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

MSc of Science in Industry 4.0 and Advanced Manufacturing

An assessment of the application of Aluminium Additive Manufacture for producing fully operational aluminium components used in commercial airline seating, with a focus on verifying the feasibility, conducting tests and development, and examining the positive environmental effects.

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Abstract:

The use of additive manufacturing technologies, specifically 3D printing, has garnered significant interest across multiple industries due to its capacity to transform conventional production methods for creating intricate and personalised components. This study investigates the possible application of 3D aluminium printing in comparison to traditional manufacturing techniques. Aluminium, renowned for its advantageous mechanical characteristics, is extensively used in both conventional manufacturing and 3D printing techniques. (Katz-Demaynetz, 2019).

The objective of this dissertation is to conduct a thorough examination of the relative strength of 3D printed and solid aluminium components. By employing both quantitative and qualitative analysis of current research, case studies, and industry practices.

Investigating the legitimacy of utilising 3D aluminium printing instead of traditional manufacturing methods to assess its usefulness, compare costs, and showcase its potential for reducing material waste, energy usage, carbon emissions, and overall environmental effect. Conducting a study on the mechanical characteristics and effectiveness of 3D printed aluminium, providing useful knowledge regarding the possible use of this technology in several engineering fields. Currently, it is not universally acknowledged as a viable option for all circumstances. However, the results will enhance our comprehension of the mechanical characteristics and ecological viability of additive manufacturing technologies, so enabling informed decision-making in relevant industry usage and applications. (Rajesh. S, 2020).

Acknowledgement:

Several individuals in my life have significantly helped, mentored, and motivated me to aspire to higher levels that I previously considered beyond my own capabilities. Regrettably, not all of them are present at this moment to partake in my display and celebration of the powers that they were aware I might exhibit. They would experience the same level of pride as those who continue to encourage me to develop.

I express profound appreciation to all individuals who have contributed to my personal growth and accomplishments, including both long-standing and recent family members, friends, and co-workers. Your support has been crucial in helping me refine my skills, advance professionally, and pursue further learning. It has enabled me to obtain valuable experience and information, which have benefited me and fuelled my desire to achieve additional academic goals.

Author's Declaration:

I declare that the work in this dissertation was conducted 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.

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1. Introduction:

Additive production (AM), which includes 3D printing, has emerged as a disruptive force that is fundamentally changing traditional production methods. The material is widely used in several industries due to its reputation for being lightweight and having good strength ratios (Hannibal, 2018).

The objective of this study is to thoroughly evaluate and compare the strength characteristics of 3D-printed aluminium with solid aluminium components. The study provides valuable information on the future design and utilisation of 3D-printed aluminium applications using advanced manufacturing techniques (JCM 2020 Members, 2021).

In the field of aviation, there are strict regulations known as Airworthiness Regulations that prioritise safety. These regulations are applicable to all types of aircraft, regardless of their purpose. It is required for all components, regardless of their size, material, or function, to meet these high requirements. The challenges faced by aviation industry are rigorous and demanding (Blakey-Milner, 2021). After establishing the requirements, a design team uses several approaches like as testing, computer-aided design (CAD), dynamic and static stress evaluations, and other techniques to evaluate the safety. Cost, performance, and the development of creative solutions are of utmost importance in manufacturing industries such as aviation, automotive, and other forms of transportation, including pleasure, commercial, and sports. SAFRAN Seats GB, a company specialising in custom luxury seating for major airlines, can potentially achieve cost savings throughout the design and development phase by closely collaborating with aircraft industries to fulfil customer specifications.

2. Research:

2.1 Aims

This study will focus on the characteristics of 7075 T6 grade aluminium, which is widely employed in the production of frame components for commercial aircraft. This type of aluminium has been globally supplied since its introduction in 1945bu Clinton Aluminium Innovative Alloys (Clinton Aluminium Innovative Alloys, 2019) and is used by air framers and airlines using CAM and CNC technologies. The analysis will investigate the characteristics of conventionally provided 7075 T6 material in comparison to Al7075 material. The Direct Metal Laser Sintering (DMLS) process, which falls under the category of Additive Manufacturing, is widely employed to assess the feasibility of commercial applications. The results obtained from this investigation indicate that the existing technology for additive manufacturing procedures and the use of aluminium powder are highly suitable.

2.2 Objectives

The feasibility of obtaining aftermarket or new components and ensuring their compliance with requirements. Considering the structural composition of 3D printing. Comparing test pieces produced using generative design artificial intelligence (AI) construction with those made using conventional subtractive manufacture from solid material. By comparing the tensile qualities, we may gather proof of the drop in development time, manufacturing cost, and carbon footprint reductions achieved through Additive Manufacturing. In order to highlight the practicality of utilising contemporary additive manufacturing techniques with aluminium powder material, it is proposed to employ these methods across the whole design and prototyping stages of developing new aircraft components. This approach aims to assess the concept design's functionality, as well as determine its compatibility with existing parts.

2.3 Justification

The aviation industry predicts that the number of passengers will continue to climb, with an expected growth prediction of 70%. The United Kingdom aviation industry has made a firm commitment to make substantial modifications and enhancements, with the goal of reducing carbon emissions from 30 million tonnes of CO2 to zero by 2050, thereby striving for a carbon-neutral industry (Adams, 2020)**.** In addition, aeroplane manufacturers and component manufacturers have also made comparable pledges to address worldwide emissions. In order to decrease carbon emissions, businesses can enhance their reputation by adopting sustainable materials, implementing energy-efficient procedures, and minimising waste production. These measures not only benefit the economy and society, but also address global concerns.

2.4 Methodology

The research investigates several ways of 3D printing, specifically focusing on Additive Manufacturing. One of the techniques studied is Selective Laser Melting (SLM), which is widely employed for creating functioning prototypes and final products. It use additive manufacturing techniques to fuse together small bits of metal powder. A laser with an elevated level of energy is used to heat and combine the metal powder, resulting in the formation of solid surfaces. One notable distinction of the SLM technology process is the utilisation of a high-power laser to selectively fuse powdered materials, such as plastics

or metals, in a layer-by-layer manner. The un-combined powder that surrounds the hardened layers serves as a support structure during the printing process. Direct Metal Laser Sintering (DMLS) is a technique in metal 3D printing where a powerful laser is used to selectively melt and fuse metal particles together, building up the object layer by layer. The procedure occurs within a high-vacuum setting to inhibit oxidation. Direct Metal Laser Sintering (DMLS) is capable of manufacturing metal components that are both structurally solid and completely operational, even when they possess intricate shapes. These are two often utilised techniques for working with metals, however there are additional alternatives available. Obtaining a precise substitute for aluminium powder in additive manufacturing can be difficult because of variations in manufacturing techniques and the distinctive characteristics of the alloy. Nevertheless, there exist aluminium powders that can offer similar mechanical qualities and features as 7075-T6. Aluminium alloy powders, such as Al7075, closely resemble 7075 T6 and are frequently employed in research methods like as selective laser melting (SLM) or direct metal laser sintering (DMLS) for additive manufacturing procedures. These powders possess commendable strength, elevated hardness, and exceptional corrosion resistance, rendering them viable substitutes for 7075-T6. It is crucial to acknowledge that the characteristics of the printed components can still be affected by the particular process parameters, such as laser power, scanning method, and heat treatment conditions. Hence, it is advisable to seek guidance from powder suppliers or additive manufacturing specialists to determine the most appropriate aluminium powder for your particular application and required mechanical characteristics.

2.5 Limitations

In the event that the results yield a bad consequence, this procedure could still be employed to demonstrate the intended design. The primary factor at play is the drive to achieve a competitive advantage by being the first to introduce a product or service to the market. The progress in emerging technologies, ongoing research, and enhancements of Additive Manufacturing machines support Just in Time (JIT) manufacturing. The rapid progress in materials, applications, design, and production, facilitated by the utilisation of cloud computing and AI, enables the development and deployment of goods at an unparalleled pace. Currently, there are numerous ongoing explorations in various sectors of aircraft manufacturing that are simultaneously investigating the use of biomaterials. These explorations aim to analyse the viability of utilising biomaterials for specific aircraft components. However, it is important to note that the current application of biomaterials in aircraft manufacturing is limited.

2.6 Ethics

Ethics refers to the branch of philosophy that deals with moral principles and values, and how they guide human behaviour and decision-making.

The carbon emissions generated by the aircraft sector provide a significant environmental hazard. The emissions from this sector rank among the highest in the world in terms of carbon dioxide output. It is imperative to decrease these emissions in order to effectively address climate change. Fortunately, there has been substantial advancement in this field in recent years due to the use of innovative technologies, operational modifications, and the utilisation of alternative fuels. Technological advancements significantly contribute to the reduction of carbon emissions by aircraft

manufacturers and airlines. The increased utilisation of additive manufacturing and the adoption of lighter materials, such as composites, have effectively mitigated the environmental impact. Technological advancements and modifications in manufacturing techniques have played a significant role in supporting endeavours to decrease carbon emissions in the aircraft industry. 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, considerable 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
CMR	Conventional Machining Requirements
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	nanometre
µm	Micrometre

3. Background:

The aviation travel business consistently claims annual growth in the volume of flight passengers. Although passenger numbers remain below pre-COVID levels, they are quickly recovering and are projected to continue growing based on historical statistics and trend forecasting. From 2009 to 2019, the revenue of the air passenger sector has increased from around $374 billion U.S. dollars to around $607 billion U.S. dollars in 2019 (statista, 2023). Air travel serves as a primary means of transportation for both passengers and commodities, employing millions of people worldwide. Aircraft safety is of utmost importance, and engineers must possess a comprehensive understanding of the physiological and psychological impacts of aircraft design, operation, and maintenance on passengers, crew, and staff aboard. Industry standards are created and regularly revised with the aim of maximising the safety and dependability of aircraft. Aircraft design necessitates meticulous diligence, stringent adherence to high specifications, and rigorous safety standards, all while prioritising optimal ergonomics, ease of operation, and customer pleasure (Singamnemi, 2019).

3.1 Predominant Material

A commercial passenger aeroplane typically consists of a vast number of components, comparable to the number of words found in a dictionary. These components vary in size and complexity, ranging from tiny micro diodes to large wing spars. Aluminium is the primary material used in the aviation sector. The first recorded usage of this material dates back to as early as 1903 (Clinton Aluminium Innovative Alloys, 2019) primarily for constructing frames in the renowned Zeppelin airships. Approximately 75%-80% of a modern aeroplane is comprised by its usage (Metal Supermarkets, 2016). Aircraft design and engineering teams must be abreast of the most recent technology, developments, and regulations. By preserving a competitive edge, the aviation industry can offer safer, more dependable, and efficient solutions while minimising the expenses associated with developing, up keeping, and replacing obsolete aircraft equipment. Aviation engineering teams must possess a comprehensive understanding of the specific requirements and criteria of a given project in order to develop systems and components that adhere to the requisite standards. To comprehensively investigate this topic, it is crucial to get insight into the mechanisms and reasons behind its widespread adoption. Aluminium is widely used for several reasons. In the manufacturing of aviation components, different grade kinds are employed, with the most commonly used ones being 6061, 6063, 2014, 2024, 5052, 7050, 7062, 7068, and 7085 (Clinton Aluminium Innovative Alloys, 2019).

3.2 Typical Uses in the Aircraft Industry

The external surface and all concealed components that are enveloped by textiles or polymers. Here are a few illustrations:

a. Fuselage structures
b. Wing spars
c. Fuel Tanks
d. Seats internals
e. Doors
f. Galleys

g. Toilets
h. Cockpit equipment and racking

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

3.3 Supply Chain and Aftermarket

The unpredictability of demand poses challenges in managing inventory levels, particularly considering that just 10% of the spare parts require frequent replacement (Singamnemi, 2019). Long-term forecasting the cost of infrequently replaced spare parts that are held for extended periods of time can be challenging and may result in high expenses. Conventional inventory management solutions may prove ineffective in such situations and result in elevated inventory expenses. Spare parts are typically classified into four distinct categories: Rotatable, Repairable, Expendable, and Consumable. Each category has its own specific policy for replacement. Inventory analysts have the responsibility of allocating these policies to numerous spare components and must frequently update them to stay abreast of market fluctuations.

The supply chain of the aircraft industry is very lengthy and intricate when compared to other industries. Aircraft Maintenance, Repair, and Overhaul (MRO) organisations need to obtain approval from authorities in order to perform regular or unscheduled maintenance tasks on aircraft, which may involve the replacement of spare parts. Customers have the option to decide whether they want to produce or purchase the spare parts, depending on the nature of the organisation. Maintenance, Repair, and Overhaul (MRO) operations contribute to around 40-50% of the industry's total revenue. Moreover, the profit generated from the sale of replacement parts usually surpasses that of the sale of original equipment (Singamnemi, 2019). Ensuring the availability of aircraft replacement parts is crucial, as it helps minimise the time that aircraft are out of service, which is beneficial for airline operators. The turnaround time (TAT) serves as a significant performance metric in this regard.

3.4 Emerging Technology

The utilisation of metal printing technologies in the aircraft industry is revolutionising the construction of aeroplanes. Metal printing, or 3D printing, is the technique of fabricating three-dimensional things from a digital model. This digital model is a necessary requirement for all 3D printing machines to generate a part (Gibson Ian, 2015). 3D printing eliminates the need to cut shapes from metal sheets and assemble them, as it enables the direct manufacturing of the final product through a single procedure. This technological innovation has proven to be highly advantageous for the aircraft industry, providing numerous benefits such as increased manufacturing speed and enhanced precision. 3D printing is primarily employed in the aircraft sector to produce very intricate components that would otherwise need many hours to construct (Blakey-Milner, 2021). 3D printing reduces the duration, resulting in both financial savings and accelerated manufacturing schedules. The components produced through 3D printing are particularly adaptable, as they are often tailored to fit a particular aircraft. By employing this type of customisation, organisations are able to reduce expenses by avoiding the need to maintain inventory of items that may not be used.

