approximately \$374 billion U.S. dollars to about \$607 billion U.S. dollars in 2019 (statista, 2023). Not only do millions of people as passengers use air travel, but it is also a major method of goods transportation and provides employments to millions of people globally. Safety is one of the most critical aspects of any aircraft, and engineers must have a thorough understanding of the physiological and psychological effects of aircraft design, operation, and maintenance on passengers, crew and staff on board. To this end, industry standards are designed and continually updated to ensure that aircraft remain as safe and reliable as possible. Aircraft must be designed with the utmost attention to detail, high specification and rigorous safety standards while allowing for the best possible ergonomics, ease of operation, and customer satisfaction (Singamneni, 2019).

3.1 Predominant Material

There are mostly likely as many components in a commercial passenger aircraft as there are words in an encyclopaedia, ranging from micro diodes to a wing spar. The most predominantly used single material in the aviation industry is aluminium. Its first use as early as **1903** (Clinton Aluminium Innovative Alloys, 2019) and for frames in construction of the famous or maybe infamous Zeppelin airships. Its use makes up around 75%-80% of a modern aircraft (Metal Supermarkets, 2016). Aircraft design and engineering teams must keep up to date with the latest technologies, advancements, and regulations. By staying one step ahead of the competition, the aviation industry is able to provide safer, more reliable, and efficient solutions while minimizing the costs associated with creating, maintaining, and replacing outdated aircraft systems. In order to create systems and components that meet the necessary required standards, aviation engineering teams must first understand the specific needs and criteria of the desired project. As part of this research, it is key to understand how and why it has such extensive use. There are several reasons why aluminium's high usage is so predominant, several grade types are used in the manufacture of aircraft components, typically the most common 6061, 6063, 2014, 2024, 5052, 7050 7062, 7068 and 7085 (**Clinton Aluminium Innovative Alloys, 2019**) [4].

3.2 Typical Uses in the Aircraft Industry

The outer skin and pretty much everything you cannot see internally that is covered with fabrics or plastics. Some examples are:

- a. Fuselage structures
- b. Wing spars
- c. Fuel Tanks
- d. Seats internals

- e. Doors
- f. Galleys
- g. Toilets
- h. Cockpit equipment and racking

There are some exceptions to the use of aluminium and those are typically found in the landing gear and engine parts (Singamneni, 2019).

3.3 Supply Chain and Aftermarket

Demand can be unpredictable, this makes it difficult to control inventory levels, especially since only 10% of the spare parts need to be replaced regularly (Singamneni, 2019). Long-term stored spare parts that are rarely exchanged are hard to predict and can become expensive. Standard inventory control strategies may not be effective in these cases and can lead to high inventory costs. Spare parts are usually divided into four categories: Rotatable, Repairable, Expendable and Consumable, each of which has its own replenishment policy. Inventory analysts are responsible for assigning these policies to thousands of spare parts and must update them often to keep up with market changes.

Compared to other industries, the aircraft industry's supply chain is one of the longest and most complex. Authorities must approve aircraft Maintenance, Repair, and Overhaul (MRO) organizations to carry out scheduled or unscheduled maintenance, including replacing spare parts, on the aircraft. Depending on the type of organization, customers can choose whether to make or buy the spare parts. MRO activities account for 40-50% of the industry's revenue and the sale of spare parts typically brings in more profit than the sale of original equipment (Singamneni, 2019). Aircraft spares availability is essential and keeping Aircraft on Ground (AOG) times to a minimum is profitable for airline operators, turnaround time (TAT) is an important performance indicator.

3.4 Emerging Technology

Metal printing technology being used within the aircraft industry is changing the way airplanes are being built. At the basic level, metal printing, also known as 3D printing, is the process of creating 3D objects from a digital model which is the prerequisite that all 3D printing machines require to produce a part (Gibson Ian, 2015). Instead of cutting shapes out of metal sheets and assembling them into a complex structure, 3D printing allows for the final product to be directly manufactured from a single process. This advancement has been a boon to the aircraft industry, granting dozens of benefits, including faster production and improved accuracy. The primary use for 3D printing in the aircraft industry is for extremely complex parts that would otherwise take hours to manufacture (Blakey-Milner, 2021). 3D printing reduces this time significantly, leading to both cost savings and faster production timelines. The parts created with 3D printing are highly customizable as well, as in some cases they are designed specifically for a certain aircraft. This method of customization decreases the costs as companies do not need to stock parts they may not use.

3.5 Traditional Manufacturing

There are a variety of ways a part can go wrong. Between the cutting, welding, and soldering, it can be challenging to create a perfectly formed component. 3D printing helps to minimize the margin of error due to its superior accuracy (Roucoules Lionel, 2020). Additionally, due to the highly detailed designs that are possible with 3D printing, the parts being created are very lightweight and therefore more efficient for an aircraft. 3D printing of metal components also has the potential to eliminate waste from traditional manufacturing processes. These components tend to be far more refined than those that are created through CNC machining, reducing the amount of scrap material at the end of the manufacturing process (Roucoules Lionel, 2020). Overall, the emerging metal printing technology is transforming the aircraft industry by providing unique benefits such as faster production times and superior accuracy. With so many potential applications for 3D printing, the future for aircraft manufacturing looks extremely promising. As the technology continues to evolve, the possibilities for 3D printing in the aircraft industry are endless.

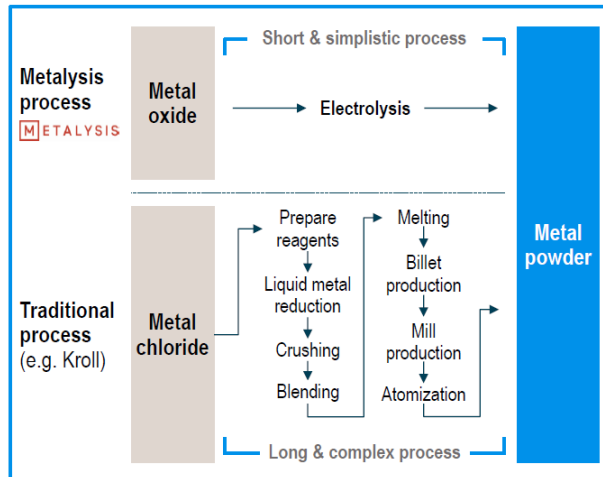
3.6 Positive Environmental Benefits

Efforts to reduce aircraft industry carbon emissions have been aided by changes to operational practices. The introduction of flight sharing, electronic flight logs, improved air traffic control systems, better weather forecasts for flight planning, and advanced air-traffic management initiatives all help make flight operations more efficient, thus reducing aircraft industry carbon footprints currently it is estimated that for each kilogram of weight reduction on a commercial aircraft will gave a saving of US\$3000 along with a reduction of 8,70 carbon emission per year (Singamnemi, 2019). Finally, the use of alternative fuels has often been touted as a potential game-changer in reducing aviation-related greenhouse gas emissions. Several fuels, such as advanced biofuels, have been developed that are dramatically less polluting than their fossil fuel counterparts. Additionally, some researchers believe advanced propulsion technologies, such as electric motors and hypersonic engines. The increased use of lighter materials such as composites has helped reduce the environmental impact of aircraft production. In addition, the redesign of aircraft cabin layouts and new cabin technologies have further sought to lessen the energy demands of aircraft operations by reducing drag and weight. 3D AM metals could drastically reduce the aircraft industry's carbon footprint further if widely adopted especially with modern cleaner technologies be utilised to produce met powders (see illustration below) (Berger, 2016).

UK technology start-up Metalysis invented a shortened production process for metal powder using electrolysis

Metalysis process vs. traditional process

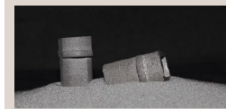
Comparison of process steps



Benefits of Metalysis process

- ✓ **Clean technology**
 - > No toxic byproducts, lower energy consumption and reduced CO₂ footprint
- ✓ **Cost effective**
 - > Fewer process steps – lower investment and operating cost
 - > High yield process with tailored particle sizes
 - > Cost reduction of 75%+ conceivable
- ✓ **Transformational**
 - > Solid-state alloying: ideal for different densities and melting points

> Metalysis are engaged in a development project with GKN Aerospace for aerospace-tailored titanium alloy AM powder



Demonstration component for an automotive turbocharger made from Metalysis titanium powder, produced on a Renishaw PBF machine

4 Manufacturing

4.1 Manufacturing Costs

The manufacture of components during design and development is in many cases an extreme costly phase of the process. Material usage is high in many cases, usually due to necessity of production of jigs and fixtures required to manufacture the component through various stages of the machining process to produce the component, more often than not these take far longer to produce and are more costly than the component itself (Roucoules Lionel, 2020). If the design of the component requires changes, then dependent on the modifications it could necessitate the complete remanufacture of everything thus far. Sustainable carbon footprint, energy reduction, social recognition, job creation and development opportunities, business and economic growth are beneficial globally (Gibson Ian, 2015) (Berger, 2016).

4.2 Aluminium Powder 3D Printing

Use of Aluminium Powders 3D printed components would enable aircraft manufacturing industry managers to more easily secure approval from executive management to provide and secure investment into a more sustainable future design and prototyping manufacturing solutions, that can be conducted using the most efficient and effective methods (Aboulkhair, 2019). Resources available with sustainability and benefits, by demonstrating that design and development of products requiring the manufacture of components from aluminium, can be carried out using AM as opposed to more wasteful conventional methods. Yet provide components that are equal in functionality and more so in strength characteristics,

due to the unique core constructions achievable through generative design software (Gibson Ian, 2015). Identify how these manufacturing methods can provide improvements like circular manufacture, waste reduction, cost savings, time reductions and enhancements through its use to encourage investment sooner.

4.3 Overview of Additive Manufacturing

Known as 3D printing, is a revolutionary manufacturing process that involves creating three-dimensional objects by adding material layer by layer. Unlike traditional subtractive manufacturing methods that involve cutting or shaping materials, additive manufacturing builds objects by precisely depositing or solidifying material in a controlled manner (Gibson Ian, 2015).

4.4 Key aspects of Additive Manufacturing

4.4.1 Applications

Additive manufacturing finds applications across various industries, including aerospace, automotive, healthcare, consumer goods, architecture, and more. It enables the production of intricate geometries, customized designs, rapid prototyping, tooling, spare parts manufacturing, and low-volume production runs (Miliwski, 2017).

4.4.2 Advantages

Additive manufacturing offers several advantages over traditional manufacturing methods, including (Gibson Ian, 2015) (Miliwski, 2017):

- a. Design Freedom: Complex and intricate designs that were previously difficult or impossible to manufacture can be realized using additive manufacturing (Roucoules Lionel, 2020).
- b. Customization: Additive manufacturing allows for the production of highly customized and personalized products (Gibson Ian, 2015).
- c. Rapid Prototyping: It enables faster and cost-effective prototyping, reducing the time to market for new products (Roucoules Lionel, 2020).
- d. Material Efficiency: Additive manufacturing can reduce material waste compared to subtractive manufacturing methods (Cowles B, 2016).
- e. Supply Chain Benefits: By producing parts on-demand, additive manufacturing can optimize inventory management and reduce the need for large warehouses (Roucoules Lionel, 2020).
- f. Reduced Costs: Additive manufacturing can reduce costs for low-volume production, eliminating the need for expensive moulds or tooling (Miliwski, 2017).

