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3D Printing Technology in Aerospace Industry – A Review

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3D printing technology has sharpened the aircraft industry in recent years. 3D printing technology makes the construction of small and complex structures more convenient. 3D printing technology uses a consecutive layer-by-layer addition of materials to construct objects from a geometrical computer design. The 3D printing technique is progressively used for the development and customization of any type of design. Based on user-defined parameters, 3D printing technology allows the low-cost creation of components. Tooling costs related to the development of molds are neglected, unlike other plastic-forming technologies. Highly customized structures with a minimum production quantity are possible. Therefore, this technology has vast applications in the aircraft industry. This review article aims to give an overview of 3D printing technologies and their uses in the aircraft industry. Materials, elements, or components along with their properties, specially developed for aircraft industry applications, are discussed. The types, advantages, applications, and limitations of 3D printing exclusively in the aircraft industry are precisely presented.

Additive Manufacturing

Additive manufacturing (AM) is a class of technologies for the construction of prototypes, patterns, tooling components, and physical models by using data gained from computers, 3D scanning systems, or any advanced digital information (Grzesiak, 2008). Unlike the traditional manufacturing techniques of subtractive machining, additive manufacturing (AM) forms physical objects by combining powder, sheet materials, or liquid layer by layer. Parts that are critical to producing using other technologies can be manufactured by using additive manufacturing (AM) technology (Kai, 1994). Three-dimensional printing (3DP), selective laser melting (SLM), stereo-lithography, and fused deposition modeling (FDM) are the few AM technologies that are currently in use.

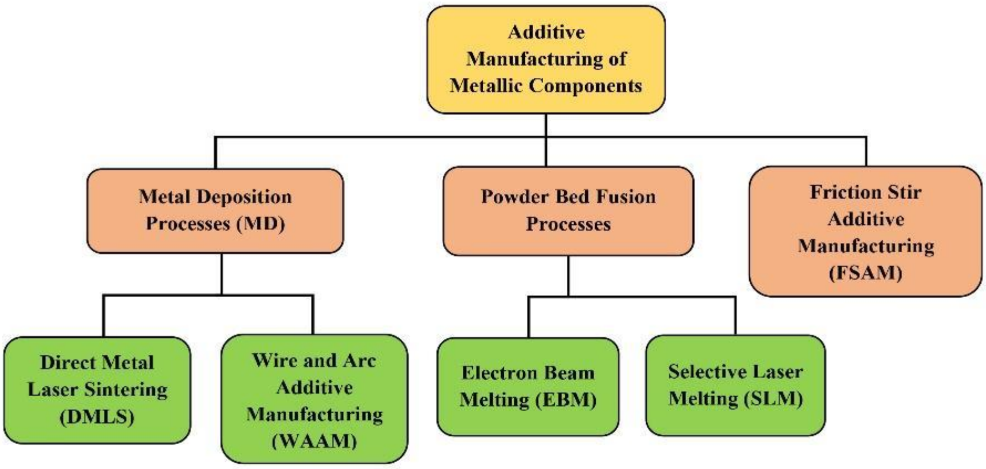
The applications of AM technologies by engineers, designers, and other professionals have been consistently growing in recent years (Moon et al., 2014). The various AM process classifications based on the power delivery system and energy source (Uriondo et al., 2015) are shown in Figure 1. Direct Metal Laser Sintering (DMLS) is a wire-based system and can only be used to make parts with metal alloys. It is a furtherance of powder metallurgy (PM), an advanced metal-molding technique to produce powdered metal parts by making use of pressure and temperature. The product manufactured by wire along with arc additive manufacturing (WAAM) is of a high standard and more preferable than conventional welding procedures (Hibbert, 2014). WAAM can be applied to an extensive range of metals, if and only if they are in wire form. Any metal which can be welded using conventional methods can also be used with WAAM, including stainless steel, nickel-based alloys, titanium and aluminum alloys, and many more.

The powder bed fusion (PBF) method is utilized to fuse and melt powdered materials together. This method uses a laser or an electron beam to fuse the powdered materials. The powder bed fusion method includes Electron

Beam Melting (EBM), Selective Heat Sintering (SHS), and Selective Laser Sintering (SLS) printing techniques. Material varieties like ceramics, plastics, and metals are used in the SLS printing technique to construct various parts. To manufacture the product with any material, the SLM printing technique is used. For the laser melting technique, EBM (Electron Beam Melting) is emerging as a high-standard replacement, and it is also being utilized to repair and manufacture turbine blades (Marx et al., 2013). Along with Powder Bed Fusion, Directed Energy Deposition, and other technologies, this can be used to manufacture structural parts for aircraft or smaller mechanical parts.