3.5 Traditional Manufacturing

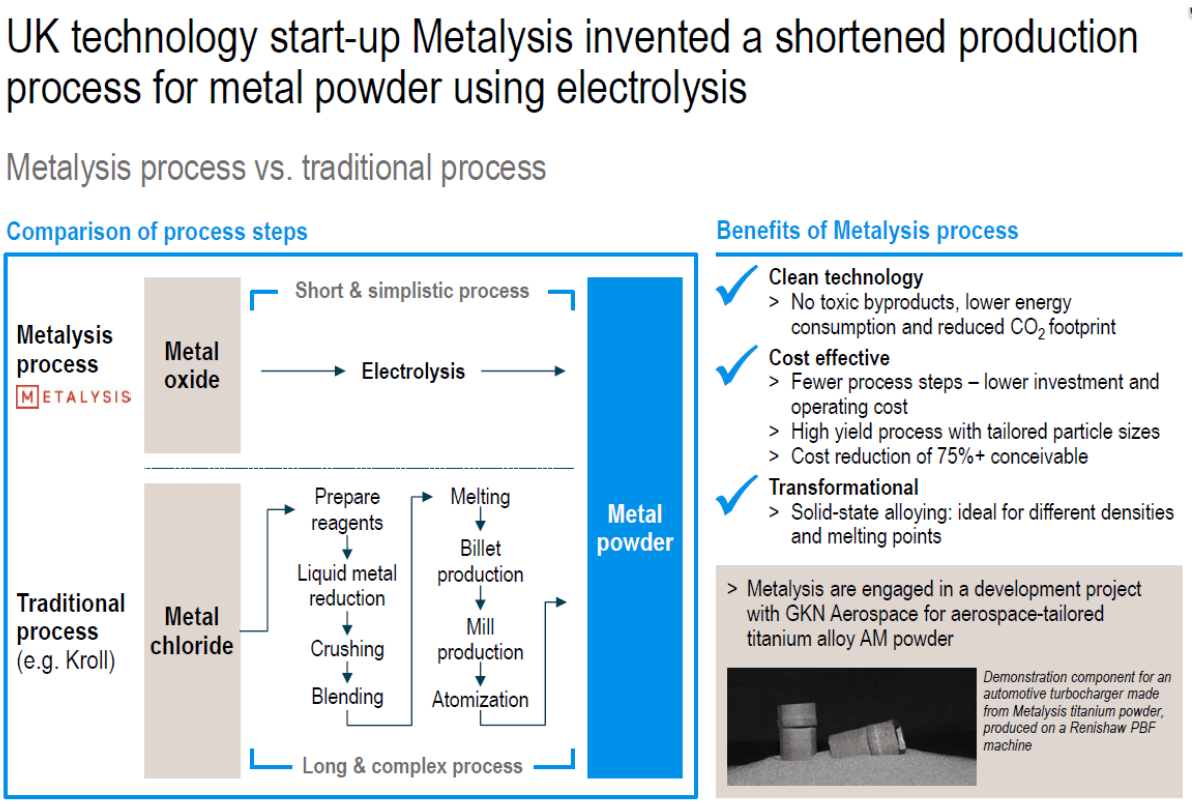
There are a variety of ways a part can go wrong. Between the cutting, welding, and soldering, it can be challenging to create a perfectly formed component. 3D printing helps to minimize the margin of error due to its superior accuracy (Roucoules Lionel, 2020)**.** There are multiple ways in which a component can malfunction. Amidst the processes of cutting, welding, and soldering, the task of creating a flawlessly shaped component can be quite arduous. 3D printing reduces the margin of error by using its exceptional precision (Roucoules Lionel, 2020). Moreover, owing to the intricate and elaborate designs achievable with 3D printing, the resulting parts are remarkably lightweight, hence enhancing the efficiency of an aircraft. The utilisation of 3D printing for metal components holds the capability to eradicate waste generated by conventional production procedures. These components are typically more sophisticated than those produced by CNC machining, resulting in a decreased amount of waste material at the conclusion of the manufacturing process (Roucoules Lionel, 2020). In general, the developing metal printing technology is revolutionising the aircraft sector by offering distinct advantages such as expedited production times and enhanced precision. The future of aeroplane production appears highly promising due to the numerous potential applications of 3D printing. The rapid advancement of technology has opened up limitless opportunities for the utilisation of 3D printing in the aircraft sector.

3.6 Potential Advantages for the Environmental

Operational practices modifications have assisted in the endeavour to decrease carbon emissions in the aircraft industry. Flight sharing, electronic flight records, enhanced air traffic control systems, improved weather predictions for flight planning, and advanced air-traffic management initiatives collectively enhance the efficiency of flight operations, hence diminishing the carbon footprints of the aircraft industry. According to Singamnemi, each kilogramme of weight reduction on a commercial aircraft is anticipated to result in a cost saving of US$3000 and a yearly reduction of 8.7% in carbon emissions (Singamnemi, 2019).

Alternative fuels have frequently been promoted as a catalyst for decreasing greenhouse gas emissions associated with aviation. Various fuels, including advanced biofuels, have been created that exhibit significantly lower levels of pollution compared to their fossil fuel equivalents. In addition, certain experts claim that the implementation of sophisticated propulsion technologies, such as electric motors and hypersonic engine designs, could impede the timeliness of market proposals (Bright Appiah Adu-Gyamfi, 2022). The utilisation of lighter materials, such as composites, has effectively mitigated the ecological consequences associated with aircraft manufacturing. Furthermore, the reconfiguration of aircraft cabin arrangements and the use of novel cabin technologies have additionally aimed to diminish the energy requirements of aircraft operations by minimising aerodynamic resistance and mass. Widespread adoption of 3D additive manufacturing (AM) metals, particularly in conjunction with cleaner modern technology for producing metal powders, has the potential to significantly decrease the carbon emissions of the aircraft sector. Berger supports this (Berger, 2016)and illustrated in *figure 1*.

Figure 1.


UK technology start-up Metalysis invented a shortened production process for metal powder using electrolysis
Metalysis process vs. traditional process
Comparison of process steps
Metalysis process
METALYSIS
Metal oxide
Short & simplistic process
Electrolysis
Traditional process
(e.g. Kroll)
Metal chloride
Prepare reagents
Liquid metal reduction
Crushing
Blending
Melting
Billet production
Mill production
Atomization
Long & complex process
Metal powder
Benefits of Metalysis process
Clean technology
> No toxic byproducts, lower energy consumption and reduced CO_2 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 production of components during the design and development phase is sometimes an unbelievably expensive stage of the process. In many instances, material consumption is elevated due to the essential need for creating jigs and fixtures during the manufacturing process of a component. These tools are necessary at various stages of machining and often require more time and money to produce than the actual component itself (Roucoules Lionel, 2020). If the design of the component needs to be altered, it may need a total overhaul of all the work done thus far, depending on the extent of the adjustments. The global benefits of sustainable carbon footprint, energy reduction, social recognition, job creation, and development prospects, as well as commercial and economic growth, have been acknowledged by (Gibson Ian, 2015), (Berger, 2016).

4.2 3D Printing using Aluminium Powder

The utilisation of Aluminium Powders in 3D printed components would facilitate aircraft manufacturing industry managers in obtaining approval from executive management to invest in more sustainable design and prototyping manufacturing solutions. These solutions can be implemented using the most efficient and effective methods (Aboulkhair, 2019). The availability of sustainable resources and their benefits can be showcased by illustrating how the design and development of goods that require aluminium components can be accomplished using additive manufacturing (AM) instead of conventional methods that generate more rubbish. However, generative design software allows for the creation of unique core architectures that result in components that are not only equivalent in functionality but also possess superior strength characteristics (Gibson Ian, 2015). Examine how different production processes can yield benefits such as circular manufacturing, waste minimization, cost reduction, time efficiency, and enhanced incentives for early investment.

4.3 An Introduction to Additive Manufacturing

4.3.1 3D printing, also referred to as additive manufacturing, is an innovative production technique that constructs three-dimensional items by incrementally adding material in layers. Additive manufacturing, in contrast to traditional subtractive processes, uses controlled deposition or solidification of material to construct products, rather than cutting or shaping materials**.** Commonly known as AM, employs machines to simplify a challenging 3D problem by breaking it down into a series of uncomplicated 2D cross-sections, each with a specified thickness. This approach eliminates the necessity of establishing connections between surfaces in a three-dimensional space. Continuity is dictated by the proximity of one cross-section to its adjacent counterpart. Unlike CNC machining, which often involves the direct creation of surfaces in 3D space, AM machines follow a distinct strategy. Generating surfaces for basic geometric shapes like cylinders, cuboids, cones, etc., is a straightforward process that entails connecting points along a defined path. However, in these instances, the points are widely spaced apart, and the tool orientation remains constant. On the contrary, when dealing with freeform surfaces, the points can be closely arranged with frequent changes in orientation. Despite the implementation of modern 5-axis interpolation control or higher in CNC machining, challenges arise when producing intricate geometries. Features such as undercuts, enclosures, sharp internal corners, and

others may encounter failure if they exceed a certain threshold (Gibson Ian, 2015).

4.3.2 Maintaining a consistent product without alterations at various stages of the process poses significant challenges when dealing with several characteristics of generative design in machining. This has resulted in AM machine manufacturers and external vendors to work collaboratively. Monitoring of temperature conditions on a layer-by-layer basis is being implemented during the additive manufacturing process by AAM equipment makers and external vendors working together. The main goal is to guarantee uniform and favourable deposition conditions for every layer throughout the construction of the part. In order to accomplish this, it is possible to incorporate cameras and optical sensors into the laser delivery optics. This would allow for a better understanding of the circumstances in the area where the material is being melted and provide extra data on how well the process is performing (Miliwski, 2017).

4.3.3 Laser scanning technologies are being developed to rapidly evaluate surface uniformity and dimensional parameters in powder bed fusion and directed energy deposition additive manufacturing processes. In arc-based systems, noncontact methods for monitoring and controlling the welding process are used. These methods involve sensing the length of the arc to guide and control the movement of the welding torch along the specified route. Recent improvements in power supply technology have not only diminished the dimensions and expenses of power supplies, but also facilitated swift, real-time regulation of arc current and voltage. Moreover, these technologies offer a live visualisation and surveillance of fundamental process parameters (Miliwski, 2017).

4.3.4 Variable polarity pulsed power supply, which use computer-based controls, demonstrate the ability to tailor arc conditions according to the specific materials and components being welded. The application of high-speed wireless multichannel data acquisition has demonstrated its durability in withstanding the demanding conditions of the additive manufacturing processing environment for arc-based systems (Miliwski, 2017).

4.3.5 Numerous challenges hinder the widespread adoption of Powder Bed Additive Manufacturing (PB-AM) in industrial manufacturing, primarily due to the integration of PB-AM into existing technological chains. These challenges encompass a range of issues, from differences in raw material acquisition to the necessity of adapting design philosophies (Gibson Ian, 2015). Although design for AM breaks free from certain traditional constraints, it introduces new, specific limitations. Overcoming these challenges requires addressing concerns such as establishing new quality control and standardization methods, making changes in component post-processing, integrating additively manufactured components into existing systems, devising novel life cycle analysis approaches, and evolving cost and resource management strategies. This undertaking significantly impacts equipment, workforce, logistics, touching every aspect of the industrial process. In essence, a new entity is born within the traditional industry, but meticulous efforts are necessary for its maturation (Miliwski, 2017).

4.3.4 Looking towards the near future, advancements in Powder Bed Additive Manufacturing (PB-AM) may take various specific directions to better realize its potential. These directions include:

Adapting and refining existing PB-AM techniques for:

a) Producing defect-free lightweight parts with high specific strength (beam-based processing).

b) Manufacturing high-performance alloys with advanced microstructure, including Ni-based super-alloys (powder bed beam-based processing with possible in situ alloying).

c) Creating Bulk Metallic Glasses (BMGs) through powder bed beam-based processing and powder bed BJP processing.

d) Developing High Entropy Alloys (HEAs) using beam-based processing with potential in situ alloying.

e) Fabricating ceramic and non-metal-based composite materials through powder-bed BJP processing.

f) Producing metal-based composite materials using beam-based PB-AM and BJP processing.

g) Crafting compositionally and functionally graded materials using PB-AM (both beam-based and BJP processing).

4.3.5 Materials research and development focusing on in situ alloying throughout beam-based PB-AM (Electron Beam Melting and Selective Laser Melting), potentially enabling the use of elemental powder and complex powder blends instead of fully pre-alloyed powders as raw materials for multi-component metallic alloys. Material research in post-processing techniques aimed at eliminating residual porosity after beam-based processing for metallic materials and after BJP processing for ceramic, composite, functionally graded materials, and BMGs. Research in PB-AM production existing routes optimisation to achieve faster and more effective manufacturing processes (Katz-Demaynetz, 2019).

4.4 Key aspects of Additive Manufacturing

4.4.1 Applications

Additive manufacturing is used in many sectors such as aerospace, automotive, healthcare, consumer goods, architecture, and others. It facilitates the creation of complex shapes, personalised designs, quick creation of prototypes, manufacturing of tools and spare parts, and small-scale production runs (Miliwski, 2017).

4.4.2 Advantages

Additive manufacturing has numerous benefits compared to conventional production techniques, as highlighted by (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 facilitates expedited and economical creation of prototypes, hence diminishing the time required to introduce innovative items to the market (Roucoules Lionel, 2020).
d. Material Efficiency: Additive manufacturing has the potential to minimise material waste in comparison to subtractive manufacturing techniques (Cowles B, 2016).
e. Supply Chain Benefits: Additive manufacturing enables the production of parts as needed, leading to improved inventory management and decreased reliance on extensive warehouse space (Roucoules Lionel, 2020).
f. Cost Reduction: Additive manufacturing has the capability to decrease costs associated with low-volume production by eliminating the requirement for costly moulds or tooling (Miliwski, 2017).

4.5 Design, Development and Industrialisation

4.5.1 Emerging Technology Innovations

The utilisation of additive manufacturing techniques in the aircraft sector, characterised by their precise and sequential material consolidation process, represents a groundbreaking advancement and is widely acknowledged as one of the most extraordinary accomplishments of contemporary times. By converting raw materials into three-dimensional shapes via the process of digitally dividing and converting CAD files into a grid of pixels, it is possible to save time and reduce costs (Miliwski, 2017). The progression from 3D printing to rapid prototyping and free-form fabrication exemplify the various phases of technological development in this field. Based on the 2016 Wohler's report, the additive manufacturing industry has a worldwide value of 5.165 billion USD. The AM techniques can be categorised into seven distinct groups: powder bed fusion, binder jetting, direct energy deposition, extrusion, jetting, sheet lamination, and vat photo-polymerization. The most commonly used methods in additive manufacturing include Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Stereo-Lithography (SLA), Fused Deposition Modelling (FDM), Direct Metal Deposition (DMD), and Direct Metal Laser Sintering (DMLS). These methods are used for the fabrication of various materials such as metals, polymers, ceramics, and composites, which are continuously being explored as potential candidates for additive manufacturing (Gibson Ian, 2015). Additive manufacturing (AM) exhibits advantages such as decreased energy consumption, enhanced mechanical efficiency, reduced material waste, and expedited design and production processes in comparison to conventional manufacturing techniques. Additionally, AM provides greater design freedom, heightened customisation options, shorter lead times, and improved supply chain solutions. The most commonly used file format for manufacturing complex 3D forms directly from digital data is *.STL. This eliminates the need for complex tooling and specialised work-tool motions, resulting in reduced manufacturing lead times and the potential for localised production. These advancements contribute to more efficient supply chain

systems (Roucoules Lionel, 2020). As a result, additive manufacturing processes quickly became useful in various industries, such as aerospace. Consequently, there has been a growing body of literature focusing on the application of additive manufacturing in the aviation sector, and this article examines the prevailing patterns observed in this regard. The application of Petersen's systematic mapping method is evident in this study, just as it was in another review article focusing on additive manufacturing. To comprehend the utilisation of additive technologies in the aircraft sector. The search query employed was 'Additive manufacturing in the aerospace industry'. The majority of publications focused on commercial applications, materials research, and the utilisation of 3D printing for tooling and indirect purposes. Web articles mostly concentrate on the results of commercial applications, but frequently lack specificity due to confidentiality. Topics such as supply chain, energy, standardisation, certification, and quality control were given less emphasis in comparison. The majority of research conducted on supply chain and energy usage has been of a general nature, without specificity to any particular case study. Typically, these studies involve comparisons between conventional procedures and 3D printing techniques. Additive manufacturing has been a popular choice in the aircraft industry because it allows for the creation of sophisticated 3D forms without the need for complex tooling. This is particularly appealing due to the industry's limitations in inventory and supply chain, as well as its potential to facilitate just-in-time manufacture (Gibson Ian, 2015). Leaders in the aviation sector have been investigating the capabilities of additive manufacturing (AM) to create components like hinges, brackets, interior elements, and even lightweight fuselage and airframe designs. The objective is to enhance fuel efficiency. AM applications in aviation components encompass several examples such as turbine blades equipped with internal cooling channels, fuel nozzles, compressors, and integrated piping systems (Miliwski, 2017).