4.5 Design, Development and Industrialisation

4.5.1 Emerging Technology Innovations

The application of additive manufacturing methods to the aircraft industry, due to their point-by-point and layer-by-layer material consolidation technique, is a revolutionary development and has been recognised as one of the most remarkable achievements of the modern era. By transforming raw materials into 3D forms, through the digital slicing and rasterising of CAD files, time and cost savings can be achieved (Miliwski, 2017). The

advancement from 3D printing to rapid prototyping and free-form fabrication demonstrate the different stages of the technology's growth. According to the 2016 Wohler's report, the additive manufacturing industry had a global worth of 5.165 billion USD. The AM processes can be divided into seven categories; powder bed fusion, binder jetting, direct energy deposition, extrusion, jetting, sheet lamination, and vat photo-polymerization. Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Stereo-Lithography (SLA), Fused Deposition Modelling (FDM) and Direct Metal Deposition (MD), Direct Metal Laser Sintering (DMLS) are the most employed methods, with metals, polymers, ceramics and composites being developed as potential material candidates (Gibson Ian, 2015). AM offers lower energy consumption, better mechanical efficiency, less material waste, and shorter design and production times compared to traditional manufacturing methods, as well as more design flexibility, higher customisation, reduced lead times and improved supply chain solutions. The ability to manufacture complex 3D forms direct from digital data most commonly used file format is *.STL ('*' being the file or part name or #), eliminating the need for complex tooling and specialised work-tool motions and the forces involved in between allow for reduced manufacturing lead times and possible localised production, contributing towards more efficient supply chain systems (Roucoules Lionel, 2020). Consequently, the additive manufacturing methods rapidly gained application potentials in different fields, including the aerospace industries. Therefore, there has also been an increasing number of publications related to the use of additive manufacturing in the aircraft industry and the general trends noticed are discussed here. Petersen's systematic mapping strategy has been applied here, as it was in another review article concerning additive manufacturing. In order to gain an understanding of the application of additive technology in the aircraft industry. The search term used was 'Additive manufacturing in the aircraft industry'. Most publications concentrated on commercial applications, materials studies, and tooling and indirect use of 3D printing. Web articles predominately focused on the outcomes of commercial applications, however, often lacking detail due to confidentiality. Supply chain, energy, standardisation, certification, and quality control topics received comparatively less attention. Most studies on supply chain and energy consumption were generic and not specific to any particular case study, usually comparing conventional and 3D printing methods. The ability to create complex 3D forms without the need for intricate tooling has made additive manufacturing a highly attractive option in the aircraft industry due to its inventory and supply chain constraints, as well as its capacity for just-in-time manufacturing (Gibson Ian, 2015). Leaders in the aircraft industry have been exploring the potential of AM to produce parts such as various hinges, brackets, interior components, and even lightweight fuselage and airframe designs, with the aim of improving fuel efficiency. Examples of AM applications in aircraft components include turbine blades with internal cooling channels, fuel nozzles, compressors, and integrated piping systems (Miliwski, 2017).

4.5.2 Design

The use of complex geometry and multidisciplinary design optimization is commonplace in most engineering industries, particularly in the aerospace

sector. Due to the stringent safety requirements (Miliwski, 2017) (Florio, 2016), engineers are required to carefully consider all design variables and constraints, such as material and structural integrity, aerodynamics, weight, reliability, manufacturability, maintainability, sustainability, and cost, leading to very little design freedom. Historically, design compromises have been made based on the limitations of traditional manufacturing methods. However, the advances of CAD and additive manufacturing technologies have eliminated some of these restrictions, offering new design possibilities including reduced weight, cellular structures, lattices, honeycomb and bionic-optimized structures (Miliwski, 2017). Furthermore, additive manufacturing permits the creation of designs that were not possible with conventional methods, along with decreased operational costs during assembly and maintenance. Topology optimisation is commonly used for weight reduction and is based on finite element analysis. This technique involves the removal of material from areas with low stress until an optimised form is created. In recent years, this technique has been used for aerospace purposes, resulting in lattice structures (Gibson Ian, 2015). Solid Isotropic Material Penalisation (SIMP) allows voxel by voxel design of a unit cell which maps structural density and allows the combination of multiple materials for improved performance. Additive Manufacturing (AM) is the only viable solution for the production of these complex, optimised parts. For example, the Airbus Innovation Group designed a nacelle hinge bracket for the Airbus A320 which reduced the weight by 64%, resulting in 10kg of mass being saved per plane and a 40% reduction in carbon emissions. Furthermore, the exit door hinges were redesigned, leading to a 33% weight reduction and a decrease in stiffness (Gibson Ian, 2015) (Miliwski, 2017). Reports have also indicated considerable weight savings on the Airbus A350XWB and A380 models due to design alterations, with selective laser melting and topology optimisation used to manufacture a lightweight bracket with a 28% weight reduction and improved safety factor (Singamnemi, 2019).

The use of AM to create complex shapes gives the chance to enhance parts for certain purposes like heat dissipation, pressure distribution, or air flow. An example of this is incorporating cooling paths into essential components. EOS revealed that measuring probes for temperature and speed in turpentine can be created with AM technology which not only resolves the instability and fracture fragility issues, but also makes the additively manufactured part 150% stiffer than the multi-part assembly of the initial design (Singamnemi, 2019).

4.5.3 Development

Conventional methods are more suitable for large-scale or batch production, which is not necessary for the production of aircraft parts, as the production volumes are usually limited and not more than a few thousand units per part. This makes additive manufacturing (AM) a more suitable option for customizing aircraft cabin designs, as all that is required is CAD files, and no extra tools. To demonstrate this, China Eastern Airline created their own AM lab in 2015 and reduced cabin component costs using flame retardant materials for interior components, such as toilet seats, leading to 90% savings in costs and significant manufacturing lead time savings compared to

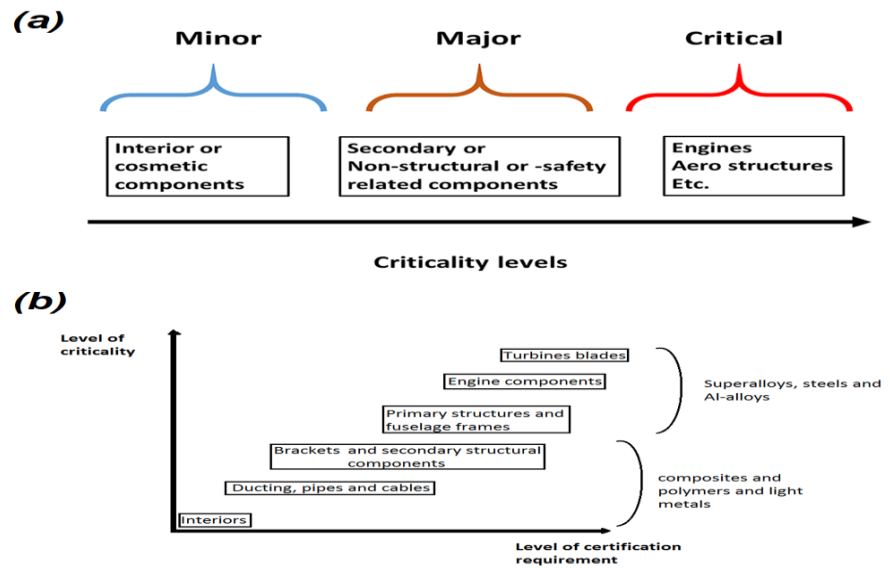
the original parts (Singamnemi, 2019). Air New Zealand also evaluated the additively produced cocktail trays for the business premier cabin based on prototypes from Auckland University of Technology. The SAVING project showed a 55% weight reduction was achievable by redesigning the seat buckles for additive manufacturing, with a predicted 73 kg weight reduction for all Airbus 380 seat buckles, amounting to 3.3 million litres of fuel savings over the aircraft's life span (Singamnemi, 2019).

4.5.4 Regulatory requirements

The Aircraft Industry is one of the most highly regulated manufacturing sectors, regulations have developed and enforced are there for safety. They are rigorous, strict and apply to the manufacture of every item, process and procedure, testing and analysed before being considered suitable for part of an aircraft assembly. To ensure that potential solutions can meet applicable regulations, engineers must also adhere to the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) guidelines for aircraft design and operation. This includes an examination of airworthiness, noise levels, and other factors that must be taken into consideration (Singamnemi, 2019). The FAA also regularly inspects completed aircraft to ensure all safety protocols are being followed. To ensure the highest level of customer service and satisfaction, engineers should strive to continuously improve the aircraft with new technologies and advancements. By considering customer input, both engineers and airline companies can benefit from increased customer loyalty, repeat sales and cost savings. Additionally, aircraft should be designed with customer comfort and ease of use in mind. Ultimately, the strict standards of the aviation industry make it challenging for engineers to create innovative aircraft systems, components, and operations. However, those that understand the necessary criteria and regulations are able to create solutions that meet the requirements and standards of the industry, while providing safe, reliable, and comfortable transportation options for their customers.

4.5.6 Categorisation and Levels of Criticality of Typical Aircraft Components

Illustration (Singamnemi, 2019).



While additive manufacturing has seen significant advancements and adoption, there are still challenges to overcome, such as material limitations, production speed, and scalability. However, ongoing research and development efforts continue to push the boundaries of additive manufacturing, making it an increasingly vital technology in the manufacturing landscape. Nevertheless, it is clear that there is significant growing focus within the aerospace industries for its inclusion as illustrate below in figures 1, 2, 3 and 4 (Singamnemi, 2019).

Figure 1. Aircraft production and maintenance models.

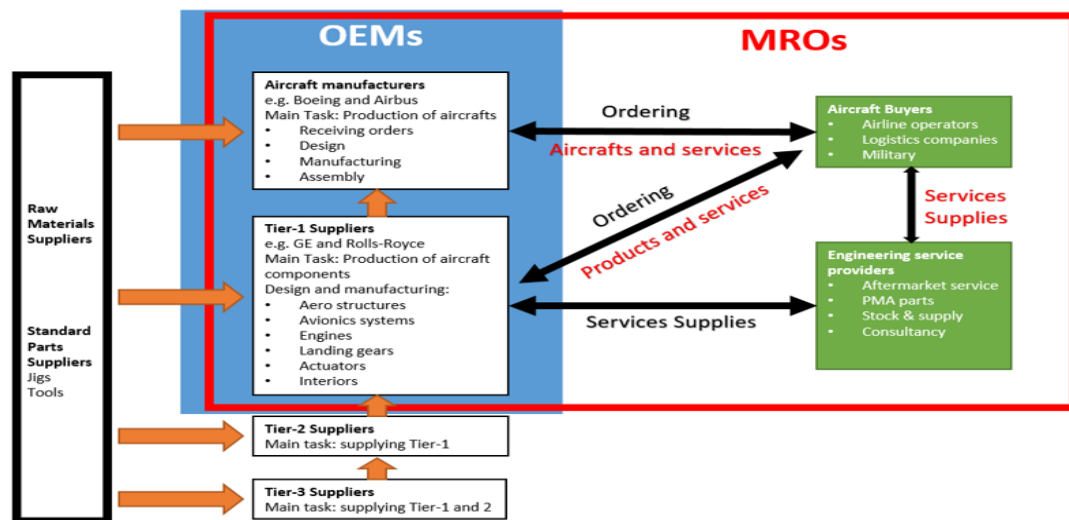


Figure 2. AM for aerospace, publication trends.