Figure 1

An Elaborated Flowchart of the Additive Manufacturing Processes (Uriondo et al., 2015)



In solid-state welding, friction stir welding (FSW) can be used without melting the work piece material. In this technique, a non-consumable tool is utilized to weld the work piece material. Friction Stir Additive Manufacturing (FSAM) is an advancement of the FSW technique in which the stacks of weld plates are lap welded and then friction stir welded to make a product layer by layer. In the aircraft industry, for manufacturing longerons, stringers/stiffeners, and wing spars, the FSAM technique could be used (Palanivel et al., 2015). Among the various AM processes, only a few meet the complete requirements of the aircraft industry. Thus, the most widely used AM processes for the aircraft industry are EBM, SLS, WAAM, and SLM (Joshi & Sheikh, 2015).

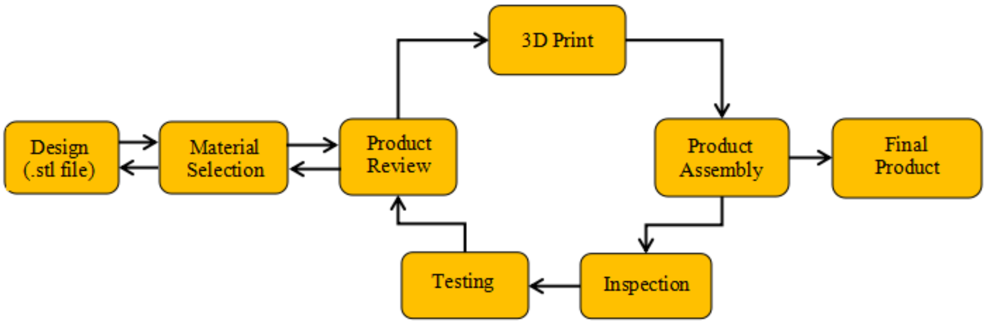
3D Printing Technology

The first commercialization of the 3D printing (stereo-lithography) process was developed and invented by Chuck Hull in 1983. This idea came into his mind when he was hardening tabletop coatings using UV light (Shahrubudin et al., 2019). 3D printing is the successive addition of material layer by layer to construct physical parts from 3D model data (ASTM International., n.d.). For 3D printer manufacturing, the product must first be designed in a CAD tool and then exported in a compatible file format to a 3D printer. High customization in product design is gained through 3D printers, which are used to print components that generally cannot be constructed by other conventional manufacturing techniques. Production of any delicate component with a significant reduction in material wastage, manufacturing costs, and time is a benefit of 3DP (Joshi & Sheikh, 2015). The design workflow included in 3DP technology is shown in Figure 2.

Stereo-lithography is the basic idea of the 3DP technology, in which the liquid photo-polymer filled surface of the vat is focused on the concentrated UV light rays. The ultraviolet light beam draws each layer by layer of the objects onto the liquid-form surface, moving them under the control of the computer. The liquid form surface finally changes into a solid wherever the UV light beam strikes the photo-polymer crosslinks or polymerizes. Mathematically, slicing the computer model of the component into several numbers of fine layers is done by using advanced CAE/CAD/CAM software. The 3D printer then builds the component layer upon layer and completes the final product at a defined time. Nowadays, 3DP technology can produce objects or parts by utilizing conventional thermoplastics, metals, graphene-based materials, and ceramics (Low et al., 2017). 3DP has many advantages, including low cost, less time consumption, and less manufacturing complexity.

Figure 2

The Workflow of 3D Printing Technology



3DP technology has been broadly utilized throughout the entire world, especially in the manufacturing and research and development industries. This has been widely developed during recent years as it is the most powerful and flexible technology in the advanced manufacturing industry (Shahrubudin et al., 2019).

The fusion of matter on a molecular or atomic level (electron beam, ultraviolet light, laser, or thermal) as well as the properties and physical state of the primary materials (solid, powder, or liquid-based processes) are used to classify 3D printing processes. There are seven kinds of 3D printers available, which are useful in producing parts or products related to the aircraft industry, viz., Digital/EBM, SLS, FDM, SLM, Laminated Object Manufacturing (LOM), Stereo-lithography (SLA), and Digital Light Processing (DLP).