4.5.2 Design, Creation or Planning of a Visual or Functional Object or System

Complex geometry and interdisciplinary design optimisation are widely used in several engineering industries, especially in the aerospace sector. Engineers must meticulously evaluate various design factors and limitations, including material and structural integrity, aerodynamics, weight, reliability, manufacturability, maintainability, sustainability, and cost, due to the rigorous safety standards (Miliwski, 2017) (Florio, 2016). Consequently, they have limited flexibility in their design choices. In the past, design compromises have been made due to the constraints imposed by conventional manufacturing techniques. Nevertheless, the progress made in CAD and additive manufacturing has eradicated certain limitations, hence presenting novel design opportunities such as decreased weight, cellular architectures, lattices, honeycomb patterns, and bionic-optimized structures (Miliwski, 2017). Moreover, additive manufacturing enables the production of designs that were previously unattainable using traditional technologies, while also reducing operational expenses during assembly and maintenance. Topology optimisation is a frequently employed technique for reducing weight, which relies on finite element analysis. This process entails the extraction of material from regions experiencing minimal stress until an optimised structure is achieved. Recently, this method has been employed for aerospace applications, leading to the creation of lattice structures

(Gibson Ian, 2015). Solid Isotropic Material Penalization (SIMP) enables the individual design of each voxel in a unit cell, allowing for the mapping of structural density and the use of varied materials to enhance performance. Additive Manufacturing (AM) is the sole feasible method for producing these intricate and optimised components. As an illustration, the Airbus Innovation Group developed a nacelle hinge bracket specifically for the Airbus A320 aircraft. This innovation successfully decreased the weight by 64%, leading to a saving of 10kg in mass per plane. Additionally, it resulted in a significant 40% reduction in carbon emissions. Additionally, the exit door hinges underwent a redesign, resulting in a 33% reduction in weight and a decrease in stiffness (Gibson Ian, 2015) (Miliwski, 2017). According to reports, the Airbus A350XWB and A380 models have achieved significant weight reduction by making design changes. This was achieved by using selective laser melting and topology optimisation techniques to build a lightweight bracket. The bracket's weight was reduced by 28% while simultaneously improving its safety factor (Singamnemi, 2019).

Using additive manufacturing (AM) enables the production of intricate geometries, providing opportunities to optimise components for specific objectives such as improving heat dissipation, distributing pressure, or enhancing air flow. One illustration of this is integrating cooling pathways into vital components. EOS discovered that additive manufacturing (AM) technology can be used to create measuring probes for temperature and speed in turpentine. This technology not only solves the problems of instability and fragility associated with traditional manufacturing methods, but also results in a part that is 150% stiffer than the original design made up of multiple parts (Singamnemi, 2019).

4.5.3 Development

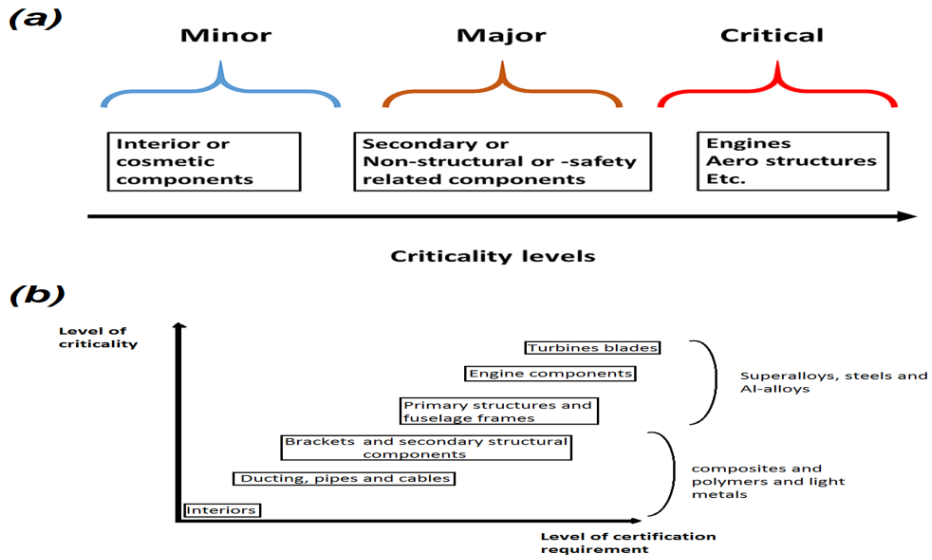
Conventional methods are better suited for large-scale or batch production, which is unnecessary for manufacturing aeroplane components due to their restricted production numbers, typically not exceeding a few thousand units per part. Therefore, additive manufacturing (AM) becomes a more appropriate choice for tailoring aeroplane cabin designs, as it only necessitates CAD files and eliminates the need for additional tools. In 2015, China Eastern Airline established their own additive manufacturing (AM) laboratory. They achieved cost reduction in cabin components by utilising flame retardant materials for interior parts, including toilet seats. This resulted in a remarkable 90% decrease in expenses and considerable time savings in the manufacturing process compared to the original components (Singamnemi, 2019). Air New Zealand assessed the 3D-printed drink trays for the business premier cabin, using prototypes provided by Auckland University of Technology. The SAVING project demonstrated that by using additive manufacturing, it was possible to achieve a significant 55% decrease in weight for seat buckles. This translates to an estimated weight reduction of 73 kg for all seat buckles in the Airbus 380 aircraft, resulting in fuel savings of about 3.3 million litres throughout the lifespan of the aircraft (Singamnemi, 2019).

4.5.4 Regulatory requirements and Statutory Mandates

The Aircraft Industry is subject to extensive rules, which are implemented to ensure safety. The manufacturing standards are stringent, rigid, and encompass every aspect of item production, process implementation, testing, and analysis. Only after meeting these standards are the components deemed fit for aeroplane assembly. In order to guarantee that prospective solutions are following relevant rules, engineers must also conform to the guidelines set by the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA) for aircraft design and operation. This encompasses an assessment of airworthiness, noise levels, and additional variables that necessitate careful attention (Singamnemi, 2019)**.** The FAA conducts routine inspections of finished aircraft to verify compliance with all safety measures. In order to guarantee optimal customer service and happiness, engineers should make a constant effort to enhance the aircraft by incorporating modern technology and developments. By taking consumer feedback into account, both engineers and airline firms can reap the advantages of enhanced customer loyalty, greater repeat sales, and reduced costs. Furthermore, it is imperative to prioritise customer comfort and user-friendliness when designing aeroplanes. The stringent regulations of the aviation sector pose a significant challenge for engineers in their pursuit of developing groundbreaking aircraft systems, components, and operations. However, those that possess a comprehensive understanding of the essential criteria and laws have the capability to develop solutions that fulfil the demands and benchmarks of the sector, while offering secure, dependable, and pleasant transportation alternatives for their clientele (Singamnemi, 2019).

4.5.6 Categorisation and Grading of Common Aircraft Parts Based on Criticality

Figure 2. Illustration Criticality table (Singamnemi, 2019)**.**



Although additive manufacturing has had notable progress and acceptance, it still has obstacles that need to be addressed, including constraints related to materials, production velocity, and scalability. Nevertheless, persistent research and development endeavours persistently expand the limits of additive manufacturing, rendering it an increasingly indispensable technology in the manufacturing domain. However, it is evident that there is a notable increase in attention within the aerospace sectors for its incorporation, as demonstrated in *figures 3,4,5 and 6* (Singamnemi, 2019)**.**

Figure 3. Aircraft production and maintenance models.

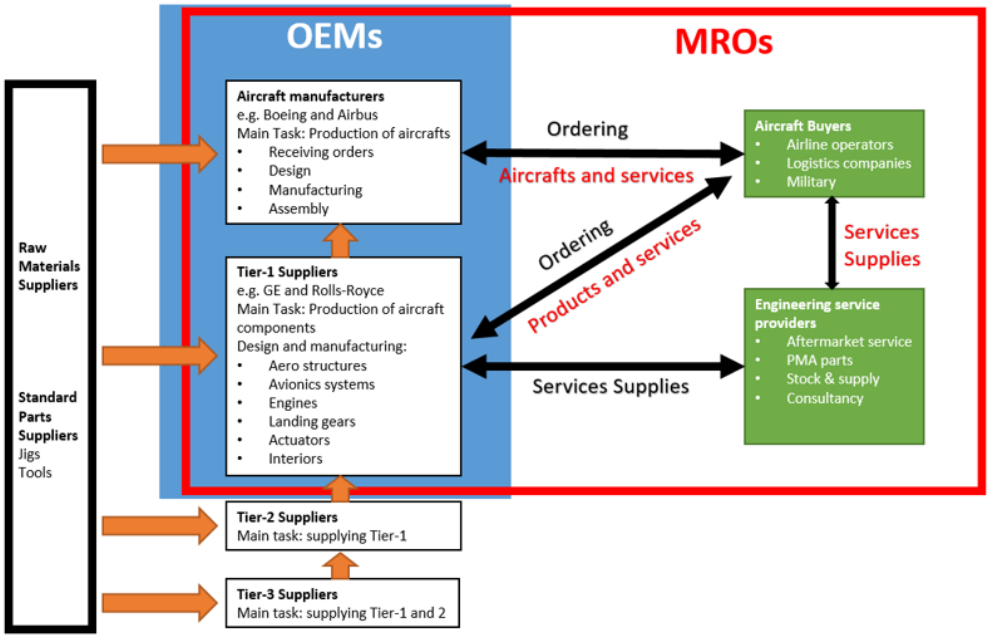


Figure 4. AM for aerospace, publication trends.

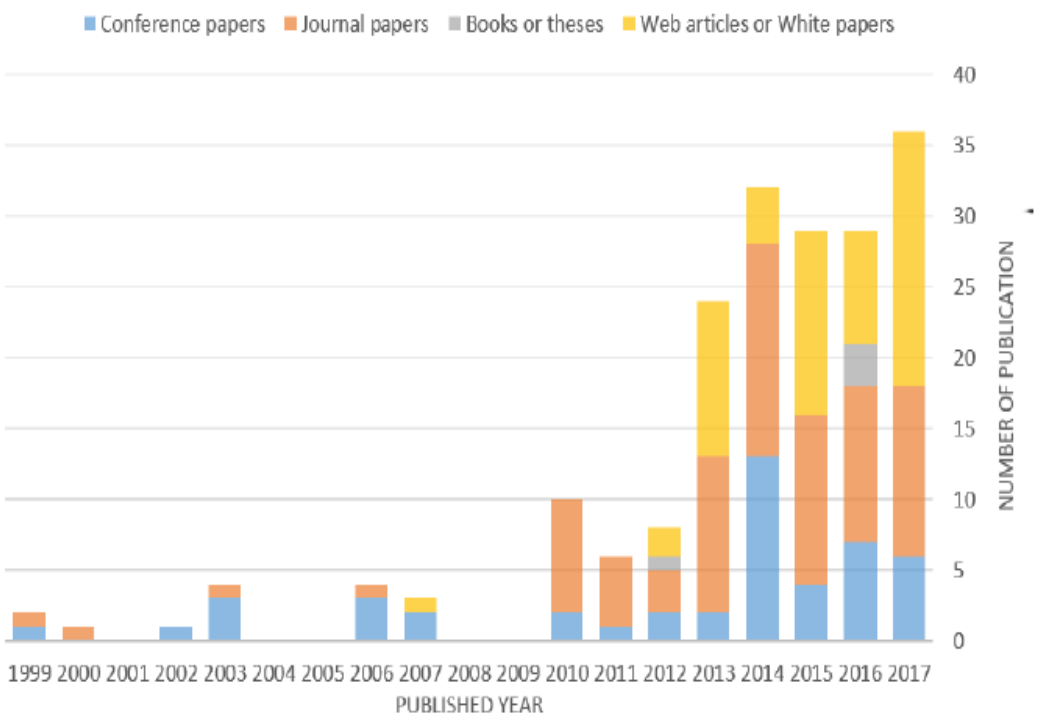


Figure 5. AM for aerospace: A classification of the topics covered in the most significant publications.

