3D printing in aerospace and its long-term sustainability

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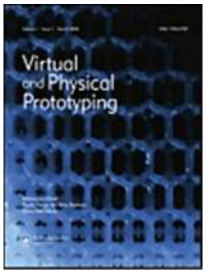

3D PRINTING IN AEROSPACE AND ITS LONG-TERM SUSTAINABILITY

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ABSTRACT: Astonishingly 3D printing has excited the world of aerospace. This paper takes the stock of the popular 3D printing processes in aerospace. Reasons for their popularity over the traditional manufacturing processes are dwelled upon. Materials developed specially for aerospace applications along with their characteristics are discussed. Ongoing activities related to 3D printing at various companies and organizations around the world are looked into. Project works in the area of extra-terrestrial printing are also highlighted. Even though 3D printing processes are operationally simple, they do have limitations in terms of the type, quality and quantity of the materials they can handle. This paper underlines these points while discussing drawbacks of the printed components. Challenges associated with 3D printing in microgravity are also touched upon. Finally, a glimpse is taken into the future appearance of aerospace industry with 3D printing.

INTRODUCTION

3D printing, also known as Additive Manufacturing (AM), is “a process of joining materials to make objects from 3D model data, usually layer upon layer” [1]. The product is designed in CAD software, which is then exported to a 3D printer. 3D printing provides a lot of customization in product design and can even print parts, which cannot be manufactured by any traditional manufacturing processes. Complex and intricate components can be manufactured with substantial reduction in manufacturing time, costs and material wastage.

3D printing technology has been around since two decades, but in the past couple of years it has ascended into a new manufacturing revolution. Earlier, known as Rapid Prototyping, the process was mostly limited to building prototypes and test products. It has evolved over a period of time into a matured process for being able to fabricate end-user products in various industries. A detailed history and development of AM may be found in [2]. This paper specifically looks into the development of 3D printing in aerospace industry and tries to take the stock of its progress, merits and demerits, and challenges involved in making 3D printing fully viable in this specialist application area of aerospace.

GENERAL OUTLOOK

AM provides unparalleled freedom in component design and fabrication. As compared to traditional manufacturing, the following complexities can be easily achieved [3]:

- **Features:** Varying thickness, deep channels and cuts.
- **Geometries:** Different and complicated shapes, topologically optimized shapes, blind holes, high strength-to-weight ratio geometry, and high surface area-to-volume ratio designs.
- **Parts consolidation:** Traditionally manufactured parts requiring joining together now can be integrated into a single printed part.
- **Fabrication step consolidation:** Conventionally fabricated nesting parts that require assembly in multiple steps can be printed simultaneously.

Traditional methods of manufacturing need a high degree of supply chain management and require large work force or machinery. The process of 3D printing is automated and relies on CAD software to print products using a variety of materials drastically reducing the amount of supply chain management [4]. In general, 3D printing does not use any costly molds nor is it in need of tools-either for machining or cutting, forms, punches, jigs or fixtures and hence is cost effective. In comparison to subtractive manufacturing process, there is a 40 % reduction in waste material in metal applications of 3D printing. Furthermore, 95 – 98 % of the waste material in 3D printing can be recycled [5]. In a study by Airbus Group Innovations, UK, and its partners showed that up to 75 % of the raw material usage can be reduced using AM [6]. Certain studies indicated that AM has 70 % less environmental impact than conventional machining [7]. Most parts manufactured through AM technology have substantially reduced weight. For example, an AM metal bracket of an aircraft has its weight reduced by 50-80%, which can save about US$ 2.5 million yearly in fuel [8]. Additive manufacturing also helped General Electric (GE) reduce up to 25% in production time and cost without comprising on performance [9].

3D printing helps in making lightweight, improved and complex geometries, which reduces product life cycle costs [5, 10]. 3D printing has the potential to drastically reduce resources, energy requirement, and process-related CO_2 emission per unit of GDP [5, 11-14]. In the aerospace industry, this could lead to fuel savings, where every kilogram of material saved reduces the annual fuel expenses by US$3000 [10]. To date, high buy-to-fly ratios of 20:1 are quite common for commercial air traffic [15]. But with 3D printing the buy-to-fly ratio is easily reduced to almost 1:1; as a result the raw material demands and material wastage is significantly reduced [16].