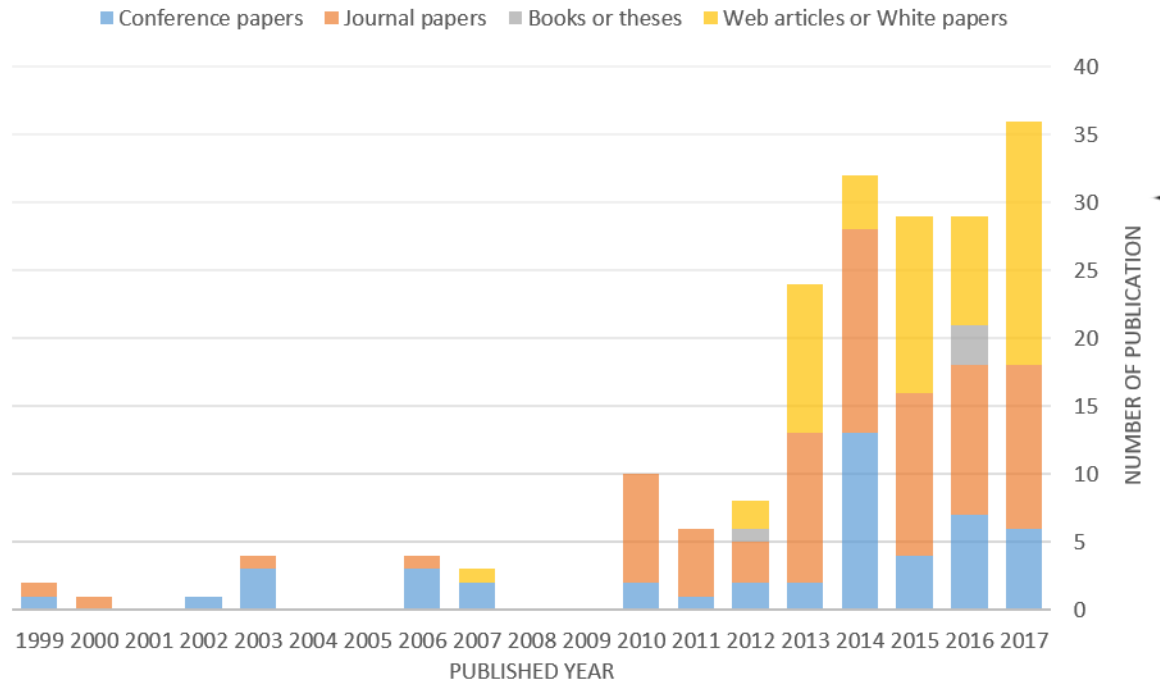


Figure 3. AM for aerospace: A classification of the topics covered in the most significant publications.

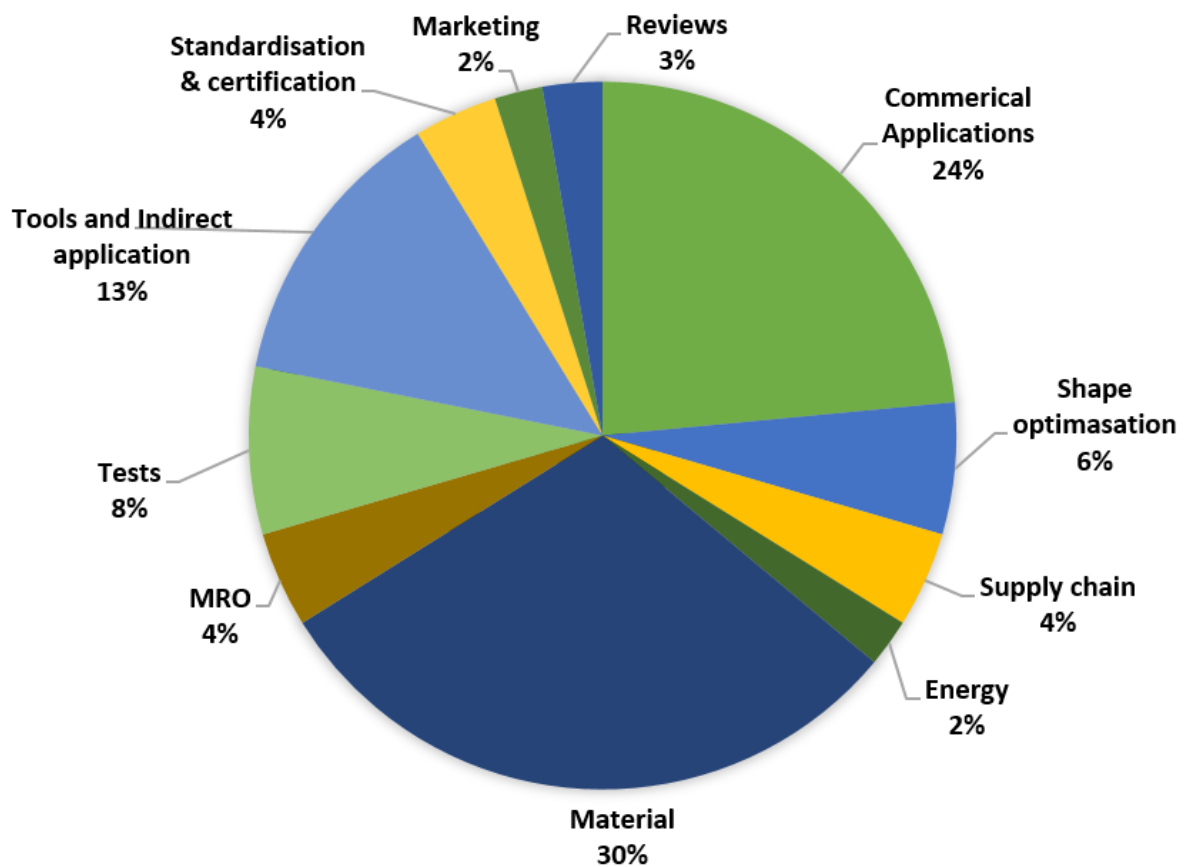
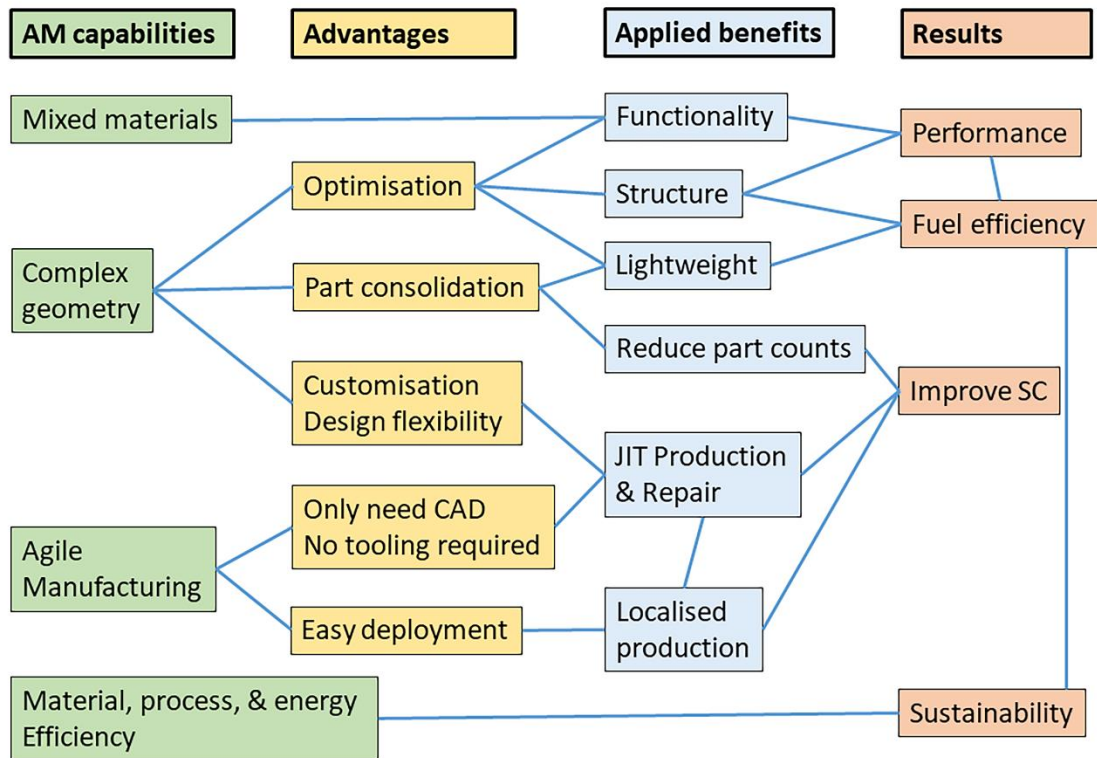
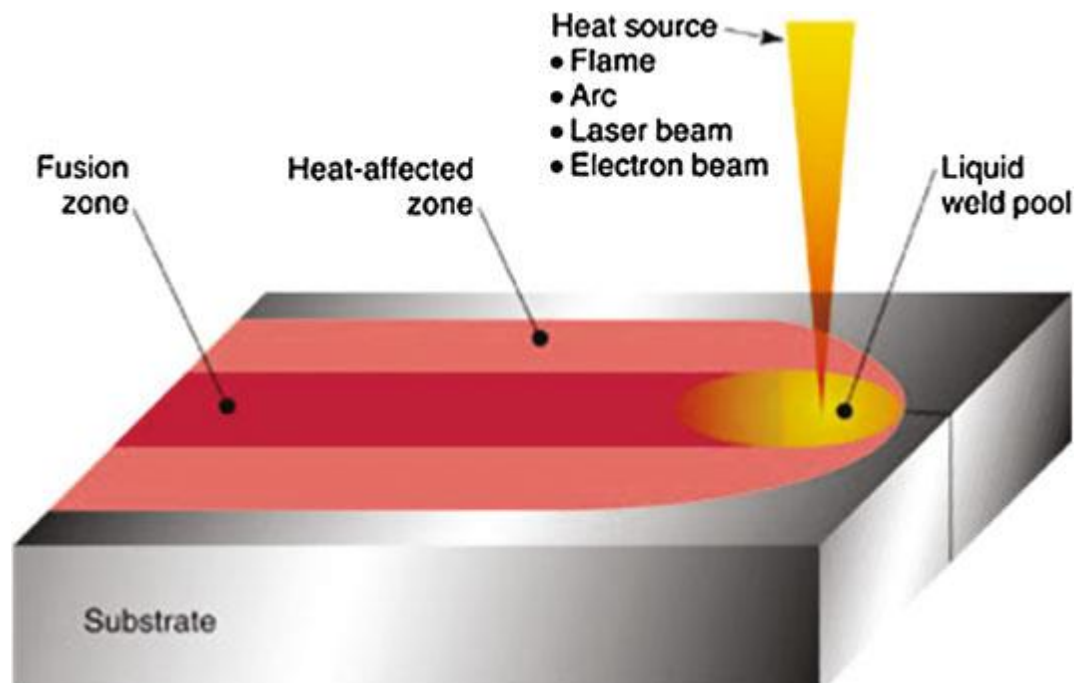


Figure 4. Critical attributes of integrating additive manufacturing within the aircraft industry.