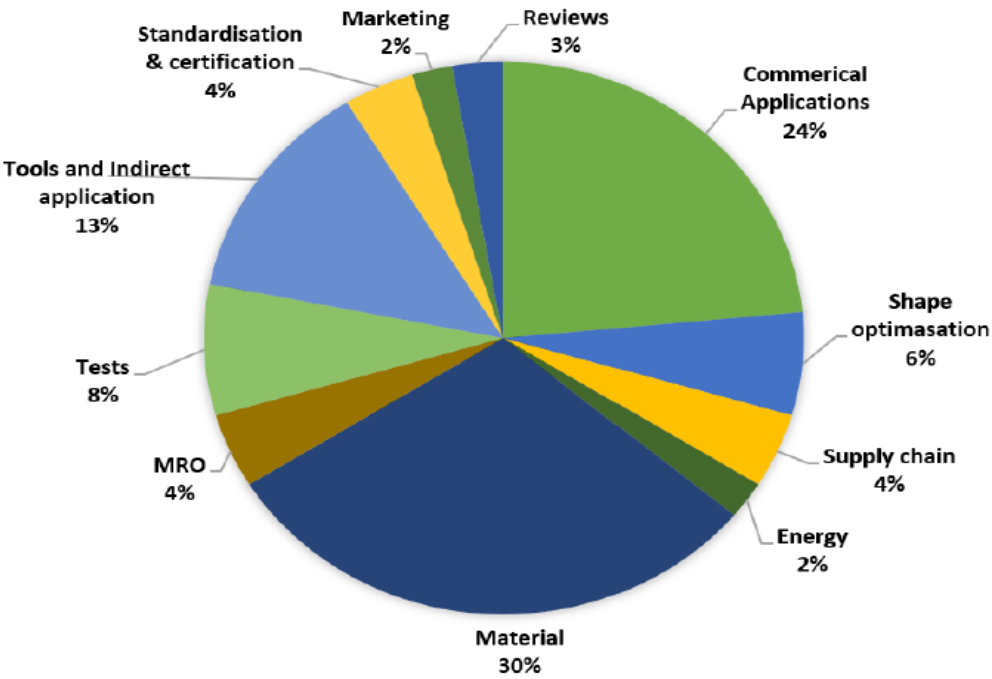
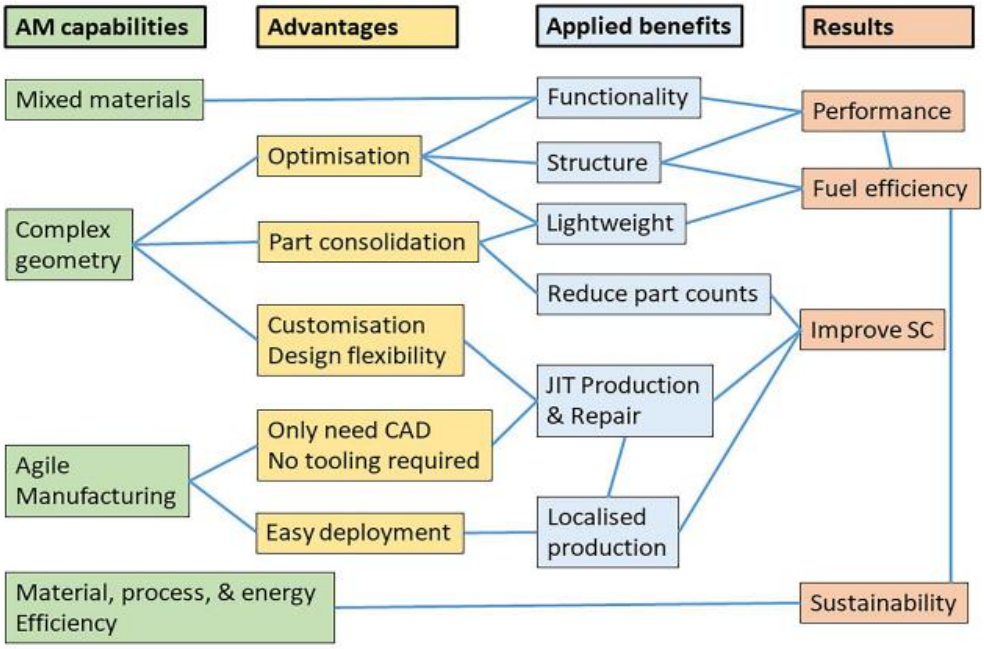


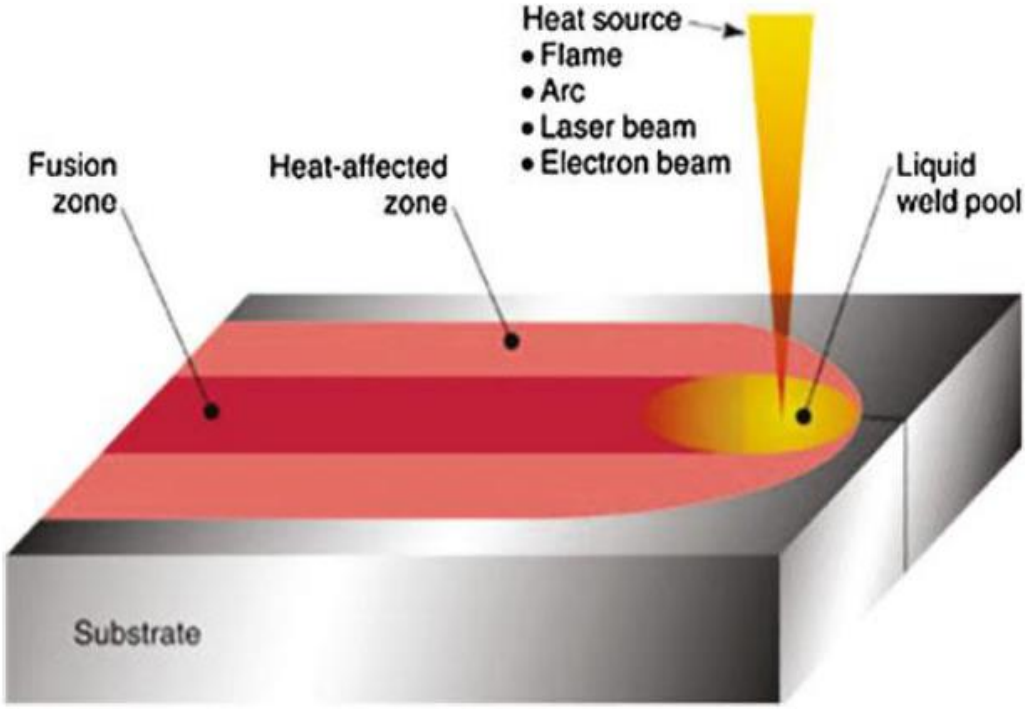
Figure 6. Critical attributes of integrating additive manufacturing within the aircraft industry.



4.6 A Selection of Types of Additive Manufacturing Processes

The diverse procedures that employ distinct techniques and technology to construct objects incrementally and merge them together. The fundamental principle at play is the utilisation of a concentrated heat source directed at a specific region in order to transform the material into a liquefied condition (Miliwski, 2017) Illustrated in *figure 7*.

Figure7. Liquifying and Fusion Process



Here are some of the commonly used additive manufacturing process techniques:

4.6.1 Powder-Bed Additive Manufacturing (PB-AM)

his manufacturing process involves the deposition of small layers of powder onto a build platform. The powder is then levelled and selectively melted using a high-powered beam. This melting process occurs layer by layer, following the path given by the 3D model (Katz-Demaynetz, 2019)**.**

4.6.2 Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is a manufacturing process that uses a laser to selectively melt and fuse powdered materials together.

Stereolithography (SLA) employs a liquid photopolymer resin that solidifies upon exposure to a precise wavelength of light, often emitted by a laser or ultraviolet (UV) light source. The build platform undergoes slow vertical movement inside a reservoir of resin, while the light source selectively solidifies the resin layer by layer, resulting in the creation of the desired object. (Katz-Demaynetz, 2019)**.** It should be noted that SLM is prone to high porosity in many different types of material caused by lack of fusion (Guanghao Gong, 2021) (Aboulkhair, 2019)**.** Metallurgical pores are most likely to develop at the slowest scan speed. As the scan speed steadily

increases, the occurrence of metallurgical pores decreases in regions, while keyhole pores become more prevalent.

4.6.3 Binder Jetting

his procedure is applying a liquid adhesive, usually a polymer, onto successive layers of powdered substance. The binder exhibits selective adhesion to the powder, effectively gluing the particles together to create individual layers. After the completion of each layer, a fresh layer of powder is evenly distributed, and this sequence is repeated until the entire thing is fully produced. Subsequently, the component is commonly subjected to sintering in order to enhance its strength (Katz-Demaynetz, 2019)**.**

4.6.4 Electron Beam Melting (EBM)

EBM is a comparable procedure to DMLS; however, it use an electron beam rather than a laser. The process entails the gradual fusion of metal particles by melting them layer by layer within a high-vacuum chamber. Electron Beam Melting (EBM) is frequently employed in the aerospace and medical sectors to manufacture superior-grade, completely solid metal parts (Katz-Demaynetz, 2019)**.**

These examples illustrate several additive manufacturing processes, and there is a constant emergence of novel technologies and approaches. Additive manufacturing is a highly adaptable and fast progressing industry, as each technique has its own advantages, restrictions, and uses.

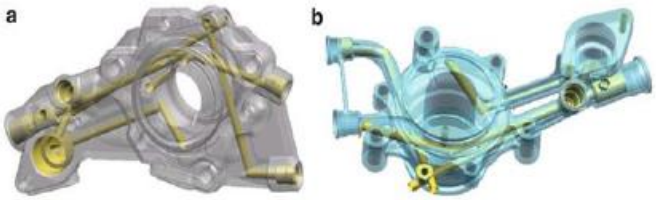
4.7 Advantages and Limitations of Additive Manufacturing

4.7.1 Advantages:

4.7.1.1 Design Freedom and Flexibility

Additive manufacturing (AM) allows for the creation of intricate shapes and structures that would be challenging or unattainable with conventional manufacturing techniques. It enables the fabrication of complex and personalised patterns, such as interior hollow spaces, lattice structures, and organic forms (Aboulkhair, 2019) (Gibson Ian, 2015)**.** The illustration below depicts an example of a front plate for a Diesel vehicle. (a) Initial design. (b) Modified specifically for the process of additive fabrication. *Figure 9* demonstrates this.

Figure 9. Example of generative design.



4.7.1.2 Minimal Material Waste

Contrary to subtractive manufacturing methods that entail removing material, additive manufacturing constructs objects by adding layers, precisely using the required quantity of material. This practice minimises material waste and has the potential to result in cost savings, particularly for materials that are costly or in limited supply (Aboulkhair, 2019). By comparison to conventional manufacturing methods in many cases waste reduction can be 80% or higher (Gibson Ian, 2015).

4.7.1.3 Rapid Prototyping

Rapid prototyping refers to the process of quickly creating a physical model or prototype of a product using advanced technology.

Additive manufacturing enables rapid and cost-efficient prototyping. The product development cycle can be accelerated by easily making and testing design iterations without the requirement for costly tooling or retooling. Initially, additive manufacturing (AM) was created with the purpose of facilitating quick prototyping (Gibson Ian, 2015).

4.7.1.4 On-demand Manufacturing

Additive manufacturing (AM) enables the production of products as needed, hence reducing the requirement for extensive stockpiles or extended waiting periods. Customised production is facilitated by this approach, which can be especially advantageous for products with low demand or that cater to a specific market segment (Aboulkhair, 2019).

4.7.1.5 Manufacturing Complexity

Manufacturing Complexity refers to the level of intricacy involved in the manufacturing process.

Additive manufacturing (AM) has the capability to create components that possess integrated functionality, such as internal channels or intricate internal structures. This obviates the necessity of assembling several components, hence diminishing production time and the likelihood of probable failures (Aboulkhair, 2019) (Gibson Ian, 2015).

4.7.1.6 Carbon footprint reduction and circular economy

The utilisation of Additive Manufacturing has the capacity to achieve a reduction of over 80% in material wastage in numerous cases (Gibson Ian, 2015), resulting in both cost

and environmental benefits. The primary advantage of implementing additive manufacturing (AM) in the aircraft sector is the reduction in weight. For instance, a 20% decrease in mass of a Boeing 787 would result in a fuel efficiency improvement of approximately 10%-12% (Blakey-Milner, 2021). This improvement translates to savings of approximately US$3000 in fuel expenditures and a reduction in carbon emissions for every kilogramme lowered. By leveraging the capability of additive manufacturing (AM) to create intricate shapes, the benefits can be realised through careful selection of materials and optimisation of geometry. Compared to traditional manufacturing methods, additive manufacturing (AM) offers a significantly more efficient alternative in terms of material, process, and energy usage.

4.8 Limitations of Additive Manufacturing

4.8.1 Restricted Material Choice

Despite the gradual expansion of available materials for additive manufacturing (AM) over time, it still falls short in comparison to the wide array of materials used in traditional production methods. Some materials, such high-performance alloys or composites, may have restricted accessibility or present difficulties in terms of processing, surface polish, and quality (Roucoules Lionel, 2020). Additive manufacturing (AM) products may have coarser surface textures in comparison to those manufactured using conventional methods. To attain the desired surface quality, it may be necessary to use post-processing procedures such as polishing or machining. In addition, additive manufacturing (AM) parts may exhibit varying mechanical qualities or internal faults, which might impact their overall quality (Gibson Ian, 2015).

4.8.2 Duration of Construction

The process of constructing objects layer by layer in additive manufacturing (AM) can be a lengthy one, particularly when dealing with sizable or intricate components. The production velocity of additive manufacturing (AM) is typically inferior to that of conventional techniques, hence posing a constraint for large-scale production. On the other hand, it is very suitable for design development and prototyping (Aboulkhair, 2019).

4.8.3 Equipment and Cost

Procuring and upkeeping AM equipment can be costly, particularly for systems of industrial calibre. The expense of

materials, specifically those that are specialised or high-performance, can also be comparatively elevated (Gibson Ian, 2015). These obstacles may impede the accessibility and implementation of additive manufacturing for certain businesses. In contrast, this technology has the potential to decrease lead time and development costs, while simultaneously offering distinctive solutions (Blakey-Milner, 2021).

4.8.4 Design Flexibility

Although additive manufacturing has the advantage of design flexibility, there are certain complex shapes or characteristics that may provide difficulties or perhaps be unattainable to manufacture. It is important to consider design limits, such as the angles of overhang or structures that are not supported. Moreover, the selection of the additive manufacturing (AM) method might have an influence on the attainable resolution, accuracy, and size constraints of the manufactured components, particularly in scenarios involving large-scale production. In such cases, it is sometimes necessary to employ secondary conventional machining processes (JCM 2020 Members, 2021).

N.B. It is crucial to acknowledge that the domain of additive manufacturing is in a constant state of development, with ongoing investigations and progress aimed at tackling these constraints.

5 Mechanical Characteristics and Properties of Aluminium:

In terms of aircraft utilisation, it may be dated back to the early 1900s. The reputation of aluminium has significantly increased since its inception in the 1930s, when it was employed in the production of aircraft to build airframes for the Japanese navy. In 1945, the standardisation of aircraft manufacture in the United States was achieved (Clinton Aluminium Innovative Alloys, 2019).

5.1 Manufacturing of Aluminium Powder and Properties

5.1.1 Production Methods and Manufacturing Processes

5.1.1.1 Melting: The process of melting pure aluminium or aluminium alloy involves the use of induction melting or other similar techniques. The selection of the alloy is contingent upon the particular demands of the 3D printing procedure and the intended characteristics of the resulting printed object (Yiyunyingliping, 2023).

5.1.1.2 Atomisation: The liquefied aluminium is subsequently exposed to a forceful stream of gas under high pressure, often using inert gases such as argon or nitrogen. The gas stream disintegrates the molten metal into little droplets (Yiyunyingliping, 2023).

5.1.1.3 Solidification: As these droplets traverse the gas stream, they undergo fast cooling and transform into minute spherical particles. The size of these particles can be regulated by manipulating the process parameters and optimising the atomization equipment design (Yiyunyingliping, 2023).

5.1.1.4 Collection: The resultant aluminium powder is gathered and subsequently subjected to further processing stages to guarantee that it conforms to the necessary criteria for 3D printing. This process may involve the utilisation of sieving techniques to attain a desired particle size distribution and the elimination of any impurities or foreign substances (Yiyunyingliping, 2023).