A qualitative assessment of 3D printing showed that this technology has the potential to reduce production costs by 170 - 593 billion US dollars, total primary energy supply (TPES) by $2.5E^{18}$ - $9.3E^{18}$ J and CO_2 emissions by 130 - 525 Ton by 2025 [16]. One of the manufacturing sectors with very high prospects for 3D printing is aerospace production industry. The potential for fuel savings due to even more lighter parts manufactured through 3D printing is the most attractive benefit for the aerospace industry. Furthermore, production in aerospace has the potential to decrease decommissioning-related CO_2 emissions and TPES demands [16].

In addition, AM technologies reduce down time, overall operation costs, and the capacity utilization. With AM customer needs can be greatly satisfied, supply chain management can be improved, and the inventory requirements can be reduced [17, 18]. Table 1 gives a comparative summary between AM and Traditional Manufacturing.

Table 1: Additive Manufacturing Technology vs. Traditional Manufacturing

	Additive Manufacturing Technology	**Traditional Manufacturing** [19]
Cost	Products can be manufactured at comparatively low costs; this is however limited to small and medium production batches.	These methods are expensive for small production batches. As costs are involved in casting molds, dyes, tooling, finishing and other different processes that goes into manufacturing the products.
Time	Products can be manufactured in a very short time. As AM makes products directly from the CAD model, it helps save time in delivering end products by cutting down on the production development step, supply chain and dependence on inventory.	Manufacturing times are very long, as it depends on the availability of the molds, dyes, inventory etc.
Resource Consumption	Only optimal quantity required to manufacture the product.	Extremely high.
Product Complexity	Used to manufacture complex geometries and products. The products are only limited by the design engineer's imagination.	Complex geometries cannot be manufactured. Many different parts have to be manufactured separately and assembled post manufacturing.
Post Fabrication Processing	Little to no post-fabrication processing is required, depending on the technique and material used.	A majority of the time, some kind of post-processing is required.
Material Quality and Application	The material quality depends on the technology used. Initially 3D manufactured parts were not used in load bearing application, but advancements in the technology is rapidly improving the material quality which has led to them being used in some load bearing applications.	Due to their excellent quality, the products have always been used for load carrying applications.
Material Wastage	There is little to no wastage of the raw material, as they can be reused.	Involves a lot of material wastage due to post-fabrication finishing processes.
Prototyping	Extremely useful for prototyping and evaluating product concepts. Allows for design changes and iteration.	Very expensive and time consuming. Not preferred for product prototypes and concepts.
Space Application	3D printing could essentially pave the way for setting up structures off-world, especially on the Moon and Mars.	It will be exorbitant to build structures off-world using these techniques.

POPULAR 3D PRINTING PROCESSES IN AEROSPACE INDUSTRY

3D printing can be divided into two classes, viz; (i) by the physical state of the raw material, i.e., liquid-, solid- or powder-based processes [2], and (ii) by the manner in which the matter is fused on a molecular level, i.e., thermal, ultraviolet light, laser, or electrons beam [20]. The most commonly applied 3D printing processes [5] are shown in Figure 1.

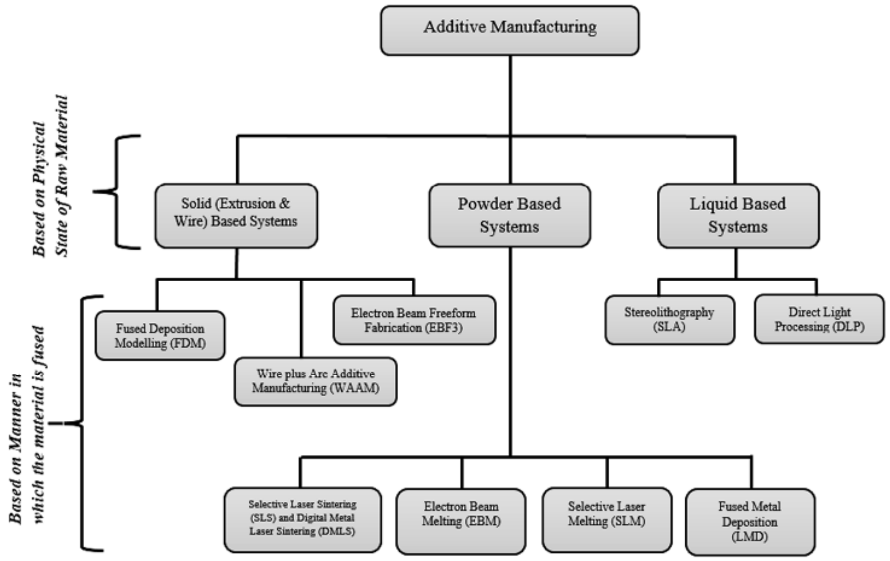

Figure 1: Classification of different AM processes.