Types of 3D Printing

3DP technology has been developed in a variety of ways with different modules. It is difficult to justify which technology and functions are better. Since each of them has its own applications and is based on customer requirements, 3DP technology is not limited to prototyping applications, but it also expands towards creating a variety of products.

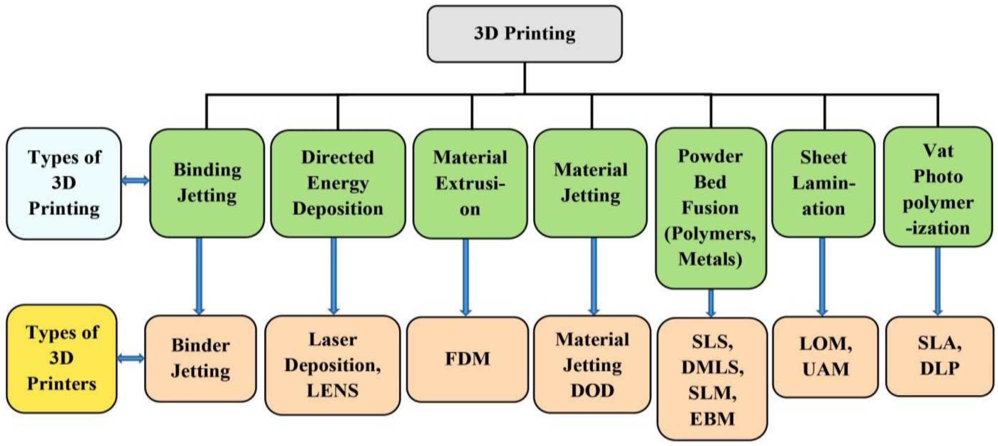
Several types of 3D printers are used in the aircraft industry, depending on the parts or components that need to be manufactured. Some research-based aircraft industries use only some particular types of 3D printers by changing or adjusting the filament and infill used in the 3D printers. The infill used in 3D printers is discussed in upcoming section.

Before selecting any type of 3D printer, we should know the filament materials used in those 3D printers to manufacture the parts and components. Furthermore, one should have prior knowledge of the sizes, types, and accuracy of the parts and components that are going to be produced by that 3D printer.

The aircraft industry has some of the highest standards in component performance. The extreme temperatures and chemicals are loaded on aircraft parts while being subjected to repeated use and also while remaining as light as possible in weight. Any individual component failure can result in the full system failure of the aircraft carrying passengers and cargo, so in the aircraft industry, failure is simply not an option. Because component precision is a critical factor in aircraft design, 3D printers are used in the aircraft industry to provide extremely high accuracy in parts and components.

The 3D printing types used to manufacture metal-based components and parts of the aircraft are DMLS, EBM, SLM, and SLA. SLS, SLA, DLP, FDM, and material jetting are the types of 3DP used to manufacture polymer or composite-based aircraft components and parts (Ahart, 2019). As per ASTM Standard F2792 (ASTM International., n.d.), 3DP technologies are catalogued into seven categories, which are shown in Figure 3.

Figure 3
3D Printing Process Types and Printer Types



Binder Jetting

In binder jetting, a binding liquid agent is used to fuse powder particles by selectively depositing on them. It is a 3D printing process with rapid prototyping. To create a layer on the spread powder, a jet chemical binder is used in the binder jetting technology (Uriondo et al., 2015). This method is faster, cheaper, and simpler and can print large-sized products.

Directed Energy Deposition

The directed energy deposition printing process is a slightly critical method and is generally utilized to add or repair supplementary materials to the extant parts. This process is capable of making a good quality product, and it also has grain structure control to a higher degree. Furthermore, this procedure is typically used with metal-based hybrids and other metals, and it can also be utilized with different ceramics and polymers, in the form of either powder or wire. Laser deposition and Laser Engineered Net Shaping (LENS) are two examples of this technology.

Materials Extrusion

The material extrusion-based 3DP technology is useful for the production of multi-color and multi-material printing on food, plastic, or living cells. FDM constructs parts from the base to the peak of the part by adding layers through the extruding of thermoplastic filament. Generally, a 3D printer with an affordable price uses FDM technology, and it is the most popular 3D printing technology. Scott Crump originally developed and executed this technology.