5.1.1.5 Quality Control: The implementation of quality control methods is necessary to evaluate the particle size, morphology, and chemical composition of the aluminium powder in order to meet the rigorous demands of the 3D printing process (Yiyunyingliping, 2023).

It is crucial to acknowledge that the attributes of the aluminium powder, such as particle size and distribution, have a direct influence on the excellence and traits of the ultimate 3D-printed parts. Various 3D printing technologies and equipment may necessitate distinct criteria for the aluminium powder used in their procedures. Consequently, manufacturers meticulously customise the production process to adhere to these criteria and guarantee uniformity in the quality of the aluminium powder for 3D printing (Yiyunyingliping, 2023).

5.1.2 Blended powder mixtures

The production of Al7075/Al2O3 composites involved the use of semisolid forming, which included the sequential procedures of powder uniform dispersion, mechanical alloying, and semisolid compaction. Al7075 elemental powders with particle sizes of 20 and 63 µm were gradually added to an ethanol solution using ultrasonic mixing. Particles of Al2O3, with sizes ranging from 5 to 120 µm, and weight fractions of 5%, 10%, and 20%, were mixed with the matrix particles using a planetary ball mill. Following that, Al7075/Al2O3 composites were compressed in the semisolid state using varying pressures (40 and 80 MPa) (Javdani A, 2016).

5.1.3 Influencing Factors that have an Impact.

The study methodically examined the impact of Al7075 and Al2O3 particle size, Al2O3 weight percentage, and compaction pressure on multiple properties, including as morphology, microstructure, compaction mechanism, density, hardness, compression modulus, strength, and phase formation. The highest level of microstructural homogeneity was attained by dispersing big Al2O3 particles (120 µm) among smaller matrix particles (20 µm). The density and hardness shown a positive correlation with both the size of the reinforcing particles and the applied pressure (Javdani A, 2016).

5.1.4 Composite Performance

The specimens with 20µm Al7075 and 20 wt. exhibited the highest composite performance. Percentage of Al2O3 powder with a particle size of 120 µm, compressed at a pressure of 80 MPa. The samples exhibited significant improvements in relative density 98.685%, hardness (Rockwell B of 70), and compressive strength (327 MPa). The findings offer vital insights that can be used in the advancement of lightweight metal matrix with impressive performance (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.

The tensile strength of aluminium 7075 can be dramatically altered by heat treatment. Applying an appropriate heat treatment method to the material can enhance its tensile strength. The predominant heat treatment method for aluminium 7075 is T6, which entails a process of solution heat treatment followed by artificial ageing.

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).

It is 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)	Yeild stress (N/mm2)	Brinell Hardnes
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)	Yeild 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

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

	Stress (Mpa)	Life cycles.
Thixoformed	140	5.5 * 107
	120	5.9 * 107
	100	6.2 * 107
ECAP1 pass + thixoformed	140	4.6 * 107
	120	4.8 * 107
	100	5.1 * 107

5.3.5 Heat Treatment

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 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 an impressive 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 todays manufacturers of these machine incorporate multiple lasers. However, in both case of PB-AM there are finite limits before excessive porosity become 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 conducted in an inert environment for SLM or in a vacuum chamber for EBM. For the production of most components there are three key factors for vital consideration; these are: component surface roughness, keep the working area at hot temperature and support structures (Katz-Demaynetz, 2019).

5.4.1 Selective Laser Melting (SLM)

SLM was the first of the techniques use 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 (DMSL), 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 whereby each layer thickness is controlled by 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 other use a slight vacuum to reduce oxidisation during the fusing process with Ytterbium fibre laser systems to sinter the alloy powder together (Katz-Demaynetz, 2019) see *figure 10 on the next page*.

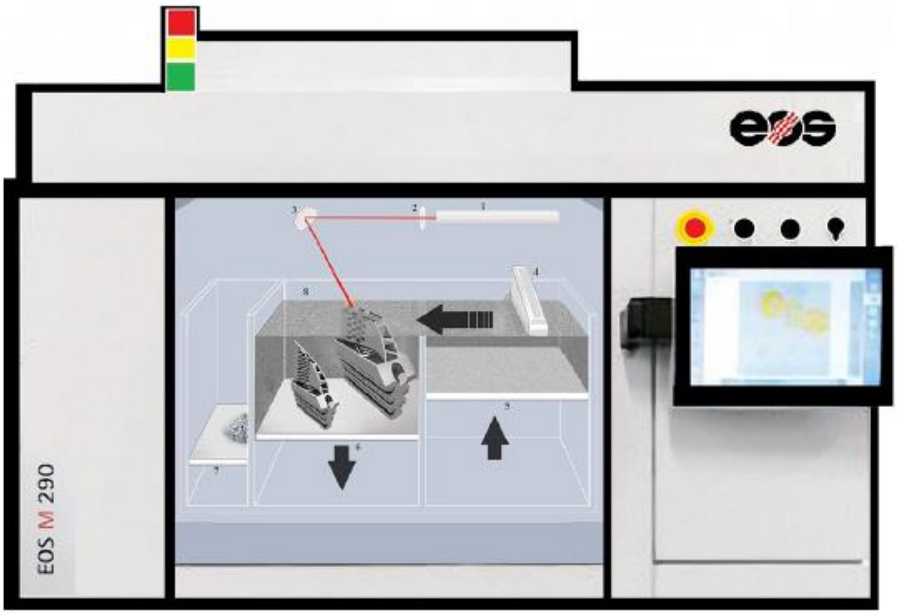


Figure 10. Selective laser melting: 1 Laser; 2 Lenses; 3 X and Y scanning mirror; 4 rake; 5 powder supply table; 6 build table; 7 table for rest; 8 powder-bed (Katz-Demaynetz, 2019)**.**

5.4.2 Electronic Beam Melting (EBM)

Figure 11

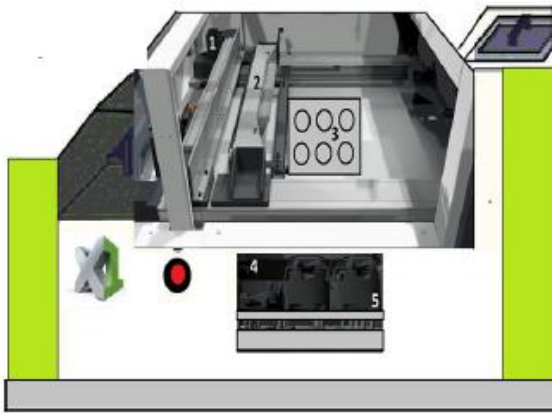


Figure 11. Electronic beam melting process: 1 electron beam; 2 electron beam control; 3 powder container; 4 build platform tank; 5 build tank; 6 working area; 7 rake.

Figure 12

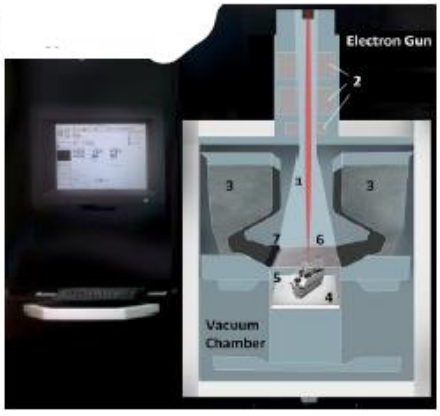


Figure 12. Binder jetting printing process: 1 jetting head; 2 rake and powder delivery; 3working area; 4 build tank; 5 build platform.

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 the powder layer and pre-heating provides 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 conducted 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).

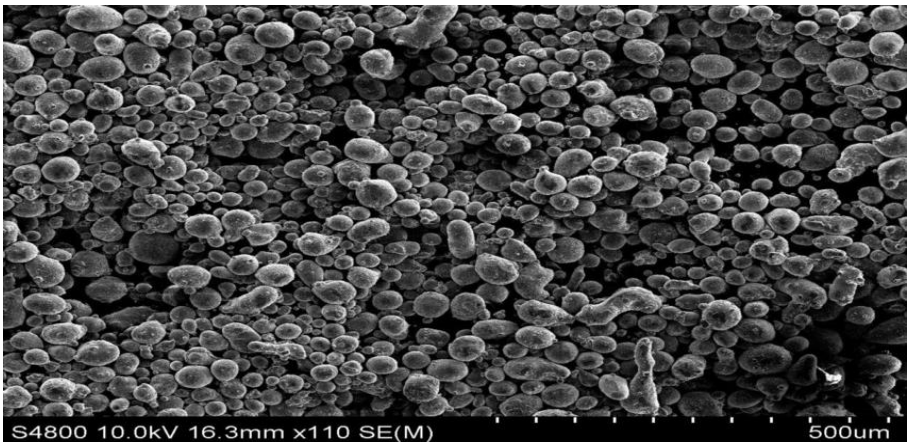
5.5 Mechanical Make Up of 3D Printed Alloys.

5.5.1 Materials

High strength to weight ratio materials along with hot 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 when fused together form microstructures that can be highly precise in definition with extremely low deformity (Katz-Demaynetz, 2019). Below is an example Al7075 viewed through a microscope. *See appendix 1.*



5.5.3 Internal Structure and Supports

The inclusion of internal structures and supports are a fundamental part of the design. Where they are deployed and their form are determined by a number or 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 constrains in line with the applicant and design intent (Katz-Demaynetz, 2019).

Figure 13.

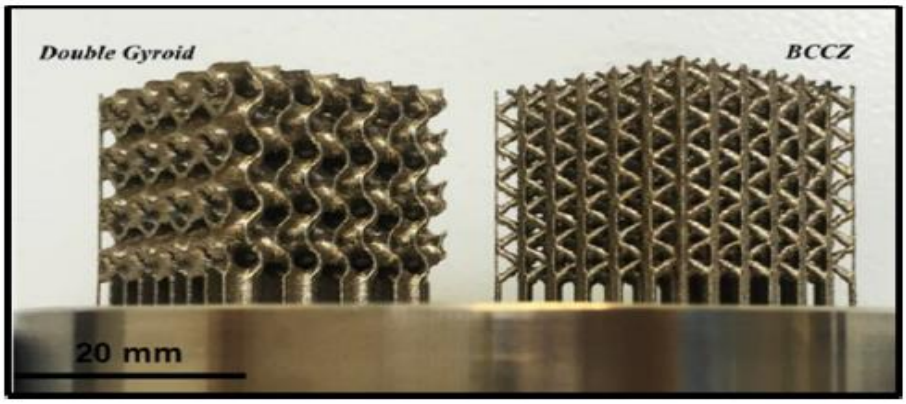


Figure 13. A double gyroid lattice (TMPS and a BCCA lattice (strut based) fabricated in the centre of Additive Manufacturing University of Nottingham (Aboulkhair, 2019).

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 to 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 of 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 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)**.**

5.5.5 Strength Properties of Materials

There are many attributes and conditions that must be considered when using materials such as Aluminium, specifically when the application used is subjected to and categorised under 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 material, structure and application, but also its physical attributes such as shape, form, length, loading, cross sectional area etcetera. Therefore, there are specific formulas that are applied to ascertain specific characteristics to calculate and determine specific strength properties of materials. The examples in the following five tables *(1, 2, 3, 4 and 5)* 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.

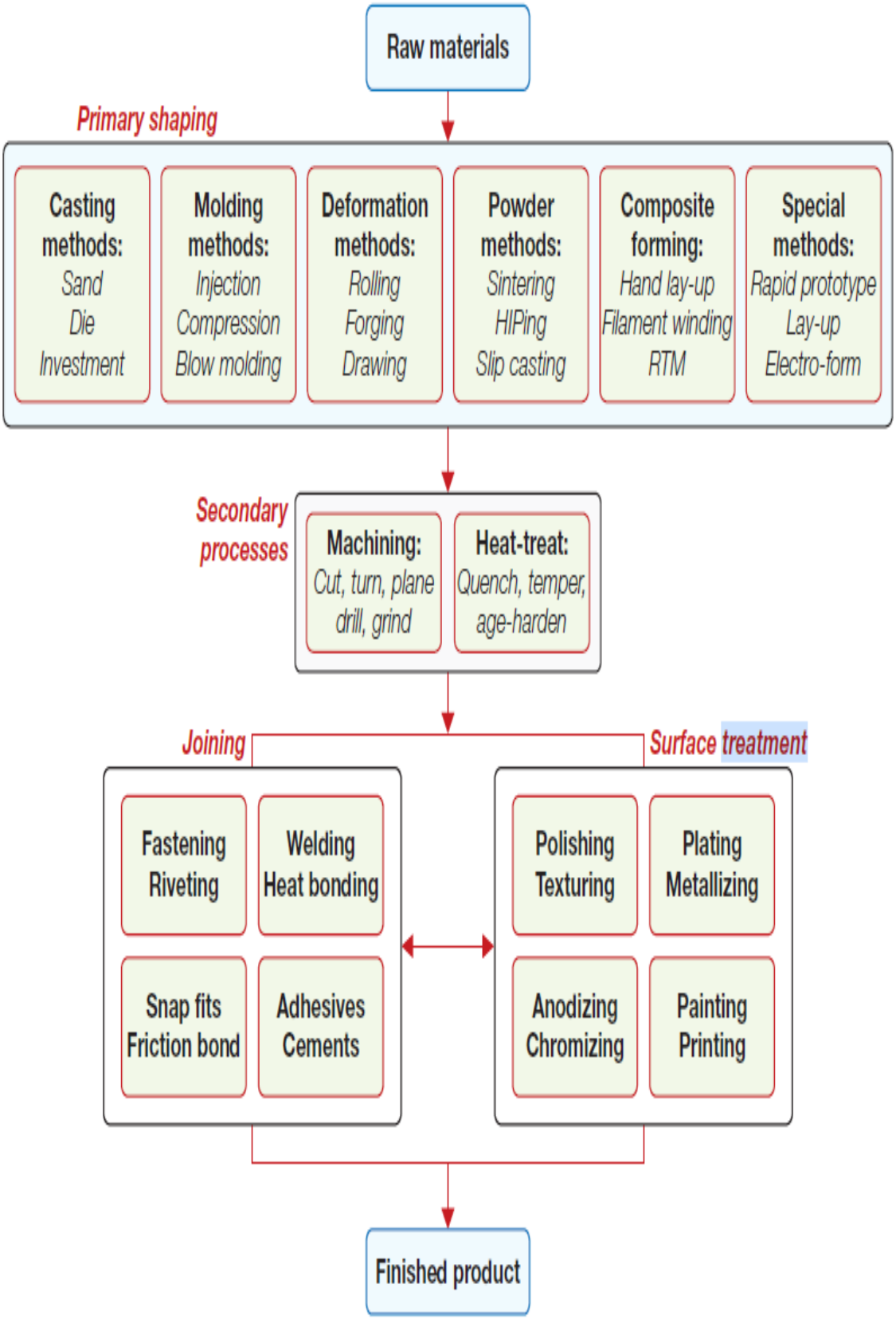
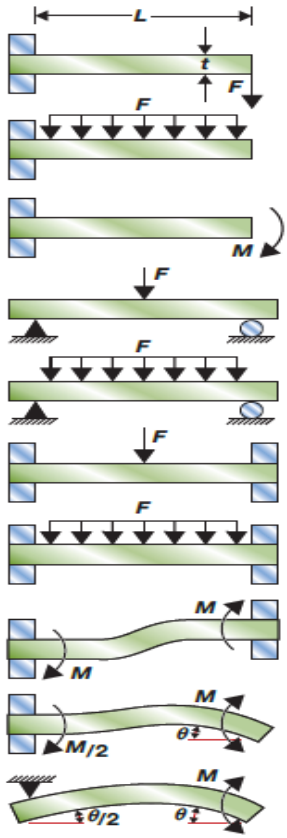


Table 2. Formulas for Calculating Moments of Sections.