Among the many different AM processes, the ones that meet the aerospace industry requirements are Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Wire and Arc Additive Manufacturing (WAAM) [21-23]. These processes can produce extremely dense components without any post-processing with comparable mechanical and electrochemical properties to other conventional manufacturing methods [24]. SLS and DMLS are in essence the same process. While SLS is used to produce parts using a variety of materials like plastics, ceramics, metals, DMLS can only be used to produce metal alloy parts. SLM can be used to manufacture with any material. It uses a high-energy laser beam to heat and melt the powdered material. The material oxidation and degradation is minimized by carrying out the process in protective environment [24]. EBM uses a very high-energy density electron beam, produces dense, void-free parts, but can process only metals. It is emerging as a high-quality substitute to laser melting and is being used to manufacture and repair turbine blades [25]. Friction Stir Additive Manufacturing (FSAM) is another AM technique and a study [26] has shown that FSAM did not only improve the mechanical properties, but the properties attained were also different from those manufactured by conventional methods. Through FSAM, strength of 400 MPa and a ductility of 17 % were achieved for an Mg-based alloy as against the strength and ductility in the base material (357 MPa, 2.9 % ductility). In the aerospace industry, FSAM could be used for the fabrication of stiffeners/stringers, wing spars and longerons in skin panels [27]. Electron Beam Freeform Fabrication (EBF3) uses an electron beam with a wire based system to fuse metals instead of powders. EBF3 can be used to produce structures with materials such as aluminum, high strength steels, titanium, titanium aluminides, nickel-base alloys, and metal matrix composites [28]. Wire plus Arc Additive Manufacturing (WAAM) is another wire-based system that effectively delivers free-space unrestricted weld metal deposition. The process can produce vertical, horizontal and angled walls, mixed-material conic sections, enclosed sections, crossovers and intersections. And since it is not constrained within a cabinet, larger components can be produced. The process uses off-the-shelf aerospace-grade wire [29]. The products obtained through WAAM are of extremely high quality and are even better than those produced by normal welding procedures, as shown by studies carried out at Cranfield University [29].

3D PRINTING MATERIALS FOR AEROSPACE APPLICATIONS

A lot of research is going on into using different types of metals and metal alloys for AM. Polymers, ceramic composites, alloys of aluminum, steel and titanium objects can be printed with a minimum layer thickness of 20 to 100 µm, depending on the AM technique used and the physical state of the material [20]. But from the aerospace industry point of view, more importance is towards Ti- and Ni-based alloys [24, 30].

Nickel-based alloys preferred in aerospace due to their tensile properties, damage tolerance, and corrosion/oxidation resistance [31]. Using AM for these alloys results in high cracking tendency, hence to improve its mechanical properties generally a Hot Isostatic Pressing process is employed [24].

In the case of Ti-Alloy, Ti-6Al-4V, as the cooling rate is different for SLM and EBM processes, the microstructure of the resultant Ti6Al4V components is different resulting in different hardness and ductility for these two processes [32]. A few studies have shown that mechanical properties of additively manufactured Ti-6Al-4V parts can be modified with heat treatment [33, 34].

Table 2 gives a glimpse into the properties variation observed due to the manufacturing process adopted including AM.

Table 2: Mechanical Properties of Ti- and Ni-based alloys obtained from different manufacturing techniques

Metal Alloys	**Manufacturing Technique**		**Yield Strength, (MPa)**	**Ultimate Tensile Strength, (MPa)**	**Ref.**
Ti6Al4V	AM Process	EBM	830	915	[33]
		SLM	990	1095	[33]
		WAAM	803	918	[35-36]
	Other Manufacturing Process	Typical Wrought	828	897	[37]
		Hot Worked and Annealed (Wrought)	790	870	[33]
		ISO 5832-3 (ISO Standard)	>780	>860	[33]

Inconel 718	AM Process	EBM	580	910	[38]
		SLM	552	904	[38]
		Shape Metal Deposition (SMD)	473	828	[38]
	Other Manufacturing Process	As-Cast	488	786	[38]
		Cast Inconel 718	915	1090	[39]
		Wrought Inconel 718	1185	1432	[40]
		Injection Moulded Inconel 718 (as Sintered)	506	667	[41]
		Injection Moulded Inconel 718 (as aged)	780	1022	[41]
		As Hot Isostatically Pressed	993	1334	[42]
		AMS 5662G specification for Wrought material	1035-1167	1275-1400	[42]

Apart from the above mentioned alloys, a few other AM materials are shown in Table 3.