Material Jetting

The inkjet printing process uses a material jetting method in which to deposit a liquid photo-reactive material onto a platform, and print heads are utilized layer by layer. The methods of material deposition differ based on the printer used and can necessitate either a Drop-on-Demand (DOD) or continuous jetting principle.

Powder Bed Fusion

As discussed earlier, SHS, SLS, and EBM printing techniques are involved in the powder bed fusion (PBF) process.

Sheet Lamination

Sheet lamination is one of the 3DP processes, where thin sheets of material are combined layer-by-layer to yield a single piece. The sheets are fed via a system of rollers for bonding. This process is comparatively inexpensive, easy for the handling of materials, and recycling of excess material is also possible. Further full-color printing is possible using this technique. Ultrasound additive manufacturing (UAM) and LOM are examples of 3DP technology that utilizes the sheet lamination method.

Vat Photo-Polymerization

Photo-polymerization is one of the most frequently used 3DP techniques, which generically describes the curing of photo-reactive polymers with the use of ultraviolet rays or lasers. Time of exposure, power supply, and wavelength are the key factors for Vat Photo-polymerization. Liquid materials are made to harden when exposed to ultraviolet light. This makes it easier to make a product with more details and a high surface finish.

3DP Materials for Aircraft Applications

High-quality materials that have compatible specifications are required in 3D printing technology to construct high-quality products. The suppliers and end-users of the products accept the controls to confirm these specifications, requirements, procedures, and agreements of materials. Materials including alloys of aluminum, titanium, ceramic, polymers, steel, and metallic, and their mixing in the form of composites, FGMs (functionally graded materials), or hybrids are used in 3D printing technology proficiently to make fully functional parts. Depending on the additive manufacturing techniques utilized and the physical state of the materials, objects with a minimum of 20 to 100 μm layer thickness can be constructed by using 3DP (Hopkinson et al., 2005; Tofail et al., 2018).

3DP materials in morphology are of four kinds: plastic film, powder material, liquid photosensitive resin, and wire material with a low melting point (Vaezi et al., 2013). These kinds of materials are considered based on weight and structural reliability like surface accuracy, wear resistance, density, thermal stability, and structural strength. Ti-6Al-4V and Inconel 718 are two Ti- and Ni-based alloys that have greater importance in the aircraft industry. Because these two alloys have good oxidation/corrosion resistance, damage tolerance, and tensile properties (Nijdam & Gestel, 2010).

The polymers which are generally used to print various aircraft components with SLS technology are carbon-fiber reinforced polyamide 12 (Carbonamide), glass bead-filled polyamide 12 powder (PA 3200 GF), aluminum-filled polyamide 12 powder (Alumide), and white polyamide 12 powder with a flame-retardant additive (PA 2210 FR) (Techno-Grafica GmbH, n.d.). The polymers which are used to print various aircraft components with FDM technology are Polyphenyl-sulfone (PPSF/PPSU)

(Stratasys Ltd., n.d.a), PEAK-Polyarylether-ketone (Quantevo-CF) (AREVO Ltd., n.d.), ULTEM™ 9085 (European Space Agency [ESA], 2013; Stratasys Ltd., n.d.b), ABSi (Stratasys Ltd., 2022), and Nylon 12 (Stratasys Ltd., n.d.a). 3D printing technology for manufacturing different aircraft parts with their processes is Martensite-hardenable steel (EOS Maraging Steel MS1) with DMLS (EOS GmbH - Electro Optical Systems, 2017), AlSi10Mg (Aluminum alloy) with DMLS (EOS GmbH - Electro Optical Systems, n.d.).

Infill is a repetitive pattern utilized to take up space inside the 3DP object. In general, the infill is hidden from view, but sometimes, the special infill is notable for boasting. Indeed, infill has other purposes too, like changing the weight of a product, based on material usage. Further, infill permits the nozzle to efficiently print the flat horizontal edges over a space. Moreover, infill is a major factor in 3D printing, and the product will become fragile due to structural and stability problems if the infill is not properly configured. Optimizing infill can be a tedious task with various patterns, densities, styles, and orientations. There are various types of infill available for 3DP technology (Pecho et al., 2019), and only a few are shown in Figure 4. The choice of infill is based on the aircraft product's uses and utilizations. The selection of infill's used in 3D printing to manufacture aircraft products depends on various things like filament, 3D printing process, strength and weight, accuracy, uses of the aircraft products, etc.