4.6 A Selection of Types of Additive Manufacturing Processes

The various processes that utilize different techniques and technologies to build objects layer by layer and fused together. The basic principle involve is a focused heat source focused at a precise area to change the media into a molten state (Miliwski, 2017) Illustration below.



Here are some of the commonly used additive manufacturing processes:

4.6.1 Powder-Bed Additive Manufacturing (PB-AM)

This additive manufacturing process is where thin layers of powder are deposited, levelled and selectively melted by a high-powered beam layer by layer onto a build platform following the path defined by the 3D model. (Katz-Demaynetz, 2019)

4.6.2 Selective Laser Melting (SLM)

SLA utilizes a liquid photopolymer resin that hardens when exposed to a specific wavelength of light, usually a laser or ultraviolet (UV) light source. A build platform gradually moves up or down within a tank of resin, and the light source selectively solidifies the resin layer by layer, creating the desired object. (Katz-Demaynetz, 2019). It should be not that with SLM is prone to high porosity in many different types of material caused by lack of fusion (Guanghao Gong, 2021) (Aboukhair, 2019) (see figure 1 below).

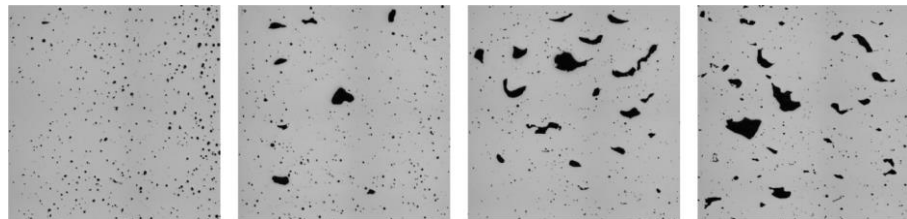


Figure 1. Metallurgical pores form at (a) the slowest scan speed and as the scan speed increases gradually in (b, c, and d) the amount of metallurgical pores decrease and keyhole pores are promoted.

4.6.3 Binder Jetting

This process involves depositing a liquid bonding agent, typically a polymer, onto layers of powdered material. The binder selectively adheres to the powder, bonding the particles together to form each layer. Once a layer is complete, a new layer of powder is spread, and the process is repeated until the entire object is formed. Afterward, the part is typically sintered to further strengthen it (Katz-Demaynetz, 2019).

4.6.4 Electron Beam Melting (EBM)

EBM is a similar process to DMLS but uses an electron beam instead of a laser. It involves melting and fusing metal powders layer by layer in a high-vacuum chamber. EBM is often used for producing high-quality, fully dense metal components, particularly in the aerospace and medical industries (Katz-Demaynetz, 2019).

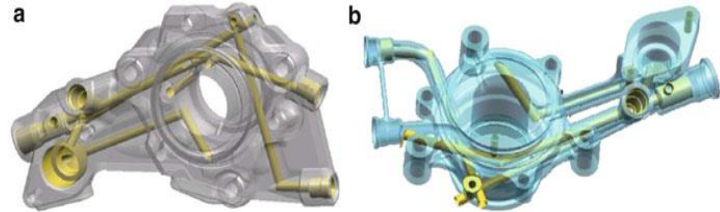
These are examples of additive manufacturing processes, and new technologies and techniques are continually emerging. Each process has its strengths, limitations, and applications, making additive manufacturing a versatile and rapidly evolving field.

4.7 Advantages and Limitations of Additive Manufacturing

4.7.1 Advantages:

4.7.1.1 Design Freedom

AM enables the production of complex geometries that are difficult or impossible to achieve using traditional manufacturing methods. It allows for the creation of intricate and customized designs, including internal cavities, lattices, and organic shapes (Aboulkhair, 2019). (Gibson Ian, 2015) Illustration below, Diesel front plate example. (a) Original design. (b) Redesigned for additive manufacturing.



4.7.1.2 Reduced Material Waste

Unlike subtractive manufacturing processes that involve cutting away material, AM builds objects layer by layer, using only the necessary amount of material. This reduces material waste and can lead to cost savings, especially for expensive or scarce materials (Aboulkhair, 2019). In comparison to conventional manufacturing methods in many cases waste reduction can be 80% or more (Gibson Ian, 2015).

4.7.1.3 Rapid Prototyping

AM allows for quick and cost-effective prototyping. Design iterations can be easily made and tested without the need for expensive tooling or retooling, accelerating the product development cycle. At the beginning AM was developed for rapid prototyping (Gibson Ian, 2015).

4.7.1.4 On-demand Manufacturing

With AM, objects can be manufactured on-demand, eliminating the need for large inventories or long lead times. This enables customized production and can be particularly beneficial for low-volume or niche products (Aboulkhair, 2019).

4.7.1.5 Manufacturing Complexity

AM can produce parts with integrated functionalities, such as internal channels or complex internal structures. This eliminates the need for assembly of multiple components, reducing production time and potential points of failure (Aboulkhair, 2019) (Gibson Ian, 2015).

4.7.1.6 Carbon footprint reduction and circular economy

Additive Manufacturing has the potential to reduce material wastage by > 80% in many instances (Gibson Ian, 2015),

leading to cost and environmental savings. The most significant benefit of applying AM in the aircraft industry is weight reduction i.e. 20% mass reduction of a Boeing 787 would improve fuel efficiency of around 10%-12% (Blakey-Milner, 2021), which can save around US\$3000 in fuel costs and carbon emissions per kilogram reduced. By taking advantage of the ability of AM to produce complex geometries, materials selection and geometry optimization can help to realize these benefits. In comparison with conventional manufacturing methods, AM could provide a much more material, process and energy efficient solution.

4.8 Limitations of Additive Manufacturing

4.8.1 Limited Material Selection

Although the range of materials available for AM has expanded over the years, it still lags behind the variety of materials used in traditional manufacturing processes. Certain materials, such as high-performance alloys or composites, may have limited availability or pose challenges in terms of processing, surface finish and quality (Roucoules Lionel, 2020). AM parts may have rougher surface finishes compared to those produced by traditional methods. Post-processing steps, such as polishing or machining, may be required to achieve the desired surface quality. Additionally, AM parts can have different mechanical properties or internal defects that can affect their overall quality (Gibson Ian, 2015).

4.8.2 Build Time

Building objects layer by layer in AM can be a time-consuming process, especially for large or complex parts. The production speed of AM is generally slower than traditional methods, which can be a limitation for high-volume production. However, by contrast lends itself greatly to design development and prototyping (Aboulkhair, 2019).

4.8.3 Equipment and Cost

Acquiring and maintaining AM equipment can be expensive, especially for industrial-grade systems. The cost of materials, particularly specialized or high-performance ones, can also be relatively high (Gibson Ian, 2015). These factors can limit the accessibility and adoption of AM for some businesses. By comparison this technology can also significantly provide reduced lead time, cost of development and provide unique solutions (Blakey-Milner, 2021).

4.8.4 Design and Process Limitations

While AM offers design freedom, certain geometries or features may be challenging or impossible to produce. Design constraints, such as overhang angles or unsupported structures, may need to be considered. Additionally, the choice of AM process can impact the achievable resolution, accuracy, and size limitations of the produced parts especially in high volume production, often requiring secondary conventional machining process (JCM 2020 Members, 2021).

N.B. It's important to note that the field of additive manufacturing is continuously evolving, and ongoing research and advancements aim to address some of these limitations.

5 Manufacture and Mechanical Properties of Aluminium

With respect to aircraft usage, it can be traced back to the beginning of the 1900's. Aluminium's reputation has grown since its creation in the 1930's where it was used in the manufacture of its aircraft to construct the airframes for the Japanese navy. By 1945 it was standardised for the production of aircraft in the United States (Clinton Aluminium Innovative Alloys, 2019).

5.1 Manufacturing of Aluminium Powder and Properties

5.1.1 Manufacturing Processes

- 5.1.1.1 **Melting:** Pure aluminium or aluminium alloy is melted using induction melting or other melting techniques. The choice of alloy depends on the specific requirements of the 3D printing process and the desired properties of the final printed product (Yiyunyingliping, 2023).
- 5.1.1.2 **Atomization:** The molten aluminium is then subjected to a high-pressure gas stream, usually inert gases like argon or nitrogen. This gas stream breaks up the molten metal into fine droplets (Yiyunyingliping, 2023).
- 5.1.1.3 **Solidification:** As these droplets travel through the gas stream, they rapidly cool and solidify into small spherical particles. The size of these particles can be controlled based on the process parameters and the design of the atomization equipment (Yiyunyingliping, 2023).
- 5.1.1.4 **Collection:** The resulting aluminium powder is collected and then undergoes further processing steps to ensure it meets the required specifications for 3D printing. This may include sieving to achieve a specific particle size distribution and removing any contaminants (Yiyunyingliping, 2023).
- 5.1.1.5 **Quality Control:** Quality control measures are implemented to assess the particle size, morphology, and chemical composition of the aluminium powder to meet the stringent requirements of the 3D printing process (Yiyunyingliping, 2023).

It's essential to note that the properties of the aluminium powder, including particle size and distribution, directly impact the quality and characteristics of the final 3D-printed components. Different 3D printing technologies and equipment may have specific requirements for the aluminium powder used in their processes. Therefore, manufacturers carefully tailor the production process to meet these specifications and ensure consistency in the quality of the aluminium powder for 3D printing (Yiyunyingliping, 2023).

5.1.2 Blended powder

Semisolid forming was employed for the fabrication of Al7075/Al2O3 composites, involving sequential processes of powder uniform distribution, mechanical alloying, and semisolid compaction. Al7075 elemental powders (20 and 63 μm) were incrementally introduced into an ethanol solution

through ultrasonic mixing. Al₂O₃ particles, varying in size (5 and 120 µm) and weight fractions (5, 10, and 20 wt. %), were blended with the matrix particles using a planetary ball mill. Subsequently, Al7075/Al₂O₃ composites were compacted at the semisolid state under different pressures (40 and 80 MPa) (Javdani A, 2016).

5.1.3 Influences

The study systematically investigated the influence of Al7075 and Al₂O₃ particle size, Al₂O₃ weight fraction, and compaction pressure on various characteristics, including morphology, microstructure, compaction mechanism, density, hardness, compression modulus, strength, and phase formation. Optimal microstructural uniformity was achieved when large Al₂O₃ particles (120 µm) were dispersed among smaller matrix particles (20 µm). The density and hardness exhibited an increasing trend with the size of the reinforcing particles and applied pressure (Javdani A, 2016).