Table 3: An overview of a few other AM materials

Base Material	**Material Name and Process**	**Characteristics**	**Tensile Strength (MPa)**	**Ref**
Polymers	Alumide® (Aluminium-filled polyamide 12 powder) with SLS	• High Stiffness • Metallic appearance • Good processing capabilities • Excellent dimensional accuracy	48	[43]
	CarbonMide® (Carbon-fibre reinforced polyamide 12) with SLS	• Good strength and stiffness • Lightweight • Good strength-to-weight ratio • Metal replacement	72	[43]
	PA 2210 FR (White polyamide 12 powder with a flame retardant additive) with SLS	• Flame retardant • Halogen-free • Good mechanical properties	46	[43]
	PA 3200 GF (Glass bead filled polyamide 12 powder) with SLS	• High stiffness • Wear resistance • High dimensional accuracy • Good thermal performance	51	[43]
	PPSF/PPSU (Polyphenyl-sulfone) with FDM	• Good chemical and heat resistance • Dimensionally accurate • Good mechanical properties	55	[44]

	Quantevo™-CF (PEAK-Polyarylether-ketone)	• Carbon fibre reinforced polymer with PEAK base • Light-weight • Non-corrosive • Excellent strength-to-weight ratio	~105	[45]
	ULTEM™ 9085 with FDM	• High strength-to-weight ratio • Good FST rating • Suitable for space applications. • 3D printed toolbox using ULTEM 9085 was sent to the ISS*.	69	[46-47*]
	ABSi with FDM	• Superior in strength to standard ABS • Translucent material • Dimensionally accurate • Durable	37	[48]
	Nylon 12 with FDM	• High fatigue endurance • Strong chemical resistance	46	[49]
Metals	EOS Maraging Steel MS1 (Martensite-hardenable steel) with DMLS	• Good strength • High toughness • Easy machinable • Good thermal conductivity • Age hardenable to approx. 54 HRC	1100	[50]
	Aluminium AlSi10Mg with DMLS	• High strength and hardness • Good dynamic properties • Good thermal properties • Low weight applications	445	[51]

3D PRINTING MATERIAL LIMITATIONS

Materials that are 3D printed have to be carefully examined for their different properties such as dimensional stability, strength, viscosity, and resistance to heat and moisture [52, 53]. Delamination and breakage under stress can be caused by weak bonding between layers. When 3D printed parts are load bearing the strength-related issues become an important factor [4].

One of the major barriers to 3D printing is structural performance [27]. The 3D printed products have solidification defects like porosities, shrinkage cavities, oxidation etc. Studies have shown that 3D printed products will cause anisotropic mechanical performance [54].

The mechanical properties of 3D printed products can be increased by reinforcing the matrix powder with fibres [55]. The study showed that by adding a fibre content of 1 % to the matrix powder, the flexural strength showed increased values of upto 180 %. And by increasing the fibre content to 1.5 %, the flexural strength increased to more than 400 %. Further, the addition of the fibres decreased the porosity from 62 % to a minimum of 56 %.

3D PRINTING AT VARIOUS INSTITUTIONS AROUND THE WORLD

An AM company, Harvest Technologies, uses plastic laser-sintering technology from Electro Optical Systems, Germany (EOS) for fabricating parts for Bell Helicopters [56]. A thorough inspection is done for every batch of the laser-sintered parts. They are also tested for their tensile and flexural properties. This shows that AM is a high quality, repeatable manufacturing process.

EADS Innovation Works and EOS, a leader in direct metal laser-sintering, have shown that replacing a cast steel nacelle hinge bracket on an Airbus A320 with an AM titanium part, optimized to place metal where there are loads, cuts raw material consumption by 75 %, saves 10 kg per shipset and reduces energy and emissions in production, operation and end-of-life recycling [57].

Oak Ridge National Laboratory in Tennessee, is working with AM equipment suppliers such as Arcam to expand the technology to new metals and larger parts, including laser-sintering of Inconel 718, a high temperature super-alloy offering both high strength and toughness and is used in turbine blades [57]. The lab has also developed a way to infuse reinforcing carbon fibres into polymer raw material to print parts that can carry loads. In general, polymer parts are low strength and are not suitable as load carrying components.