Generally, there are many variants of filaments available on the market. Each filament has its advantages and disadvantages, and its utilization depends on the aircraft product applications. PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene Styrene) are the most commonly used filaments.

Table 1

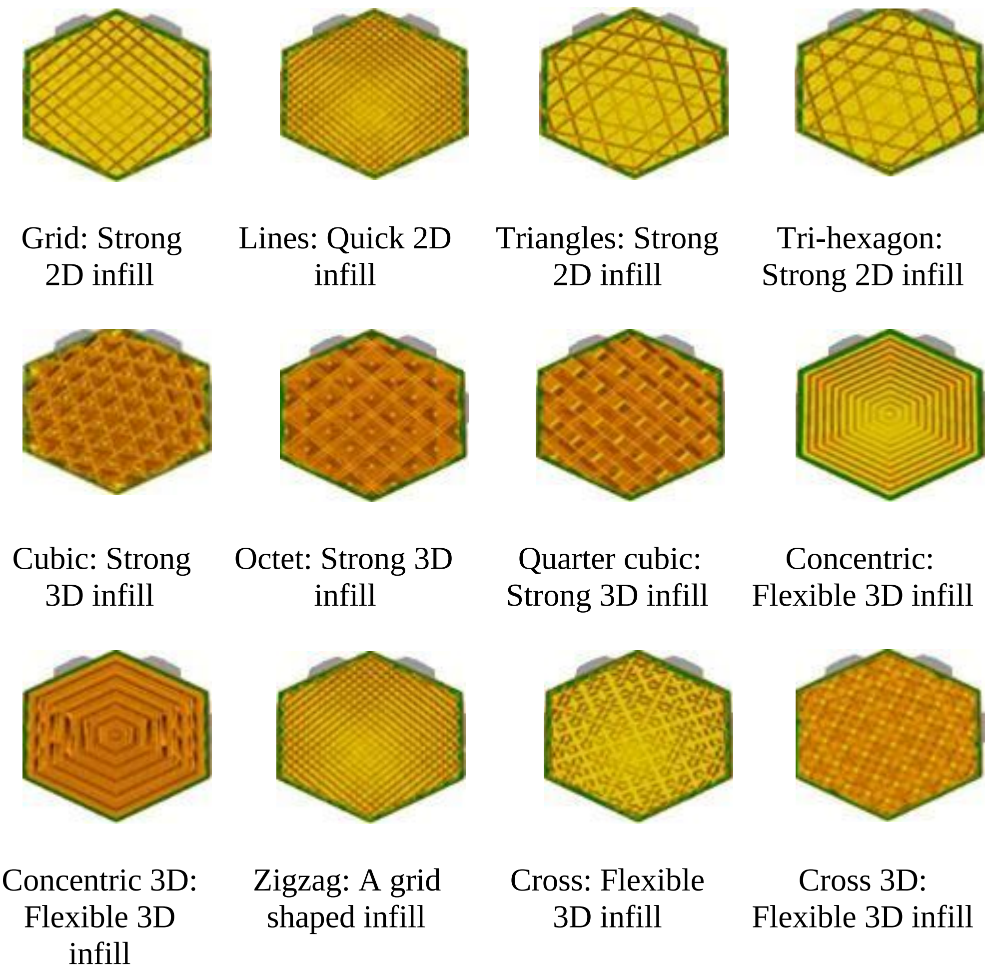
Mechanical Properties of Ti and Ni-Based Alloys From AM and Other Techniques (Joshi & Sheikh, 2015)

<table>
<tr><th>Alloys</th><th colspan="2">Technique</th><th>Yield Strength (MPa)</th><th>Ultimate Tensile Strength (MPa)</th></tr>
<tr><td rowspan="6">Ti6Al4 V</td><td rowspan="3">AM Process</td><td>EBM</td><td>830</td><td>915</td></tr>
<tr><td>SLM</td><td>990</td><td>1095</td></tr>
<tr><td>WAAM</td><td>803</td><td>918</td></tr>
<tr><td rowspan="3">Other Manufacturing Process</td><td>Typical Wrought</td><td>828</td><td>897</td></tr>
<tr><td>Annealed (Wrought)</td><td>790</td><td>870</td></tr>
<tr><td>ISO 5832-3 (ISO Standard)</td><td>>780</td><td>>860</td></tr>
<tr><td rowspan="3">Inconel 718</td><td rowspan="3">AM Process</td><td>EBM</td><td>580</td><td>910</td></tr>
<tr><td>SLM</td><td>552</td><td>904</td></tr>
<tr><td>Shape Metal Deposition (SMD)</td><td>473</td><td>828</td></tr>
</table>