Elastic		
Uniaxial	$\epsilon = \frac{\sigma}{E}$	
General	$\varepsilon_1 = \frac{\sigma_1}{E} - \nu(\sigma_2 + \sigma_3)$	etc.
Plastic		
Uniaxial	$\sigma \geq \sigma_y$	
	$\sigma_1 - \sigma_3 \geq \sigma_y$ $(\sigma_1 > \sigma_2 > \sigma_3)$	or
General	$[\frac{1}{2}\{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\}]^{\frac{1}{2}} > \sigma_y$	
Creep		
Uniaxial	$\dot{\varepsilon} = \dot{\varepsilon}_o (\frac{\sigma}{\sigma_o})^n$	
General	$\dot{\varepsilon}_1 = \dot{\varepsilon}_o \frac{\sigma_o^{n-1}}{\sigma_o^n} \{\sigma_1 - \frac{1}{2}(\sigma_2 + \sigma_3)\}$	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
n	= Poisson's ratio
σ_y	= Plastic yield strength
n, ε_o, σ_o	= Creep constants
K_{1C}, a	= Fracture toughness, crack length
C	≈ 1 Tension
C	≈ 15 Compression

Table 3. Elastic Bending of Beams.



C_1	C_2
3	2
8	6
2	1
48	16
$\frac{384}{5}$	24
192	–
384	–
6	–
–	4
–	3

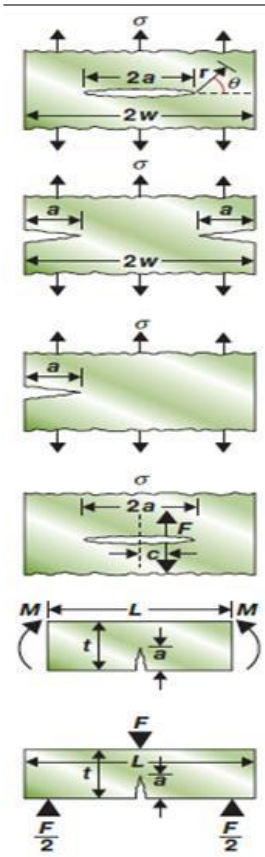
$$\delta = \frac{FL^3}{C_1 EI} = \frac{ML^2}{C_1 EI}$$

$$\theta = \frac{FL^2}{C_2 EI} = \frac{ML}{C_2 EI}$$

E = Young's modulus (N/m^2)
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 (m^4)
y = Distance from neutral axis (m)
R = Radius of curvature (m)

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

Table 4. Cracks.



C
1.0 if $a \ll w$ $\left(\frac{2w}{\pi a}\tan\frac{\pi a}{2w}\right)^{\frac{1}{2}}$
1.1 if $a \ll w$ $\left(\frac{\frac{2w}{\pi a}\tan\frac{\pi a}{2w}}{1-\frac{a}{w}}\right)^{\frac{1}{2}}$
1.1 if $a \ll w$ $\frac{1.1\left(1-0.2\frac{a}{w}\right)}{\left(1-\frac{a}{w}\right)^{\frac{3}{2}}}$
$\frac{2}{\pi}\left(\frac{a+c}{a-c}\right)^{\frac{1}{2}}$
$\frac{1.1\left(1-\frac{3}{2}\frac{a}{t}\right)}{\left(1-\frac{a}{t}\right)^{\frac{3}{2}}}$
$\frac{1.1\left(1-\frac{3}{2}\frac{a}{t}\right)}{\left(1-\frac{a}{t}\right)^{\frac{3}{2}}}$

$K_1 = C\sigma\sqrt{\pi a}$
Failure when
$K_1 \geq K_{1c}$

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

Point load on crack face

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

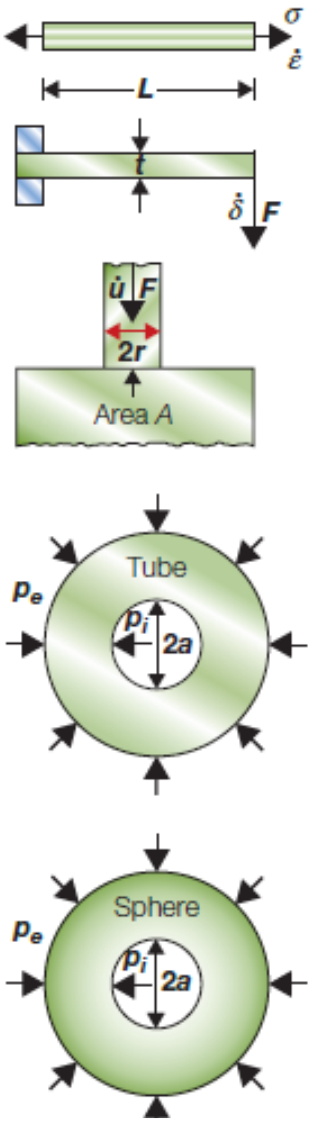
Moment on beam

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

3-point bending

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

Table 5. Cree p and Creep Fractures.



$$\dot{\varepsilon} = \dot{\varepsilon}_o \left(\frac{\sigma}{\sigma_o}\right)^n$$

$$\dot{\delta} = \frac{2\dot{\varepsilon}_o}{n+2}\left(\frac{(2n+1)}{n s_o}\frac{F}{bt}\right)^n \left(\frac{L}{t}\right)^{n+1} L$$

$$\dot{u} = C_1 \dot{\varepsilon}_o \sqrt{A}\left(\frac{C_2 F}{\sigma_o A}\right)^n$$

σ	= Stress (N/m^2)
F	= Force (N)
$\dot{\delta}, \dot{u}$	= Displacement rates (m/s)
$n,\ \dot{\varepsilon}_o, \sigma_o$	= 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

$$\dot{\rho} = 2\dot{\varepsilon}_o \frac{\rho(1-\rho)}{(1-(1-\rho)^{1/n})^n}\left(\frac{2}{n}\frac{(p_e-p_i)}{\sigma_o}\right)^n$$

$$\dot{\rho} = \frac{3}{2}\dot{\varepsilon}_o \frac{\rho(1-\rho)}{(1-(1-\rho)^{1/n})^n}\left(\frac{3}{2n}\frac{(p_e-p_i)}{\sigma_o}\right)^n$$

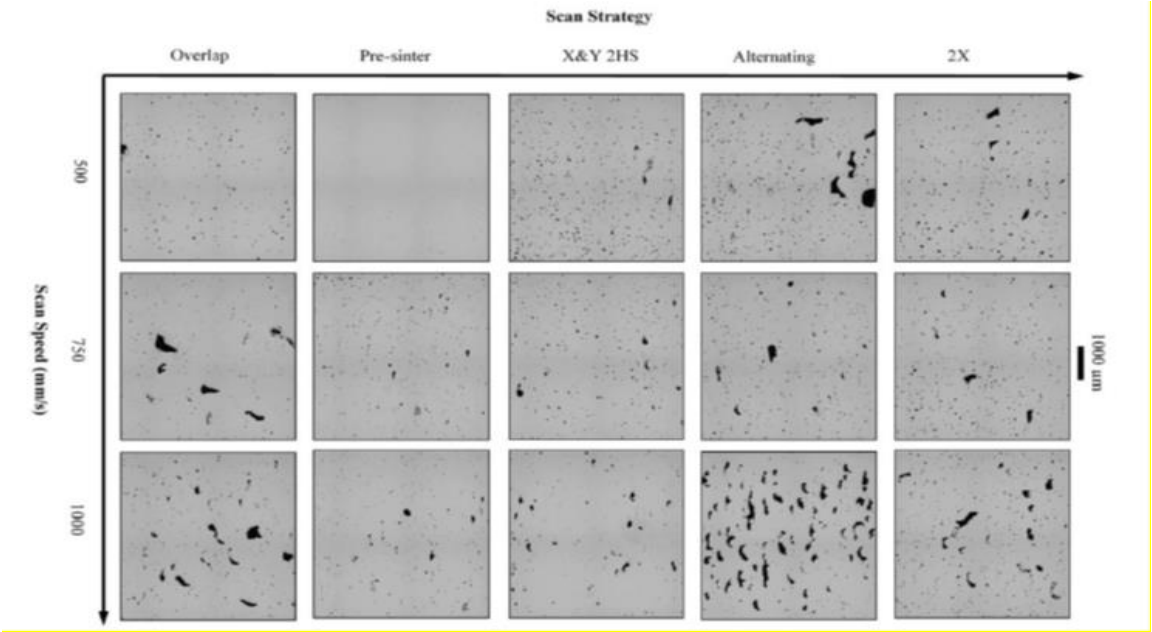
6 Surface Quality and Roughness:

6.1 Influence of Process Parameters

6.1.1 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 as in figure 14.

Figure 14. The effects of changing parameters.



6.1.2 Porosity and Inclusions

These are micro fractures and imperfections or cavities that may occur and are associated with 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 it is 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 viewpoint and the number of pores produces from a qualitative viewpoint. 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 6* (Aboulkhair, 2019).

Table 6.

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/mm³)	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 TrumaForm LF130	–	–	–	–	250	500	0.15	0.05	67	> 99
	SLM-250 HL	–	–	–	–	350	1140	0.17	0.05	36	N/A
	Custom-made	300–1000	500–4500	0.15–0.3	0.05	1000	2200	0.15	0.05	61	99.5
AlSi12	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.

6.2 Layer Thickness and Resolution

In most cases laser bases systems deposit thinner layer of powder compared to electron beam providing better defined resolution. The effect of changing the scan speed and scan strategy on porosity developed in AlSi10Mg. 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).

6.2 Surface Finish Roughness of 3D Printed Aluminium

Surface finish and roughness play a crucial role in the performance and aesthetics of 3D-printed aluminium components. Achieving the desired surface quality is essential for applications in aerospace, automotive, and various engineering fields. Several factors influence the surface finish of 3D-printed aluminium, and accurate measurement techniques are employed to assess and control these surface characteristics (Aboulkhair, 2019).

6.2.1 Factors Influencing Surface Finish in 3D-Printed Aluminum:

a) Process Parameters: The selection of process parameters, such as layer thickness, build orientation, and printing speed, significantly impacts surface finish. Optimizing these parameters is vital to minimize surface irregularities.

b) Powder Characteristics: The quality and characteristics of the aluminium powder used in the printing process play a crucial role. Particle size, distribution, and composition affect the final surface finish of the printed component.

c) Post-Processing Techniques: Post-processing steps, including heat treatment, machining, or chemical treatments, are often employed to enhance the surface finish of 3D-printed aluminium parts.

6.2.2 Measurement Techniques for Surface Finish and Roughness:

a) 3D Optical Profilometry: This non-contact method provides high-resolution three-dimensional surface maps, allowing precise measurement of surface roughness and texture.

b) White Light Interferometry: Interference patterns created by white light reflections enable accurate measurements of surface roughness. This technique is particularly useful for capturing minute details.

c) Scanning Electron Microscopy (SEM): SEM allows for high-resolution imaging of the surface, revealing microstructural details and irregularities that contribute to roughness.

d) Atomic Force Microscopy (AFM): AFM provides nanoscale topographical information by scanning a sharp tip over the surface, making it effective for characterizing extremely fine surface features.

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 and in some cases better mechanical properties resulting in improve safety (Singamnemi, 2019). 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 (Katz-Demaynetz, 2019).

7.2 Scale and Sizing Advantages and Limitations

Currently in most cases the size of the powder bed chamber is a factor that limits the manufacture of in some instances of a single piece component, meaning that it may need to be printed in a number of section s that would then require further processes to assembly the desire shape. Nevertheless it may still be possible to print all the sections in one operation by stacking the sections. Alternatively, there is the option to scale down the component, this could be considered a limitation on one hand or an advantage on the other. It is completely dependent on the desired or intended use. this may or may not be feasible and depends on the application and final requirement.

Scale and sizing in 3D printing present both advantages and limitations, influencing the applicability of this technology across various industries. Additive manufacturing (AM), commonly known as 3D printing, offers notable advantages in producing objects of varying scales with increased design flexibility.

7.2.1 Advantages:

a) Design Freedom: 3D printing allows for intricate and complex designs at various scales, enabling the production of customized components tailored to specific requirements (Kruth, 2005).

b) Complex Geometries: The layer-by-layer construction in 3D printing facilitates the creation of intricate geometries, including internal structures, which may be challenging or impossible with traditional manufacturing methods (Gibson Ian, 2015).

c) Rapid Prototyping: AM's layer-wise approach expedites the prototyping process, enabling quick iterations and modifications to designs, thereby accelerating product development (Kruth, 2005).

7.2.2 Limitations:

a) Build Volume Constraints: One of the limitations in 3D printing is the build volume, restricting the size of objects that can be produced in a single print

job. Large-scale items may require assembly from smaller printed components (Wong, 2015).

b) Print Speed: While 3D printing is advantageous for prototyping, the layer-wise construction can be time-consuming for large-scale production, impacting overall print speed (Gibson Ian, 2015).

c) Material Limitations: The range of available printing materials may have limitations regarding size and strength, affecting the suitability of 3D printing for certain applications (Wong, 2015).

Understanding these advantages and limitations is crucial for effectively utilizing 3D printing technology in diverse sectors, from aerospace to healthcare, where scale and sizing considerations play a pivotal role in achieving desired outcomes.

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 cleaner environments globally from manufacture to operation within the aircraft industry.

7.4 Current Challenges and Future Benefits

7.4.1 Additive manufacturing like all modern technologies demand grows and accelerates once the concept is realised, the visualisation of application understood and the potential demonstrated. It has unique abilities to produce light weight, complex components with inbuilt features previously unachievable with traditional manufacturing processes. The continued research and development or materials and machines to provide reduced processing times and energy reduction is a key driver. Currently the associated benefits are weight and cost savings per components (Katz-Demaynetz, 2019).

7.4.2 Comparative reductions of process times of AM to CMR coupled with CAM are fully complimentary to all industries capability in meeting supply and demand specifically when fulfilling requirements for replacement or spare parts to end users at affordable of head costs especially with hard to process complex parts (Katz-Demaynetz, 2019).