5.1.4 Composite Performance

The highest composite performance was observed in specimens with 20 µm Al7075 and 20 wt. % of 120 µm Al₂O₃ powder, compacted under 80 MPa. These samples demonstrated notable enhancements in relative density (98.685%), hardness (Rockwell B of 70), and compressive strength (327 MPa). The findings provide valuable insights for the development of high-performance lightweight metal matrix (Javdani A, 2016).

5.2 Properties Aluminium 7075 T6

- a. It has high strength.
- b. It is lightweight.
- c. It is ductile.
- d. It is malleable.
- e. High cyclical fatigue resistance.
- f. Corrosion resistance.
- g. Performance in extreme variable climatic conditions
- h. Can be easily machined and formed

Heat treatment can significantly affect the tensile strength of aluminium 7075. By subjecting the material to a suitable heat treatment process, the tensile strength can be improved. The most common heat treatment for aluminium 7075 is T6, which involves solution heat treatment followed by artificial aging.

5.2.1 Hardness

Rockwell B = 87.0 (Stainless and Aluminium Limited, 2023).

5.2.2 Tensile strength

Typical range of around 510-570 MPa (74,000-82,700 psi) (Stainless and Aluminium Limited, 2023).

5.2.3 Yield strength

Range of around 460-530 MPa (67,000-77,000 psi) (Stainless and Aluminium Limited, 2023).

5.2.4 Average cost

Price per kilogram £3.46 (Metalex, 2021).

It's important to note that the actual tensile strength achieved can vary dependent with respect to the specific heat treatment parameters, such as time, temperature, and cooling rate determine the mechanical properties for the given material.

5.3 Mechanical Properties of Aluminium Powder Al7075

5.3.1 Hardness

Mechanical properties of Al7075 alloy			
Property	Ultimate tensile stress (N/mm2)	Yield stress (N/mm2)	Brinell Hardness
Value	572	503	150

(Rajesh. S, 2020, p. 6439).

5.3.2 Tensile strength and Yield Strength

Tensile Test Results					
Casting	Al7075	SiC	Fly ash	Ultimate tensile stress (N/mm2)	Yield stress (N/mm2)
1	100%	0%	0%	572	503
2	95%	5%	0%	586.6	511.9
3	95%	0%	5%	584.1	508.6
4	95%	2.50%	2.50%	581.9	507.4
5	90%	10%	0%	592.8	513.5
6	90%	0%	10%	587.3	512.2
7	90%	2.50%	7.50%	588.6	513.1
8	90%	5%	5%	599.2	518.4
9	90%	7.50%	2.50%	601.9	519.6

(Rajesh. S, 2020, p. 6439).

5.3.3 Aluminium Powder Cost

Average cost per kilogram £82.0

5.3.4 Fatigue Resistance

Table results showing life cycle values of a specimen (Hiremath S Somashekhar, 2018).

	Stress (Mpa)	Life cycles
Thixoformed	140	5.5 * 10 ⁷
	120	5.9 * 10 ⁷
	100	6.2 * 10 ⁷
ECAP1 pass + thixoformed	140	4.6 * 10 ⁷
	120	4.8 * 10 ⁷
	100	5.1 * 10 ⁷

5.3.5 Heat Treatment

Table Results showing hardness values (Hiremath S Somashekhar, 2018).

Before heat treatment	After heat treatment	
	Cycle 1	Cycle 2
372HV/20/30	174HV/20/30	145HV/20/30

5.4 Typical Machine Types Selective Laser and Electronic Beam.

Selective laser melting (SLM)/Selective laser sintering (SLS) is generally the predominant type of method to be found in industry the advantage this has over Electronic beam melting (EBM) and Binder jetting printing (BJP) is that there is a great range of materials available compared to EBM which has fewer. Therefore, providing a more competitive market for SLM. Manufacturing of part using this type of technology is favoured very much in today's manufacturing easy to control but not to implement. High powered lasers may provide faster melting with reduced processing time and today's manufacturers of these machines incorporate multiple lasers. However, in both cases of PB-AM there are finite limits before excessive porosity becomes a problem due to fusion defects being introduced and feature definition becomes unstable and small features are unable to be produced spatial resolution diminishes therefore beam intensity needs to be at levels that provide achievable results. These processes are either carried out in an inert environment for SLM or in a vacuum chamber for EBM. For most of the production of most components there are three key factors for vital consideration; these are: component surface roughness, keep the working area at high temperature and support structures (Katz-Demaynetz, 2019).

5.4.1 Selective Laser Melting (SLM)

SLM was the first of the techniques used for alloy printing, today there is a multitude of manufacturers of these types using the same process but using alternative terminology i.e. direct metal laser sintering (DMLS), metal powder-bed fusion (MPBF) nevertheless technically speaking they are one in the same. Powder is deposited on a pre-heat carrier plate on the bed layer upon layer where by each layer thickness is controlled by a raking system that brushes the powder maintaining a thickness of around 30-60 microns and some systems use inert gas generally nitrogen or argon, while others use a slight vacuum to reduce oxidation during the fusing process with Ytterbium fibre laser systems to sinter the alloy powder together (Katz-Demaynetz, 2019).

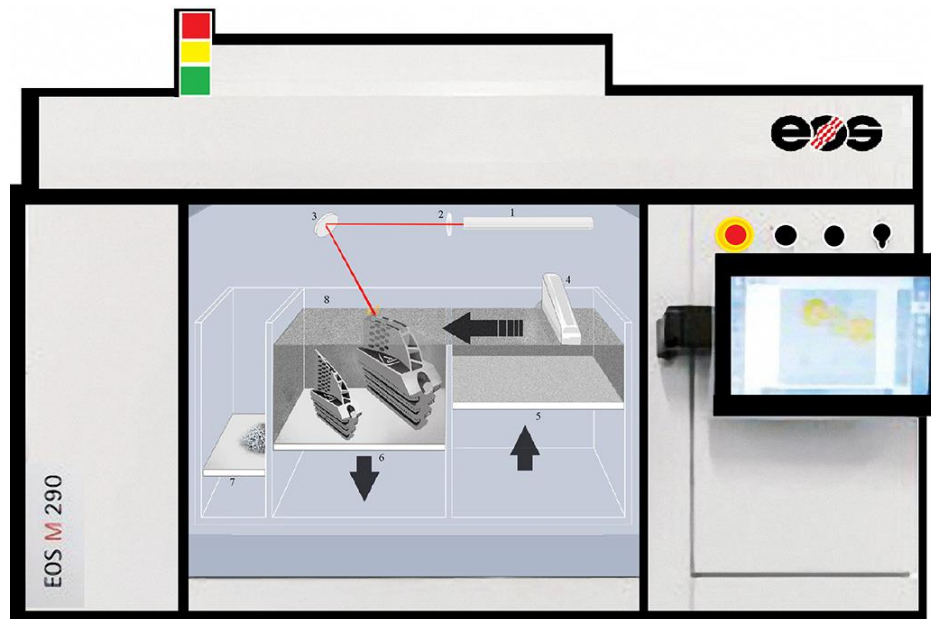


Figure 1. Selective laser melting: 1 Laser; 2 Lenses; 3 X and Y scanning mirror; 4 rake; 5 powder supply table; 6 build table; 7 table for rest; 8 powder-bed (Katz-Demaynetz, 2019).

5.4.2 Electronic Beam Melting (EBM)

Figure 2

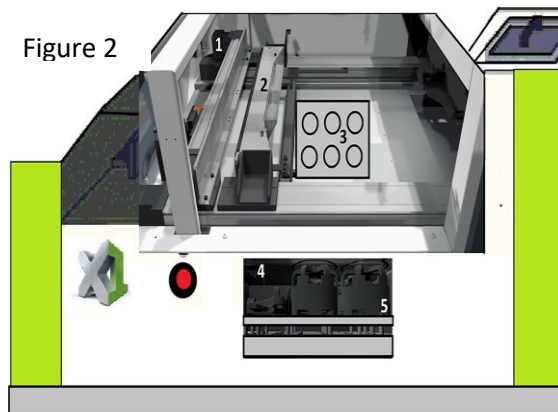


Figure 2. Electronic beam melting process: 1 electron beam; 2 electron beam control; 3 powder container; 4 build platform tank; 5 build tank; 6 working area; 7 rake.

Figure 3

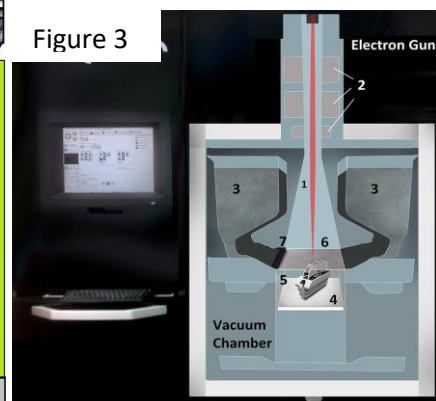


Figure 3. Binder jetting printing process: 1 jetting head; 2 rake and powder delivery; 3 working area; 4 build tank; 5 build

EBM has derived from Electron beam welding (EBW) a well-known method used for Titanium alloys, steels and some other metals. EBM developed by merging high power beam with precision control creating a new method EBM of Selective electron beam melting (SEBM). This process with higher beam energies enables powders with a grain size of around 75-150 microns to be used and typically deposit layers of between 20-200 microns can provide a faster process times compare to

laser type machines. This is achievable as EBM machines operate with a vacuum level down to 10^{-5} bar, whereby semi-sintering powder layer and pre-heated providing temperatures around 50% of the melting point, this prevents oxidation of the component and powder during the process. It is an important part of the process the high power electron beam results in charging of the loose powder. This results in the powder rising up in the vacuum chamber creating a cloud (called smoke). The pre-heating and pre-sintering of the powder layer deposit is carried out by increasing the beam current creating positive and negative charges within the environments with higher power beams and vacuum conditions, these combinations provide a lower spatial resolution shape and detail, higher surface roughness and leads to much lower internal stress levels and in some case greater mechanical properties. All of this combined makes it easier to build up layers of components and maximise the production process (Katz-Demaynetz, 2019).

5.5 Mechanical Make Up of 3D Printed Alloys.

5.5.1 Materials

High strength to weight ratio materials along with high temperature are the types of critical properties demanded by the aerospace industries. The development of these new manufacturing technologies has become a mainstay for AM processes. Aluminium falls into the family entropic alloys, these types of alloys are extensively used in the aerospace industries due to their intrinsic properties. They can provide complex internal support structures, passageways and ports from light weight alloys are able to provide high strength to weight ratios. This AM process is also contributing to the rapid development of new types of materials providing results the like of which have never been seen before. (Katz-Demaynetz, 2019).

5.5.2 Grain Structure

There are a number of factors that affect the overall and final grain structure during PB-AM process. The better the spherical properties of the powder the better the definition of the built up layers these range in size and are typically 60-80 microns for laser based systems and 75-150 for electron beam systems. Consequently, these fine powders allow when fused together form microstructures that can be highly precise in definition with very low deformity (Katz-Demaynetz, 2019).