		Casting	488	786
		Cast Inconel 718	915	1090
		Wrought Inconel 718	1185	1432
	Other Manufacturing Process	Injection Molded (as Sintered)	506	667
		Injection Molded (as aged)	780	1022
		Pressed - Hot Isostatically	993	1334
		AMS 5662G (for Wrought material)	1035-1167	1275-1400

Figure 4

A Few Types of Infill Used in 3DP with Ultimaker Cura (Pecho et al., 2019)



Application of 3DP in the Aircraft Industry

By joining powder, liquid, or sheet materials layer upon layer, 3D printers create different parts and products. 3D printing technology gives unique freedom in the manufacturing and production of various components. 3DP technology can provide improved quality for complex geometries and make lightweight parts, which can reduce resource and energy requirements.

So, this technology can be highly beneficial in the aircraft industry (Joshi & Sheikh, 2015). 3DP technology leads to fuel savings due to reduced material used to produce aircraft parts. Further, 3DP machinery has been heavily utilized to manufacture or repair the additional components for engines, wings, fuselages, and empennage. Usually, a few parts of the engine can easily get damaged during operation, requiring frequent replacement. Thus, for the procurement and replacement of such spare parts, the use of 3DP technology can be very useful (Wang et al., 2019). Rapid manufacturing, rapid prototyping, and/or rapid tooling can all be accomplished with 3DP technology (Wang et al., 2019). The different classifications among those 3DP applications are shown in Table 2.

The 3DP technology applications in the space and aircraft industries were observed using feedback by the major aircraft manufacturing industries, the market for its utilizations, materials used, applications for aircraft maintenance, and space industry utilizations.

Nowadays, due to upgrades in technology, only 60 designers with the help of 40 kinds of industrial design data are required for the manufacturing of one aircraft engine. But soon, by using 3DP technology, the production of such an engine will be easier and will only require a 3D printer, a set of design data, and a few engineers (Wang et al., 2019).

Table 2

The Different Classifications of 3DP Applications in the Aircraft Industry

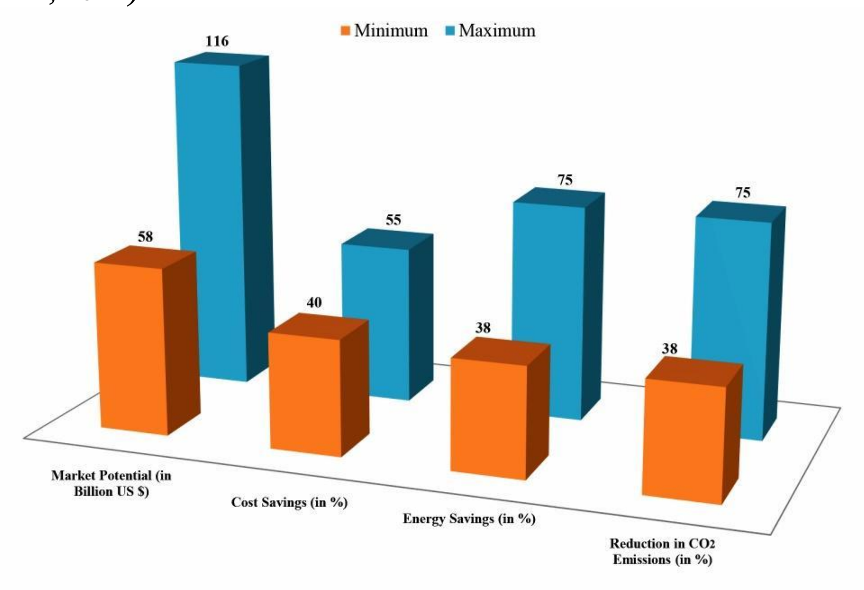
Category	Applications
Rapid prototyping	• For testing the spare parts of the platforms, vehicles, or engines (Kochan, 2000) • To create prototypes of various aircraft parts (Torres et al., 2011) • For validating the mold's machine ability (Budzik, 2007)
Rapid tooling	• For molding the turbocharger impellers and blades (Budzik, 2007) • For producing aircraft or spacecraft parts by replicating existing structures (Goel et al., 2014) • Associating elastic performance with truss lattice for UAV wings (Moon et al., 2014)
Rapid manufacturing	• For making aircraft spare parts for maintenance (Chen & Lin, 2017; G. Budzik, 2007; Kochan, 2000) • To construct an entire UAV or drone (Moon et al.,