7.4.3 The emerging benefits of material developments coupled with AM technologies are seeking to provide lower levels of porosity allowing for great strength components, by reductions of flaws in the manufacturing process already demonstrated. Thereby providing greater safety and reliability of manufactured components specifically for the aircraft/aerospace industries by controlling the microstructures, varying composition of powder blends and intensity of electronic beam energy for 3D printing processes (Katz-Demaynetz, 2019).

7.4.4 Traditionally designers have compromised on shape and complexity constricted by conventional manufacturing methods. Advancements in CAD and CAM technologies have had significant impacts in reducing these previously imposed

restrictions. Software's currently available and undergoing enhanced development continually open avenues of design and manufacture. These software applications enable designers to optimise designs for lightweight designs providing topological formed lattice structures from an isotropic material approach that maximise functional performance (Katz-Demaynetz, 2019).

7.4.5 AM appears to be the sole solution able to produce these types of components. This innovation success has been proven by and Airbus innovation group, the trails and testing manufacture of a hinge bracket for the A320 aircraft resulted in a 64% weight reduction providing a total saving of 10Kg mass per aircraft. Furthermore a redesign of the hinges on the exit doors showed results of around 33% weight savings with only a moderate reduction in stiffness. Other reports monitoring applied design modifications to other brackets used on the A350XWB and A380 models showed results with improves safety aspects (Singamnemi, 2019).

8 Conventional Manufacture of Machined Components Comparisons:

8.1 Process Times

8.1.1 The comparison between conventional machining and additive manufacturing (AM) extends beyond waste considerations to include process times, providing insights into the efficiency and speed of production. Conventional machining, relying on subtractive methods like milling and turning, often involves complex setups, multiple tool changes, and extensive machining durations. The time-consuming nature of these processes can be attributed to the sequential removal of material, impacting overall production speed (Li, 2019).

8.1.2 In contrast, additive manufacturing, particularly 3D printing, introduces a paradigm shift in production timelines. AM builds components layer by layer, offering the potential for faster prototyping and production. Research by Zhang et al. (2018) demonstrates that additive manufacturing processes, such as Selective Laser Melting (SLM), can significantly reduce lead times compared to conventional machining methods (Zhang, 2018).

8.1.3 The layer-wise construction in additive manufacturing allows for the simultaneous production of intricate geometries, reducing the need for multiple setups and tool changes common in conventional machining. Additionally, additive manufacturing enables the production of complex structures in a single step, eliminating the time-consuming processes associated with traditional manufacturing techniques. While the specific process times can vary depending on factors such as part complexity, material properties, and machine capabilities, studies indicate that additive manufacturing has the potential to offer notable time savings. Rapid prototyping and on-demand production are key advantages of AM, facilitating quicker iterations and responsiveness to design changes, which is particularly valuable in industries with dynamic and evolving requirements (Gibson et al., 2014). Conventional machining and additive manufacturing process times highlights the efficiency gains associated with AM. The layer-wise, additive approach enables faster production, reduced setup times, and the concurrent manufacturing of complex structures. As industries increasingly prioritize agility and responsiveness, the accelerated production timelines offered by additive manufacturing contribute to its growing prominence in various applications.

8.2 Waste Comparison

The comparison between conventional machining and additive manufacturing (AM) waste underscores a fundamental shift in resource utilization and sustainability. Conventional machining, characterized by subtractive processes like milling and turning, generates substantial waste through the removal of excess material. This traditional approach often results in a significant loss of raw material, with studies indicating that material wastage can range from 50% to 90% in certain machining operations (Yan, 2016).

8.2.2 On the contrary, additive manufacturing techniques, notably 3D printing, offer a more resource-efficient paradigm. AM builds components layer by layer, adding material only where needed, minimizing waste in the production process. Research

by Mokhtarian et al. highlights the potential for additive manufacturing to reduce material waste by up to 90% compared to conventional machining methods, emphasizing the efficiency gains in material utilization. This substantial reduction in material waste aligns with broader sustainability goals and environmental considerations. As industries increasingly prioritize eco-friendly practices, the resource-efficient nature of additive manufacturing positions it as a promising alternative to traditional machining, not only in terms of waste reduction but also in the overall lifecycle environmental impact of manufactured components (Mokhtarian, 2016).

8.3 Cost Comparison

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).

8.4 Waste Removal Costs

8.4.1 The comparison between conventional machining and additive manufacturing (AM) extends to the realm of waste removal costs, shedding light on the economic and environmental implications of these manufacturing processes. Conventional machining, characterized by subtractive techniques like milling and turning, often generates substantial material waste. The removal of excess material in machining results in significant disposal costs, as well as environmental considerations related to the disposal of metal chips, swarf, and the consumption of additional raw materials (Yan, 2017).

8.4.2 In contrast, additive manufacturing, particularly in processes like Selective Laser Melting (SLM) and Powder Bed Fusion (PBF), exhibits distinct advantages in waste reduction. AM builds components layer by layer, adding material precisely where needed, minimizing overall waste generation. Research by Hopkinson et al. (2006) highlights the efficiency of additive manufacturing in terms of material utilization, as it significantly reduces the volume of wasted material compared to traditional subtractive methods (Hopkinson, 2006).

8.4.3 The nature of AM, which involves the creation of intricate and complex geometries in a layer-wise manner, contributes to optimal material usage and reduced waste production. This inherent efficiency aligns with contemporary sustainability goals and resource conservation initiatives. Moreover, the reduction in waste removal costs in AM extends to the fact that any excess material generated during the printing process can often be recycled and reused, further minimizing environmental impact. As industries increasingly emphasize sustainability and cost-effectiveness, the waste reduction potential of additive manufacturing becomes a significant factor influencing its adoption. The comparison between conventional machining and additive manufacturing waste removal costs underscores the economic and

environmental advantages associated with AM. The minimal material waste in AM processes, coupled with the potential for recycling, contrasts with the higher disposal costs and environmental concerns linked to the material removal approach of traditional machining methods (Hopkinson, 2006).

9 The Environment and Carbon footprint:

9.1 Aircraft Industry Commitment

The technologies being used today are the culmination joint drive, collaboration and merging together minds, industries, science and the will for a better cleaner 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).

9.2 Environmental Comparison

9.2.1 AM will negate a requirement for carry substantial amounts of spares inventory as storage. Requirements will diminish due to all required data being readily available stored as computer files that allow quick manufacture of parts on an ad-hoc basis as and when required (Katz-Demaynetz, 2019). This compliments the target reductions for carbon footprint by the aircraft industry.

9.2.2 This innovation success has been proven by and Airbus innovation group, the trails and testing manufacture of a hinge bracket for the A320 aircraft resulted in a 64% weight reduction providing a total saving of 10Kg mass per aircraft. Along with approximately 40% reduction in carbon emissions from an eco-assessment directly as a result of this weight reduction. Furthermore a redesign of the hinges on the exit doors showed results of around 33% weight savings. Other reports monitoring applied design modifications to other brackets used on the A350XWB and A380 models showed results with improves safety aspects while providing around 28% reduction in weight (Singamnemi, 2019).

9.3 Environmental Impacts

9.3.1 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 increasingly 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).

9.3.2 This progress has come through the adoption of modern 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.

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).

9.3.4 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 Al2O3. The extraction of metal from its oxide necessitates significant energy inputs, thereby characterizing aluminium metal as an energy-intensive investment (Marcel Dekker Inc, 2003).

9.3.5 Currently, airframes are composed of approximately 70%-80% aluminium by weight, with a huge 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).

9.3.6 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 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).

10 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 10.1 Lead time and cost reduction for repair. Secondly 10.2 a seat component designed and manufacture by SAFRAN SEATS GB.

10.1 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. Franűhofer ILT successfully utilized LMD and selective laser melting (SLM) for the refurbishment of the Inconel 718 turbine case and compressor seal, 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).

10.2 Specific Case Study Analysis of 7075 T6 – Al7075

The component chosen for this case study has undergone all regulatory testing and certification for air worthiness (Florio, 2016). 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 allowing a free form and then subjected to AI generation to provide results for conventional manufacture and free from design AM simulation and testing.

As in the case study 10.1 a scenario was followed, from the viewpoint of aftermarket support for supply of a one legacy part to see if the outcomes were similar. The results produced indicated a positive outcome.

See appendix 2 for supporting documentation.

11 Conclusion

In conclusion, the primary focus of this dissertation was to thoroughly investigate the use of 3D-printed aluminium additive manufacturing in the aviation industry. The aims, in particular, were in relation to commercial airline seating. The study conducted a thorough analysis of the mechanical properties, viability, and environmental impact of 3D-printed aluminium in comparison to conventional production techniques, along with the comparative effectiveness of 3D-printed and solid aluminium components. The investigation specifically focused on key criteria including cost, reduction of material waste, and energy efficiency, providing detailed and nuanced insights, viability, and environmental impact. Used both quantitative and qualitative studies, taking into consideration cost, material waste reduction, and energy efficiency.

Advancements in collaborative additive manufacturing technologies highlighted breakthroughs in metal fusion at room temperature. Emphasised flexibility in additive manufacturing, providing designers with unparalleled freedom for complex structures and rapid prototyping, along with the challenges and innovations in additive manufacturing processes. Collaborative solutions include partnerships with machine manufacturers and advancements in temperature monitoring and scanning technologies. Anticipated future progress in powder bed additive manufacturing (PB-AM). Exploiting the full potential of 3D-printed aluminium showed that the Direct Metal Laser Sintering (DMLS) process is highly viable for commercial aircraft frame components. Constraints and continuing progress identified obstacles such as material limitations and construction times. The long-lasting importance of aluminium in aerospace was explored in historical terms dating back to the 1930s, as was its lasting role in aircraft production. The manufacture and tailoring of aluminium powder emphasised meticulous customisation for uniform powder quality, considering particle size and distribution.

The properties and heat treatment of aluminium alloy 7075 T6 highlighted its exceptional strength, lightweight nature, and suitability for aerospace applications. Stressed the pivotal role of the T6 heat treatment method. Technologies for advanced manufacturing were examined, such as selective laser melting (SLM) and electron beam melting (EBM), crucial for effective aerospace manufacturing. The prospects for the integration of aluminium in the future position the combination as opening new frontiers in aerospace engineering with ongoing research and technological advancements. Evaluation of the surface quality and roughness emphasised the critical role of parameter control and challenges in selective laser melting (SLM). Enhancing surface finish via optimisation is for the optimisation of achieving desired visual and tactile characteristics.

Achievements and financial savings showcased success stories like Airbus's hinge bracket and substantial cost and time efficiencies in Maintenance, Repair, and Overhaul (MRO) operations. SAFRAN Seats GB's Exploration of AM Technologies is an example of a case study focusing on the 7075 T6-AI7075 components. Provided a baseline for evaluating environmental benefits and efficiencies.

Practices and transformations for sustainable aluminium are aligned with development goals. Recognised aluminium's role in various transportation sectors and its transformative impact on traditionally conservative industries. It is apparent that there is a paradigm shift in how the aerospace industry transforms constraints and future directions to tackle material

degradation and environmental impact. Showcased ongoing progress in reducing processing times and energy consumption. The environmental consequences and efficiency improvements in aerospace explored the potential to transform inventory management and reduce carbon emissions through AM technologies. Effects and Sustainable Initiatives in Materials Development recognised progress in reducing carbon footprints through alternative materials like textiles and composites. Acknowledged the aerospace industry's strides in carbon reduction (Nyamekeye Patricia, 2024).

The outlook offered a detailed analysis of mechanical properties, practicality, and environmental impact. Positioned additive manufacturing and sustainable practices as guiding principles for technological advancement and environmental stewardship. The progression of additive manufacturing in aerospace highlighted various additive manufacturing methods and their advantages, including design freedom, waste reduction, and rapid prototyping (Han, 2020). The broader influence beyond manufacturing processes includes generative design and topology optimisation for lighter, more efficient, and more environmentally friendly components. Continuous research and development efforts are underway to establish additive manufacturing as an essential technology dedicated to decreasing carbon emissions. Demonstrated potential for cost savings and innovation through collaborations like SAFRAN Seats GB. Focused on assessing the practicality, performance, and ecological consequences of 3D-printed aluminium. Reducing environmental impact through technological limitations and ethical considerations. Advocated for the adoption of additive manufacturing and sustainable practices to meet carbon reduction targets.

Advancements in collaborative additive manufacturing technologies with respect to the present state of additive manufacturing technology demonstrate the outcome of collaborative endeavours spanning various industries, scientific disciplines, and inventive intellects. The groundbreaking nature of additive manufacturing is exemplified by the advancements made in metal fusion at normal room temperatures. The unique characteristic of additive manufacturing, which distinguishes it from subtractive processes, grants designers unparalleled flexibility. This allows for the creation of complex interior structures and facilitates the quick production of prototypes. In line with the objective: a thorough exploration of the use of 3D-printed aluminium additive manufacturing in aviation, and not just specifically commercial airline seating. collaborative additive manufacturing technologies across industries. Exploring the difficulties in additive manufacturing, especially regarding intricate surfaces and geometries, and exploiting the full potential of 3D printed aluminium, emphasising the transformative capacity of 3D printed aluminium, specifically the 7075 T6 grade.

The current state of 3D printed aluminium additive manufacturing and lay the groundwork and insight for the future progress of additive manufacturing in aerospace, exploring the transformative influence of additive manufacturing in the aerospace sector, though not limited to this, and looking at the broader influence beyond manufacturing processes, showcasing the impact of additive manufacturing beyond manufacturing. The constraints and continuing progress address challenges faced by additive manufacturing and ongoing efforts to overcome them.

The intricate production processes of aluminium powder, the heat treatment of aluminium alloy 7075 T6, and the mechanical properties of aluminium alloys such as 7075 T6 provide insights into advanced 3D printing technologies. Prospects for the integration of aluminium

in the future and the potential of integrating aluminium and advanced manufacturing in aerospace. The long-lasting importance of aluminium in aerospace is a direct result of its historical evidential use, leading to the enduring significance of aluminium in aerospace engineering. The future direction and future potential rely on the importance of process parameters relating to strength, structure, and quality for aluminium components, enhancing the significance of optimising layer thickness, resolution, and surface finish to overcome the constraints in additive manufacturing and showcase its future trajectory.

Environmental Consequences and Efficiency Improvements in Aerospace of Additive Manufacturing in Aerospace Sustainable initiatives in material development examine environmental effects beyond aluminium and advancements in materials for sustainability. The practices and transformations for aluminium are highlighted by the continued development of technology to analyse sustainable practices in aluminium production for lightweight solutions. SAFRAN Seats GB's Exploration of Technologies interest in additive manufacturing is part of its transformational contribution to the aerospace industry. Dedicated to decreasing carbon emissions, it is part of the aviation industry's commitment to reducing environmental impact through technology. Emphasise the role of technology, operational changes, and lighter materials needed to tackle material degradation and environmental impact. Showcased ongoing progress in reducing processing times and energy consumption.