5.5.3 Internal Structure and Supports

The inclusion of internal structures and support are a fundamental part of the design. Where they are deployed and their form are determined by a number of factors to the unknowing these would look like labyrinth of random shaped meshes, walls and corridors. Whereas in actual fact they are a complex amalgamation of design requirements, computed mathematics to provide a form that is not just functional in terms of providing a component a given geometrical shape but also able to provide structure that is able to withstand specific forces, loads and constraints in line with the applicant and design intent (Katz-Demaynetz, 2019).

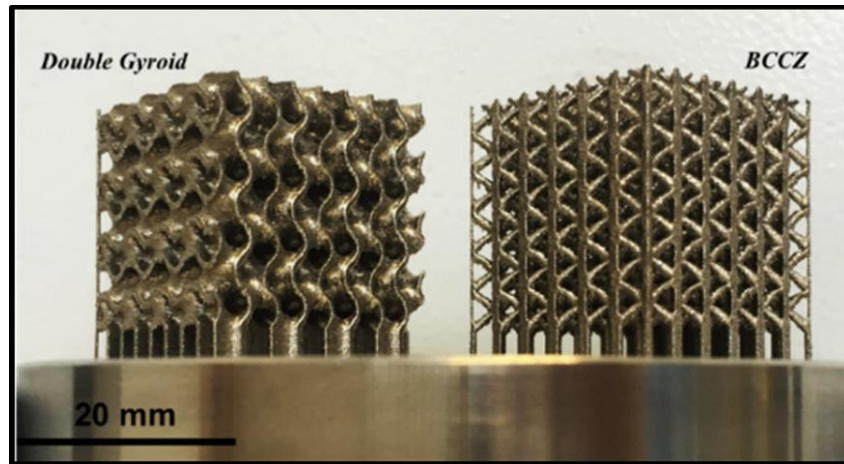


Figure 1. Above a double gyroid lattice (TMPS and a BCCA lattice (strut based) fabricated in the centre of Additive Manufacturing University of Nottingham (Aboulkhair, 2019).

To this end specific computations have to take place using specialised software, utilisation of artificial intelligence (AI) and high power computers to provide the results that enable AM of the designed component. This process is referred to as Generative Design (GD) where the aims are to optimise the design allowing greater freedom of design allowing for weight savings with no detriment and ensuring it maintains the requirements of the design intent with respect to function, strength, loads and surfaces by optimising the distribution of material within the boundary constraints of the component. GD allows engineers explore many options and to analyse computerised results that would not be conventionally possible before deciding on a design that fulfils all the requirements. However, it should be noted that AM alone is not capable providing surfaces that are sufficiently smooth for all engineering requirements and conventional machining methods are still required to achieve this (Roucoules Lionel, 2020).

Often during the design and AM process there is a requirement to add temporary support to maintain shape, accuracy and prevent deformation of the component that becomes redundant after the process of AM and are later removed.

5.5.4 Porosity and Inclusions

Porosity and inclusions are micro fractures and imperfections or cavities that may occur and are generally associated from the escaping of hydrogen gases during the heating and fusing process of AM. These flaws are apparent in all forms of material manufacture and are not unique in any way to the AM process (Marcel Dekker Inc, 2003). One of the drawbacks with SLM is that porosity is the most common defect. There is a distinct correlation between speeds of 250mm/s and lower and the size of the pores in the influence of porosity from quantitative point and the number of pores produces from a qualitative view point. Also, material qualification is that the optimisation of parameters are not yet transferrable between machines, meaning that each machine manufacturer have to develop their own set of parameters for each of the materials as demonstrated in table 1 below (Aboulkhair, 2019).

Examples for the outcome from some material qualification studies on a range of Al alloys listing the optimized process parameters (P: laser power, v: scan speed, h: hatch spacing, and t: layer thickness).

Alloy	Machine used	Investigated range [†]				Optimised values				Energy density (J/mm ³)	Relative density (%)
		P (W)	v (mm/s)	h (mm)	t (mm)	P (W)	v (mm/s)	h (mm)	t (mm)		
AlSi10Mg	Realizer SLM-50	100	250–1000	0.05–0.25	0.04	100	500	0.050	0.04	100	99.8
	Concept Laser M2	100–200	700–2000	0.075–0.12	0.05	175	1025	0.098	0.05	34	99.7
	Concept Laser M1	–	–	–	–	200	1400	0.105	0.03	45	99.4
	Renishaw AM250	–	–	–	–	200	570	0.130	0.025	108	99.9
	Trumpf	–	–	–	–	250	500	0.15	0.05	67	> 99
	TrumaForm LF130 SLM-250 HL	–	–	–	–	350	1140	0.17	0.05	36	N/A
AlSi12	Custom-made	300–1000	500–4500	0.15–0.3	0.05	1000	2200	0.15	0.05	61	99.5
	Realizer SLM-100	100	100–600	0.1–0.20	0.05	100	150	0.150	0.05	89	89.5
	Custom-made	100–200	70–200	0.1–0.5	0.2–1	200	120	0.1	0.2	67	77
	Realizer SLM-100	200	375–2000	0.15	0.05	200	500	0.15	0.05	53	98
AlSi12Mg	N/A	–	–	–	–	350	921	0.19	0.05	40	99.86
AlSi20	SLM-250 HL	–	–	–	–	320	1455	0.11	0.05	40	N/A
A356 [‡]	EOSINT M280	200–370	400–3000	0.08–0.18	0.03	250	1400	0.1	0.03	60	99.8
A357	EOSINT M280	100–370	500–5000	0.1	0.03	300	2000	0.1	0.03	50	99.7
Al-Cu-Mg [§]	Custom-made	200	83–333	0.07–0.13	0.04	200	83	0.07	0.04	860	99.8
AA-2219	Realizer SLM-50	70–100	N/A ^{**}	0.05–0.17	0.03	N/A	N/A	N/A	0.03	235	97.5
AA-2618	Realizer SLM-50	70–100	N/A ^{**}	0.05–0.13	0.03	N/A	N/A	N/A	0.03	235	> 99.5
AA-6061	Realizer SLM-100	50–100	50–1000	0.05–0.30	0.05	100	150	0.150	0.05	89	88.7

[†] The (–) means that a parametric study was not presented in this work.

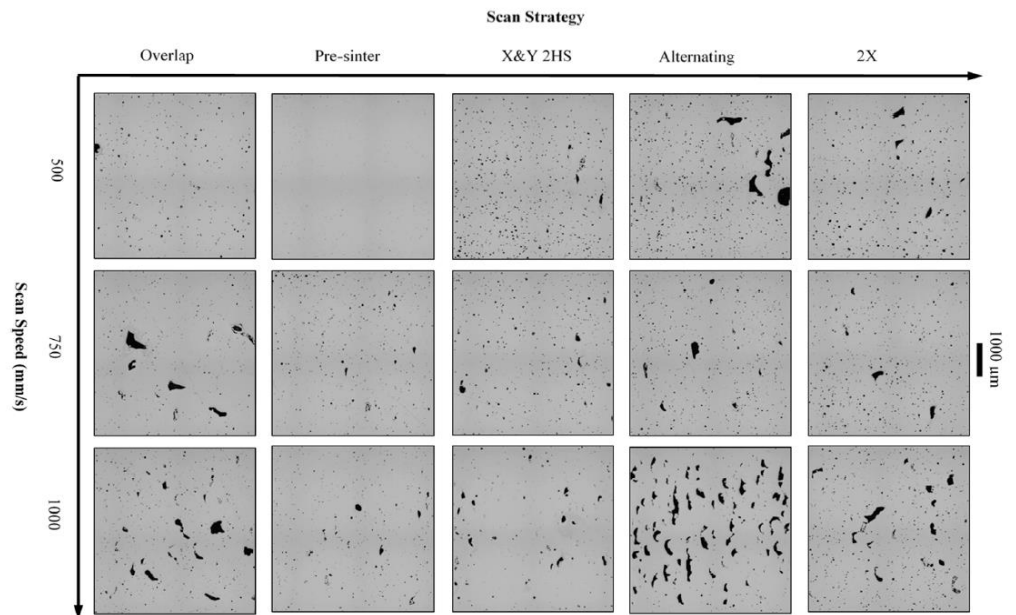
[‡] Also known as AlSi7Mg0.3.

[§] Chemical composition close to AA-2024.

^{**} Ranges of exposure times and point distances were reported instead of scan speeds.

5.5.5 Phase Transformations

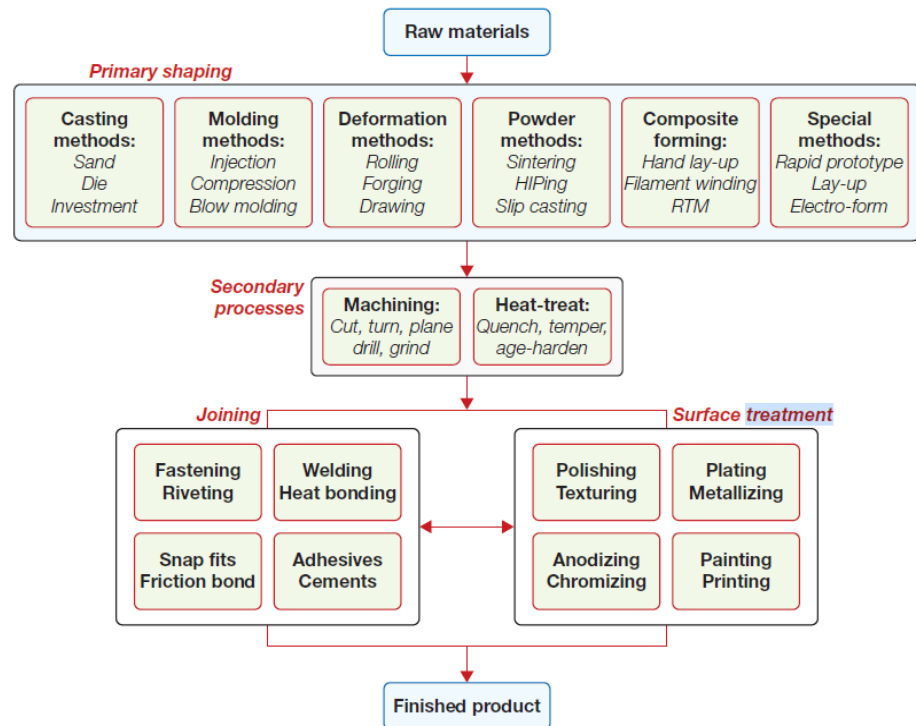
This is controlled by parameter setting during the process such as speed of deposition and power of electron beam or laser where the correlation of these cause the powder to become molten, forming a pool and fusing together (see table below).