	2014) • To establish a global supply and distribution chain for spare parts (Chen & Lin, 2017)

3D printing technology is often used in aircraft maintenance to build different spare parts for engine components, which are frequently damaged and need to be replaced during maintenance. The 3DP technology market is not yet fully developed in the aircraft industry as of now, but by 2025, the 3DP market and its benefits in the aircraft and space industry are projected in Figure 5 (Chen & Lin, 2017).

Figure 5

3D Printing Technology Projected Effects in the Aircraft Industry by 2025 (Chen & Lin, 2017)



Advantages and Limitations of 3D Printing Technology in the Aircraft Industry

3DP technology, in general, has various advantages. However, when compared to traditional manufacturing techniques, it has some drawbacks (Gebler et al., 2014). The advantages of 3DP in the aircraft industry are greater optimization towards strength/weight, a larger reduction in the overall weight of the component, depletion in several components or parts, a short span or machining time for manufacturing, low cost of customization, and less manpower requirements.

The major issue is the size limitation of the product (the EBM machine has a size limitation of 350 mm in diameter x 380 mm in height, which is the typical example of size limitation). Indeed, the dimensions of product making are increasing slowly nowadays. The process is slow for making the product, but it is partly recompensed by using the near-net shape, which is directly acquired. Due to some causes of fatigue or for optical results, 3DP products might require some finishing due to high surface roughness. These are the usual limitations faced by 3DP technology, and it is improving slowly.

Table 3

Basic Advantages of 3D Printing Technology (TWI Ltd., n.d.)

Easy design	Fast design	On-demand printing	Good strength
Less weight	Fast production	Less wastage	Cost-saving
Ease of access	Environment friendly	Advanced healthcare	Aircraft Industry

Basic Drawbacks of 3D Printing Technology (TWI Ltd., n.d.)

Less availability of materials	Limited build volume	Post-processing required	Manufacturing of bigger volume remains costly
Reduction in the job for human employees	Lower tolerances	Part structure*	Copyright issues#

*In the 3DP methods, products are formed layer by layer, and they can de-laminate under certain stress or orientation. This problem is more significant in FDM. Sometimes it is good to use injection molding as it creates homogeneous parts that will not separate and break.

#Using 3D printing technology, anyone can create completely counterfeit or duplicate parts, and it can be crucial to find the difference between the original and duplicate products, which may create copyright issues.

Future Scopes of 3D Printing Technology in the Aircraft Industry

3D printing of aircraft and space components on a larger scale and with larger dimensions, which is required for installation and use in accordance with future requirements, is critical. In the future, 3D printing technology can use various material alloys for more strength, weight reduction, and other better solutions for aircraft components. 3D printing can also be possible at nano-size by using different kinds of nanomaterials to make some complex objects that can be used in space programs and aircraft industries. Companies like SpaceX and NASA are working on developing societies on other planets like Mars by using 3D printing technology on a large scale. Many other future developments are possible in 3DP technology and its uses in the aircraft industry.

Conclusion

The aircraft and defense industries were exceptional pioneers in 3DP and continue to be enormously committed to its economic growth. As early as 1989, several aerospace companies immediately started implementing this advanced technology, and the successful adoption of 3D printing grew reasonably over the following years. In 2015, the aerospace and defense industries contributed approximately 16% of 3D printing to $4.9+ billion in global revenues. In this review, additive manufacturing technology and 3DP technology and their uses in the aircraft industry were described precisely. Types of printers used in 3D printing technology and types of printing done by using 3D printers were observed and presented. Materials used in 3D printing technology as filaments for manufacturing different aircraft components, with material properties, their applications, and manufacturing techniques used specifically for that filament, were understood from various literature and presented. Applications of 3D printing technology with advantages and few drawbacks in the aircraft industry were noted, and it is believed to produce larger parts on a larger scale with improved materials in the near future.

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