The difficulties encountered in additive manufacturing methods, specifically in handling intricate freeform surfaces and complex geometries, Exploratory endeavours were undertaken to investigate creative ways for addressing these difficulties by fostering collaboration between machine manufacturers and external vendors, using temperature monitoring and advanced scanning technology. The study also emphasised the changing nature of powder bed additive manufacturing (PB-AM) and predicted future progress in the sector.

Although additive manufacturing (AM) has the ability to bring about significant changes, it encounters obstacles such as limited options for materials, extended construction times, and high expenses for equipment. Nevertheless, continuous research and development endeavours are actively tackling these constraints, presenting additive manufacturing as an increasingly essential technology in the manufacturing field. The manufacture and tailoring of the production of aluminium powder, a vital ingredient in sophisticated procedures such as 3D printing, entails complex and detailed procedures. The customisation of production processes is conducted with great diligence in order to achieve consistency in the quality of the powder. This involves careful consideration of parameters such as particle size and distribution. The mechanical characteristics of aluminium alloy 7075 T6, renowned for its exceptional strength, low weight, and ability to withstand harsh conditions, make it highly suitable for use in aircraft applications. The T6 method of heat treatment is crucial in modifying the tensile strength of the alloy. However, the study found that there is consideration for this during the manufacturing process, such as the Direct Metal Laser Sintering (DMLS) process, which is used in additive manufacturing and is highly suitable for commercial applications when combined with existing technology and the use of aluminium powder.

The dissertation emphasised the significance of technology, operational changes, and the use of lighter materials in reducing the environmental effects of the aircraft industry while also recognising its limitations and ethical problems. With the evolution of the aviation

sector, it becomes crucial to adopt additive manufacturing and sustainable practices as a key approach to meet carbon reduction targets and tackle global environmental issues. The environmental consequences and efficiency improvements in the aerospace industry have been assessed, and additive manufacturing (AM) in the aerospace sector demonstrates its capacity to fundamentally transform inventory management and reduce carbon emissions. Implementing AM technologies diminishes the necessity of maintaining a substantial stock of spare parts, in line with the industry's overarching objective of minimising its environmental impact.

Ethical consideration is now evident globally in the aviation sector of the effects and sustainable initiatives of material development for environmental benefits. The environmental effects of additive manufacturing go beyond just aluminium, as continuous advancements are leading to the development of new materials that enhance the production process. Exploring alternate materials, such as textiles and composites, helps to minimise environmental impacts by promoting the use of resources in a circular economy. The study recognised the significant progress made by the aircraft industry in reducing its carbon footprint through the implementation of advanced technologies, alternative fuels, and materials.

The report highlighted the aviation industry's dedication to significantly reducing carbon emissions and the crucial need to use sustainable materials and implement energy-efficient operations. The potential for cost reductions and innovation was demonstrated through strategic alliances, such as the one with SAFRAN Seats GB. The study focused on evaluating the practicality, performance, and ecological consequences of 3D-printed aluminium parts. This research provided vital knowledge to make well-informed choices in the effort to achieve a carbon-neutral aviation sector by 2050. Dedication to decreasing carbon emissions and reducing environmental impact through technological advancements and innovative solutions. It is crucial to tackle the constraints of additive manufacturing (AM), such as material degradation and environmental impact, in order to ensure its ongoing incorporation. The continuous progress in decreasing processing times and energy usage demonstrates the prospective path of additive manufacturing (AM) in influencing the future of manufacturing constraints and future direction.

12 Appendices

Appendix 1 Aluminium powder abstract

Martin, John & Yahata, Brennan & Hundley, Jacob & Mayer, Justin & Schaedler, Tobias & Pollock, Tresa. (2017). 3D printing of high-strength aluminium alloys. Nature. 549. 365-369. 10.1038/nature23894. The article discusses the potential of metal-based additive manufacturing, or 3D printing, as a disruptive technology in various industries such as aerospace, biomedical, and automotive. While the technology allows for greater design freedom and manufacturing flexibility, only a few alloys can be reliably printed due to issues in the printing process that lead to undesirable microstructures. The study introduces a solution by incorporating nanoparticles of nucleants to control solidification during additive manufacturing. By applying this method to high-strength aluminium alloys (7075 and 6061 series), the researchers achieved crack-free, equiaxed microstructures with material strengths comparable to traditional wrought material. The approach is said to be applicable to a wide range of alloys and can be implemented using various additive machines, laying the foundation for broader industrial use. The technology could extend to other alloy systems, including non-weldable nickel superalloys and intermetallics, and may find applications in conventional processing methods like joining, casting, and injection molding.. © 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.

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Appendix 3 SAFRAN Case study supporting documentation.

The controlling data applied is as follows:

Material type:

Solid; 7075T6

Powder; AlSi10Mg

Load weight 285Kg

Gravit factor applied 9.087

Force 5G

Figure 1. Component Model

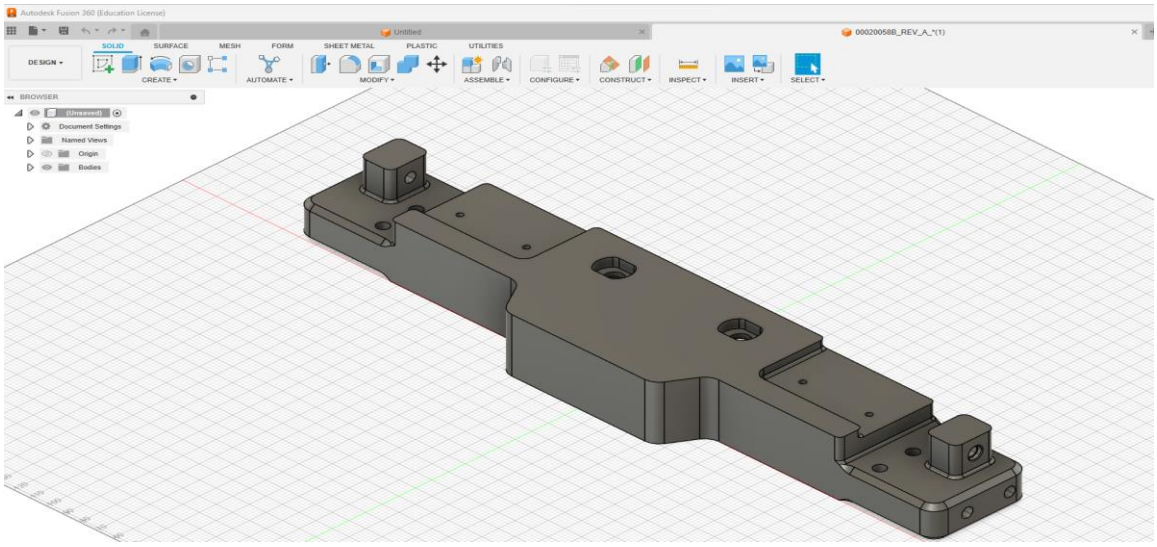


Figure 2. Load and Force direction applied to model for both Conventional & Additive.

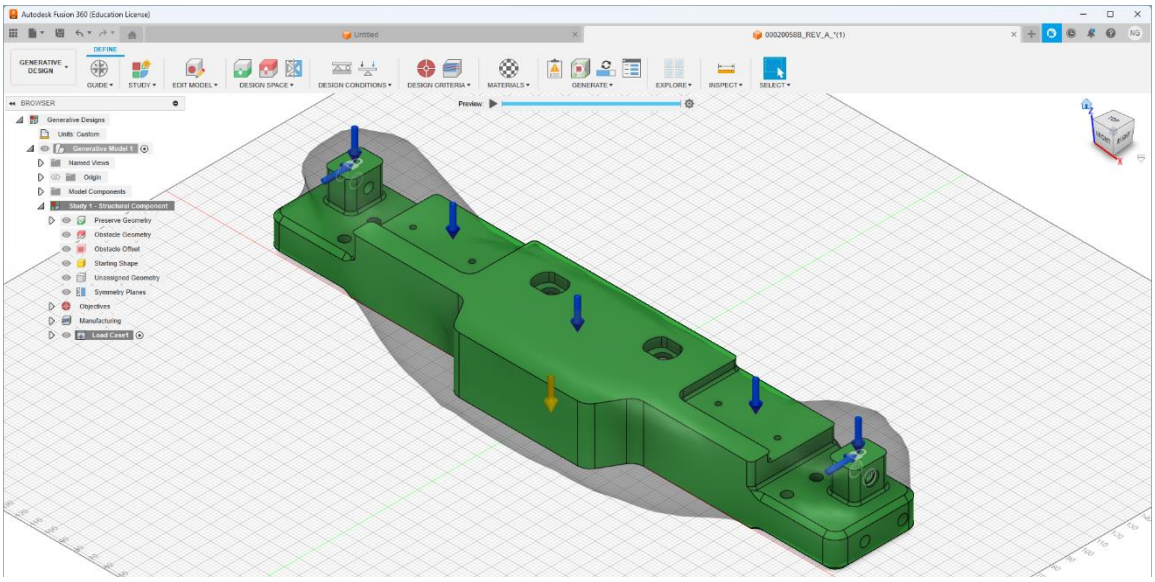
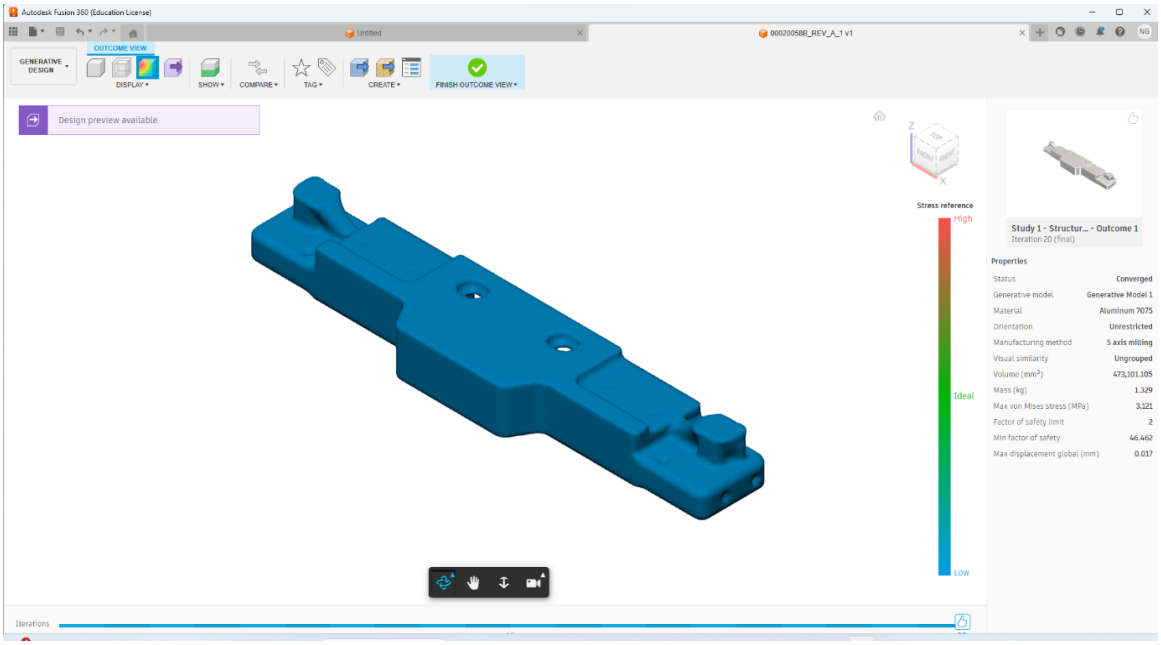


Figure 3. Generative Design for Additive.



Calculated Estimated Gains for Case Study 10.2

Case Study Results based on 1 off component for Aftermarket Supply				
Costs based on Ave £95 p/h	**Coventional**	**Genrative**	**% Saving/Gain**	**Comment**
Materials stock weight Kg	5.443	1	81.63%	Carbon footprint reduction, no over production of raw material required
Component Weight Kg	2.134	1.735	18.70%	Provides a fuel usage reduction for aircraft
Waste Material Weight Kg	3.309	0	100.00%	Carbon footprint reduction, significant waste reduction
Processing Time mins	1152	873	24.22%	Also provides significant reducting or energy requirements, supplimenting carbon footpring reduction
Setting time	75	5	93.33%	Also provides significant reducting or energy requirements, supplimenting carbon footpring reduction
Material Cost for Part Manufacture	£73.50	£0.46	99.38%	
Cost of Waste Material	£44.68	£0.00	100.00%	A positive impact for the enviroment
Component Material Value	£28.82	£0.46	98.42%	
Processing cost	£1,824.00	£1,382.25	24.22%	
Setting costs	£118.75	£7.92	93.33%	
Initial Costs	£2,089.75	£1,391.08	33.43%	
Secondary Machining Operation. This was required on additivive part for tolerance criteria.				
Setting time		5		
Processing Time mins		10		
Settiing cost		£7.92		
Processing time		£15.83		
Secondary cost add to generative		£38.75		
Total Cost	£2,089.75	£1,429.83		

Appendix 4 Further recommended reading.

1) Sustainability aspects of additive manufacturing; Leveraging resource efficiency via product design optimization and laser powder bed fusion: *Patricia Nyamekye, Rohit Lakshmanan, Vesa Tepponen, Sami Westman. (web https://doi.org/10.1016/j.heliyon.2023.e23152). Heliyon 10 (2024) e23152 Science Direct December 2023.*

2) Recent advances in multi-material additive manufacturing: methods and applications: *Daehoon Han, Howon Lee (web https://doi.org/10.1016/j.coche.2020.03.004) 2020 Elsevier Ltd. une 2020.*

3) Integrating product function design, production technology optimization and process equipment planning on the example of hybrid additive manufacturing: *Alexander Jacoba, Simeon Steimera, Nicole Strickera, Benjamin Häfnera, Gisela Lanzaa. Procedia CIRP 86 (2019) 222–227 Science Direct 2019.*

4) Icct Report. CO^2 Commercial Aviation 2013, 2018 and 2019: *Brandon Graver, PH. D, Dan Rutherford, PH. D, Sola Zheng. The International Council on Clean Transportation. October 2020.*

5) Prospective life cycle inventory datasets for conventional and hybrid-electric aircraft technologies*: Nils Thonemann, Karen Saavedra-Rubio, Eleonore Pierrat, Katarzyna Dudka, Mathilde Bangoura, Nils Baumann, Christian Bentheimer, Priscilla Caliandro, Roeland De Breukerf, Cor de Ruiter, Mario Di Stasio, Julie Elleby, Alexe Guiguemde, Bruno Lemoine, Martin Maerz, Valerio Marciello, Markus Meindl, Fabrizio Nicolosi, Manuela Ruocco, Benjamin Sala, Anna Lia Scharling Tromer Dragsdahl, Andrea Vezzini, Zhangqi Wang, Thomas Wannemacher, Julius Zettelmeier, Alexis Laurent. Journal of Cleaner Production 434 (2024) 140314. Science Direct (web https://doi.org/10.1016/j.jclepro.2023.140314) Elesvier Ltd December 2023.*

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