The effect of changing the scan speed and scan strategy on porosity developed in AlSi10Mg [32]. The strategies used were overlap (scanning each layer twice with the second scan melting the overlap between each two adjacent melt pools), Pre-sinter (scanning each layer twice with the first scan at reduced power), X&Y 2HS (scanning each layer twice, rotating 90° between scans and changing the hatch spacing per scan), Alternating (rotating the scan direction by 90° every layer), and 2X (scanning each layer twice) (Aboulkhair, 2019).

5.5.6 Heat Treatment

In general heat treatment is considered one of the longest processes. Heat treatment is used to condition toughness, strength and ductile properties of materials. It enables the material to be conditioned not only for processing but also application of design intent where their constraints in terms of the required flex, rigidity and robustness dependant on the application, environment and forces that are involved either in the part itself or connecting parts, complimenting or compensating for inhere properties of adjoining parts in and assembly for example. There are varying classes as depicted in the chart below (Ashby, 2011).



5.5.7 Strength Properties of Materials

There are many attributes and conditions that must be taken into account when using materials such as Aluminium specifically when the application used where there are significant stringent regulations and safety concerns for transportation, none more so the aircraft where safety is the number one priority. Each trait and character of the material properties must be calculated in order to ensure conformity and fitness for purpose for the intended applications. Mechanical deformation of a component is affected by not only the properties of the and application, but also its physical attributes such as shape, form, length, loading, cross sectional are etcetera. Therefore, there are specific formulas that are applied to ascertain specific characteristics to calculate and determine specific strength properties of a materials the examples in the following five tables below are typical of the calculations used, there are many others that also need consideration and where appropriate need to be applied. (Ashby, 2011).

Table 1. Mechanical Responses.

Elastic

Uniaxial	$\epsilon = \frac{\sigma}{E}$	
General	$\epsilon_1 = \frac{\sigma_1}{E} - \nu(\sigma_2 + \sigma_3)$	etc.

Plastic

Uniaxial	$\sigma \geq \sigma_y$	
	$\sigma_1 - \sigma_3 \geq \sigma_y$	$(\sigma_1 > \sigma_2 > \sigma_3)$ or
General	$\left[\frac{1}{2} \{ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \} \right]^{\frac{1}{2}} > \sigma_y$	

Creep

Uniaxial	$\dot{\epsilon} = \dot{\epsilon}_0 \left(\frac{\sigma}{\sigma_0} \right)^n$	
General	$\dot{\epsilon}_1 = \dot{\epsilon}_0 \frac{\sigma_0^{n-1}}{\sigma_0^n} \left\{ \sigma_1 - \frac{1}{2}(\sigma_2 + \sigma_3) \right\}$	etc.

Fracture

Uniaxial	$\sigma \geq C K_{1C} / (\pi a)^{1/2}$	
General	$\sigma_1 \geq C K_{1C} / (\pi a)^{1/2}$	$(\sigma_1 > \sigma_2 > \sigma_3)$

E = Young's modulus

ν = Poisson's ratio

σ_y = Plastic yield strength

n, ϵ_0, σ_0 = Creep constants

K_{1C}, a = Fracture toughness, crack length

$C \approx 1$ Tension

$C \approx 15$ Compression

Table 2. Moments of Sections.

	Area A	Moment I	Moment K	Moment Z	Moment Z_x
	C_1	C_2			
	3	2			
	8	6			
	2	1			
	48	16			
	$\frac{384}{5}$	24			
	192	-			
	384	-			
	6	-			
	-	4			
	-	3			

$$\delta = \frac{FL^3}{C_1EI} = \frac{ML^2}{C_2EI}$$

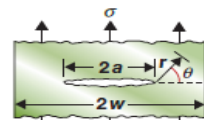
$$\theta = \frac{FL^2}{C_2EI} = \frac{ML}{C_2EI}$$

E = Young's modulus (N/m²)
 δ = Deflection (m)
 F = Force (N)
 M = Moment (Nm)
 L = Length (m)
 b = Width (m)
 t = Depth (m)
 θ = End slope (-)
 I = See Table B.2 (m⁴)
 y = Distance from neutral axis (m)
 R = Radius of curvature (m)

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{E}{R}$$

Table 3. Elastic Bending of Beams.

Table 4. Cracks.



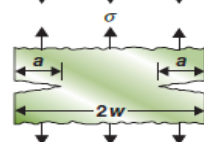
$$C$$

$$1.0 \text{ if } a \ll w$$

$$\left(\frac{2w}{\pi a} \tan \frac{\pi a}{2w} \right)^{\frac{1}{2}}$$

$$K_1 = C \sigma \sqrt{\pi a}$$

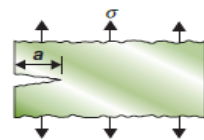
Failure when
 $K_1 \geq K_{1c}$



$$1.1 \text{ if } a \ll w$$

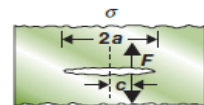
$$\left(\frac{2w}{\pi a} \tan \frac{\pi a}{2w} \right)^{\frac{1}{2}}$$

K_1 = Stress intensity ($\text{N/m}^{\frac{3}{2}}$)
 σ = Remote stress (N/m^2)
 F = Load (N)
 M = Moment (Nm)
 a = Internal crack half-length (m)
 c = Surface crack length (m)
 w = Half-width (center) (m)
 b = Width (edge crack) (m)
 b = Sample depth (m)
 t = Beam thickness (m)



$$1.1 \text{ if } a \ll w$$

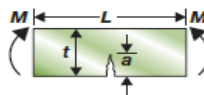
$$\frac{1.1 \left(1 - 0.2 \frac{a}{w} \right)}{\left(1 - \frac{a}{w} \right)^{\frac{3}{2}}}$$



$$\frac{2}{\pi} \left(\frac{a+c}{a-c} \right)^{\frac{1}{2}}$$

Point load on crack face

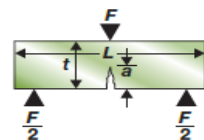
$$\sigma = \frac{F}{2ab}$$



$$\frac{1.1 \left(1 - \frac{3}{2} \frac{a}{t} \right)}{\left(1 - \frac{a}{t} \right)^{\frac{3}{2}}}$$

Moment on beam

$$\sigma = \frac{6M}{bt}$$

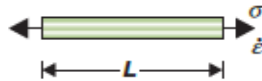


$$\frac{1.1 \left(1 - \frac{3}{2} \frac{a}{t} \right)}{\left(1 - \frac{a}{t} \right)^{\frac{3}{2}}}$$

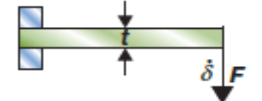
3-point bending

$$\sigma = \frac{3FL}{2bt}$$

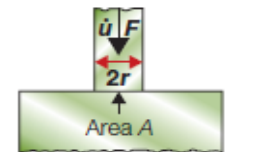
Table 5. Creep and Creep Fractures.



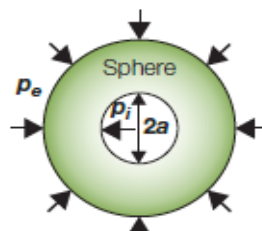
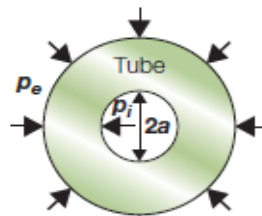
$$\dot{\epsilon} = \dot{\epsilon}_0 \left(\frac{\sigma}{\sigma_0} \right)^n$$



$$\dot{\delta} = \frac{2 \dot{\epsilon}_0}{n+2} \left(\frac{(2n+1) F}{n s_0 b t} \right)^n \left(\frac{L}{t} \right)^{n+1}$$



$$\dot{u} = C_1 \dot{\epsilon}_0 \sqrt{A} \left(\frac{C_2 F}{\sigma_0 A} \right)^n$$

 σ = Stress (N/m^2) F = Force (N) $\dot{\delta}, \dot{u}$ = Displacement rates (m/s) $n, \dot{\epsilon}_0, \sigma_0$ = Creep constants L, b, t = Beam dimensions (m) a, b = Radii of pressure vessels (m) ρ = Relative density, $\frac{b^3 - a^3}{b^3}$ $\dot{\rho}$ = Rate of change of ρ C_1, C_2 = Constants

$$\dot{\rho} = 2 \dot{\epsilon}_0 \frac{\rho (1 - \rho)}{(1 - (1 - \rho)^{1/n})} \left(\frac{2 (\rho_e - p_i)}{\sigma_0} \right)^n$$

$$\dot{\rho} = \frac{3}{2} \dot{\epsilon}_0 \frac{\rho (1 - \rho)}{(1 - (1 - \rho)^{1/n})} \left(\frac{3 (\rho_e - p_i)}{2 \sigma_0} \right)^n$$

6 Surface Quality and Roughness

6.1 Influence of Process Parameters

6.2 Layer Thickness and Resolution

In most cases laser based systems deposit thinner layer of powder compared to electron beam ultimately providing better defined resolution.

6.3 Surface Finish of 3D Printed Aluminium

6.4 Surface Roughness Measurement

6.5 Surface Treatment Techniques

7 Limitations and Challenges

7.1 Material Degradation

Tests and other research have shown Additive manufacture materials to be not dissimilar to conventionally manufactured components from traditional materials. In this paper metal alloys has been the consideration. However, these is not the only materials considered for additive manufacturing, likewise ceramics, composites and organic materials are all undergoing research trials and development, each with their own complications. Degradation or the lack of during the serviceable life of a components specifically for transportation use is paramount to safety. However, the opposite is true when that components comes to the then end of its life cycle.

7.2 Size, Scale and Material Limitations

Currently the size of the powder bed chamber is a factor that limits the manufacture of in some instances of a single piece component.

7.3 Carbon Footprint and Environment

The manufacture of powder materials is not in itself a purer process than that of conventional materials, it is the subsequent process that provide the gains. Materials research and development in material types and manufacturing processes are constantly evolving. Not being unique to aircraft and aerospace industries, but is part of strategy to provide a cleaner environments globally from manufacture to operation within the aircraft industry

7.4 Cost and Economic

7.5 Future Challenges

Like all new technologies demand grows and accelerates once the concept is realised, the visualisation of application understood and the potential demonstrated.

8 Specific Case Studies

For this section of the study the areas of interest detailed are centred on cost and benefit. A couple of specific aircraft scenarios have been chosen firstly 9.1 Lead time and cost reduction for repair. Secondly 9.2 a seat component designed and manufacture by SAFRAN SEATS GB.

8.1 Aircraft Maintenance, Repair, and Overhaul.

(MRO) facilities encounter the necessity to manufacture or refurbish specific components intermittently, often in minimal quantities, while facing unpredictable production demands and widely dispersed supply chains. Additionally, MROs are occasionally tasked with the restoration or substitution of components in legacy aircraft, where the requisite tools may no longer be procurable from Original Equipment Manufacturers (OEMs). According to Northrop Grumman, the aviation industry typically experiences a turnover rate three times greater than the initial investment, implying that the cost savings realized through the application of Additive Manufacturing (AM) technologies must surpass threefold the initial investment in AM equipment (Singamnemi, 2019).

The potential benefits of employing AM in comparison to Computer Numerical Control (CNC) machining. The study reveals a substantial reduction in both costs and lead time associated with repairing a helicopter part, decreasing from US \$2000 and 45 days to US\$ 412 and 2 days, respectively. This outcome significantly exceeds the 3:1 investment benchmark, highlighting the efficacy of AM technologies in achieving considerable cost efficiencies within the context of aircraft MRO operations (Singamnemi, 2019).

To mitigate expenses and shorten turnaround times, aviation maintenance enterprises employ laser metal deposition (LMD) techniques for the restoration of engine housings, compressor components, and turbine blades. Franúhofer ILT successfully utilized LMD and selective laser melting (SLM) for the refurbishment of the Inconel 718 turbine case and compressor seal, ultimately obtaining certification from Rolls-Royce Deutschland.

Rolls-Royce asserted a 30% reduction in production time through the adoption of additive manufacturing (AM) methodologies (Singamnemi, 2019).

Hedges and Calder demonstrated the viability of net-shape processing, specifically laser-engineered net shaping (LENS) technology, for the repair of T700 helicopter engine parts. Numerous investigations into the material and mechanical properties of the mended components further substantiated the feasibility of employing AM in aviation Maintenance, Repair, and Overhaul (MRO) tasks. Ongoing advancements encompass the development of a geometrically adaptive toolpath laser processing approach for precise repairs by Qi et al. Ren et al.'s hybrid manufacturing method for the restoration of dies and cores and Wilson et al.'s application of direct laser deposition in turbine blade repair. The latter study highlighted substantial energy and carbon footprint reductions achieved in comparison to the replacement of components with new parts (Singamnemi, 2019).

8.2 Specific Case Study Analysis of 7075 T6 – Al7075

The component chosen this case study has undergone all regulatory testing and certification for air worthiness. It is currently in production today at SAFRAN Seats GB. SAFRAN is no stranger to AM within other group sectors but currently not yet deployed as a direct manufacturing resource within the UK Seats division. Nevertheless, there is significant interest with a number of collective to provide a base line to compare technical data from conventional subtractive manufacture. The same base line manufacturing model data loaded to Fusion 360 and then subjected to AI generation, AM simulation and testing. **(WAITING STRESS DATA FOR COMPLETION)**

9 Conventional Manufacture of Machined Components Comparisons

9.1 Process Times

9.2 Waste Comparison

9.3 Cost Comparison

9.5.1 Material Costs

9.5.2 Processing Costs

9.5.3 Energy Costs

9.5.4 Waste Removal Costs

10 The Environment and Carbon footprint

10.1 Aircraft Industry Commitment

10.2 Environmental Comparison

10.3 Materials and Usage

10.4

11 Conclusion (Draft notes for completion)

11.1 Additive Manufacturing – Conventional Machining

- 11.1.1 The technologies being used today are the culmination joint drive, collaboration and merging together minds, industries, science and the will for a cleaner better future. The technologies to come some already in development and others not yet though of will hope all be game changers as some that we have seen in recent years. Imaging for example additive manufacturing with metal fusion being successfully conducted at ambient room temperatures (Gibson Ian, 2015)
- 11.1.2 From the many types of AM only a few can truly be regards can be defined as printing and additive compared to the subtractive. The many benefits of AM is the freedom of choice for designers as they are less constrained by geometrical shape and the sometimes impossible porting and routing of internal form or structure that could not be achieved with conventional methods of manufacture. Designs can quickly be manufactured by comparison for prototype and prove-out of concept giving a 1:1 ratio for an of the shelf philosophy and also allow for significant cost savings through lower material usage requirement, waste reduction, lower energy use (Katz-Demaynetz, 2019).

11.1.3 INCLUDE ADDTION DATA SECTIONS FROM NOTES

11.2 Environmental Impacts

- 11.2.1 AM manufacturing technology has and is driving development of new materials that complimenting to process results and providing greater opportunities for additional environmental gains within the aerospace challenge to reduce CO² emissions. In addition to aluminium use, there are many types of materials currently being more and more widely used with aircraft/aerospace sectors which is not limited to metal alloys, other materials are being developed and used for fabrics and composite structure to further reduce environmental impacts through reduced utilisation of

raw materials and circular economic material usage the further reduce environmental issues. Although the aircraft industry's carbon footprint remains a significant source of global carbon emissions, much progress has been made in recent years in its reduction (Marcel Dekker Inc, 2003).

- 11.2.2 This progress has come through the adoption of new technologies, effective operational changes, the use of alternative fuels and materials. As the urgent need to combat climate change continues to grow, efforts to reduce carbon emissions from aircraft industry must remain a key focus (Marcel Dekker Inc, 2003).
- 11.2.3 Over the past three decades, scrutiny has been directed towards the alignment of aluminium production with the tenets of sustainable development and associated ideologies. The primary apprehension centres around the notion that, despite aluminium being the most abundant metal on Earth, access to high-grade bauxite deposits is somewhat restricted. Another contention arises from the substantial energy requirements involved in the production of primary aluminium. However, it is noteworthy that the impetus behind aluminium recycling is primarily driven by market dynamics and the inherent characteristics of aluminium, rather than being dictated by state legislation, as observed in the case of plastic materials and, to a certain extent, steel (Marcel Dekker Inc, 2003).
- 11.2.4 The disparity in energy consumption between the production of primary aluminium from raw materials and the re-melting process for secondary metal renders recycling endeavours highly economically viable. The emergence of an "aluminium bank" is indicative of this trend, wherein the exchange of metal with the market occurs through the sale of finished products and the acquisition of scrap. A closed-loop system has been well-established, with approximately 30% of materials incorporated into new components originating from secondary sources. The pivotal force propelling the functioning of the material bank predominantly lies in energy, often sourced from hydroelectric power plants. It is pertinent to note that, absent human intervention, aluminium in its pure metallic form would be non-existent in nature, given the relentless process of oxidation over time, resulting in the formation of Al_2O_3 . The extraction of metal from its oxide necessitates significant energy inputs, thereby characterizing aluminium metal as an energy-intensive investment (Marcel Dekker Inc, 2003).
- 11.2.5 Currently, airframes are composed of approximately 70%-80% aluminium by weight, with a significant portion manifested in the form of profiles. While demands for lightweight materials in other segments of the transportation industry have not historically been as stringent, emerging environmental concerns and escalating competition, encompassing both pricing and speed, are driving the introduction of novel materials and concepts. Notable instances include the utilization of aluminium in high-speed trains like the French TGV Duplex, the German Maglev system, and the Japanese superconducting Maglev system (Marcel Dekker Inc, 2003).
- 11.2.6 Transformations are underway even in traditionally conservative sectors such as shipping. Passenger transport has, for a considerable duration, employed aluminium intensive fast ferries, and ongoing developments involve the exploration of high-speed surface effect ships for goods transportation. The increased integration of aluminium frames in buses and commercial vehicles signifies an impending breakthrough in the automotive industry. However, despite the execution of Life Cycle Assessments (LCAs) within this sector, consumer attention remains predominantly fixated on initial costs rather than those associated with ongoing

usage. Consequently, the pursuit of lightweight solutions in the automotive industry is not as fervently sought after as observed in other branches of the transportation sector. New cars contain about 70 kg of aluminium parts, and smaller production series of more expensive cars have been made with so-called spaceframes of aluminium. Such frames comprise the structural elements of the car (Marcel Dekker Inc, 2003).

12 Appendices

Secondary reading (including additional referenced material from 'Works Cited')

- 1) Powder-bed Additive Manufacturing for Aerospace
- 2) Advancements in in the Processing Characteristics and Application of Lightweight Materials
- 3) Aeronautical and Aerospace Engineering
- 4) Aluminium uses in aircraft
- 5) History of Aluminium in the Aerospace Industry
- 6) 3D printing of Aluminium Alloys
- 7) Aluminium 7075T6 Properties
- 8) Additive Manufacturing in the Aviation Industry
- 9) Additive Manufacturing of Metals – From Fundamental Technology to Rocket nozzles, Medical implants and Custom jewellery
- 10) Mechanical Properties of Al7075
- 11) Additive Manufacturing Technologies 3D Printing, Rapid Prototyping and Direct Digital Manufacturing
- 12) Metal Additive Manufacturing in Aerospace
- 13) Additive Manufacturing for the Aircraft Industry
- 14) Materials and Design. The Art and Science of Material Selection in Product design 3rd Edition
- 15) Disruptive technologies
- 16) Advances on Mechanics, Design Engineering and Manufacturing
- 17) Airworthiness. An Introduction to Aircraft Certification and Operations
- 18) Airworthiness. An Introduction to Aircraft Certification; A Guide to Understanding JAA, EASA and FAA Standards
- 19) Alternative Lubrication Metal Cutting
- 20) CAD/CAM/CIM
- 21) CO² Commercial Aviation
- 22) General Practical Machining I & II
- 23) Engineering Materials 1, 3rd edition. An Introduction to Properties, Application and Design
- 24) Engineering Materials 2, 3rd edition. An Introduction to Microstructures, Processes and Design

- 25) Environment and Aviation Facts and Figures
- 26) Handbook of Aluminium, Physical Metallurgy and Processes
- 27) Introduction to Manufacturing Processes
- 28) ISO 9001, ISO 14001 and New Management Standards
- 29) ISO 9001 A Complete Guide to Quality Management Systems
- 30) Joint Federal Aviation Report; Additive Manufactured Parts
- 31) Additive Manufacturing with the lightweight material aluminium alloy EN AW-7075
- 32) Laser Additive Manufacturing
- 33) Lubricants Green Cutting
- 34) Materials Selection in Mechanical Design 4th Edition
- 35) Mechanical Properties of Al7075
- 36) Modelling and Simulation of Functionalised Materials for Additive Manufacturing and 3D Printing
- 37) A Comprehensive Review: Role of Energy Consumption, Cutting Tool and Work Piece Materials towards Environmentally Conscious Machining
- 38) Practical Aviation and Aerospace Law
- 39) Pre-Heat Treated Al7075
- 40) Printing with Metal
- 41) Recycling Al7075
- 42) A Study of Additive Manufacturing
- 43) UK Aviation Industry Promises to be Carbon Neutral by 2050
- 44) Fabrication of Al7075
- 45) Fused Deposition Al7075
- 46) Advances in Manufacturing Technology: Select Proceedings of ICAMT 2018
- 47) Fabrication of Al7075/Al Two Phase Material
- 48) Blended Powder Semisolid Forming Al7075
- 49) Understanding Aluminium Alloys Powder
- 50) Fundamentals of CNC Machining
- 51) Programming of CNC Machines Fourth Edition
- 52) Machinery's Handbook pocket companion
- 53) Metal Cutting
- 54) Predictive simulation for windows for powder bed fusion additive manufacturing
- 55) Additive manufacturing to veterinary practice

13 Further recommended reading and research directions

- 1) Improved Material Characterization Technique
- 2) Advanced Process Optimization
- 3) Hybrid Approaches and Multi-Material Printing
- 4) Integration with Design Optimization
- 6) Recycling AL7075
- 7) CO² Commercial Aviation
- 8) Disruptive Technologies
- 9) Advancements in the Processing Characteristics and Applications of Lightweight Materials

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