National Aeronautics and Space Administration, USA (NASA), on the other hand, is funding research to test feasibility of AM techniques for making aerospace components on Earth, aboard the International Space Station (ISS), in open space and on the moon or on Mars [58]. As part of NASA’s bid to develop technology for Mars exploration, its engineers have 3D printed the first full-scale, copper rocket engine part [59]. NASA created GRCo-84, a copper alloy, which was used to make the part. The part was built in 10 days and 18h at Marshall’s materials and processing laboratory using a SLM, which fused 8255 layers of the copper powder. Engineers at NASA, have also been working on 3D-printed components for liquid-propellant rocket engines. In another project, 3D printed metal rocket-engine injectors reduced at least 80% of the cost of the US$ 300,000 part. Testing is also planned to evaluate 3D-printing of a fuel turbo-pump [60]. In 2013, liquid oxygen and gaseous hydrogen injector made by laying down nickel chromium in a laser sintering process generated a record 20,000 pounds of thrust which was tested by NASA Marshall [58]. The part manufactured by Directed MFG, Inc., of Austin, Texas, has design similarities to the injectors used in large engines, like the RS-25 engine for the Space Launch System.

Last year a Zero-Gravity 3D printer, built by Made In Space, a company in California, in co-operation with NASA Marshall, was launched to the ISS. Aboard the ISS, it 3D printed a ratchet wrench which was later sent back to earth for analysis and testing. Following the success of the Zero-G Printer, Made In Space plans to send a second 3D printer called the AM Facility (AMF) later this year [61]. The AMF will have the capacity to use multiple aerospace grade materials to manufacture larger and more complex parts faster and with finer precision. It will serve as a permanent manufacturing facility aboard the International Space Station.

Tethers Unlimited, Inc., of Bothell, Washington, has been working since 2012 under a NASA Innovative Advanced Concepts contract to develop a technique for making multifunctional spacecraft structures in open orbit [58]. As part of the company's plan to launch self-fabricating satellites, it has proposed a device called "Trusselator". This device would automatically extrude layers of material to form lightweight carbon fibre truss structures which would be robotically assembled into solar arrays, antennas or other components.

SpaceX has successfully tested a 3D printed engine named the SuperDraco to be used to power the launch escape system of the Dragon spacecraft [62]. About 16,000 pounds of thrust is produced by the SuperDraco engine. DMLS of Inconel was used to manufacture the engine chamber of the SuperDraco. SpaceX also uses laser-sintering AM to make impellers and other parts for the Merlin engines that drive its Falcon 9 launch vehicle, which is currently in the process of being certificated for human spaceflight [63].

Last year BAE Systems had a military jet fly with a metallic 3D printed part on-board for the first time [29]. The stainless-steel bracket was printed using powder deposition technology. BAE is also using 3D printing to produce ready-made parts for supply to four Squadrons of Tornado GR4 aircraft. Support struts on the air intake door, protective covers for cockpit radios, and protective guards for power take-off shafts are some of the other non-metallic 3D printed parts for the Tornado jet.

Rolls-Royce claims to have produced the largest engine component using AM for a Trent XWB-97 engine [64]. The titanium structure is a front bearing housing made up of 48 aerofoils, all of which have been produced using AM. The structure is 1.5m in diameter and 0.5 m thick. The Trent XWB-97 has undergone several ground-test, and would be flight-tested later this year. The Trent XWB is the sole engine type available for the A350.

Researchers at the School of Mechanical and Materials Engineering, Washington State University, have 3D printed parts using raw lunar regolith simulant [65]. Also, earlier this year, engineers from Monash University, Australia and Amaero Engineering, successfully 3D printed two jet engines [66].

SPECIFIC ADOPTION OF AM IN AEROSPACE INDUSTRY

In early 2015, the FAA qualified the first 3D printed commercial jet engine part from GE. The part was printed of silver to house the compressor inlet temperature sensor inside the jet engine. GE Aviation is working with Boeing to retrofit GE90-94B jet engines with more than 400 3D printed parts. The next-generation LEAP jet engine from GE, which has 19 3D-printed fuel nozzles [67, 68], is being currently flight tested. Their target use is to power the Boeing 737MAX and the Airbus A320neo aircrafts [67]. GE Aviation plans to produce over 100,000 AM parts for its LEAP and GE9X engines by 2020 [69]. It is also aiming to replace the forged and machined titanium leading-edge blades cover with 3D printed ones [70].

There are about 100 AM parts used for the air-cooling ducts in the Super Hornet jets [18]. Some parts of a system on Bell 429 helicopter were also produced using laser-sintering technology [56]. Bell is further planning to expand the use of laser-sintered parts to its other helicopters.

AM was used to fabricate a wing spar on the Lockheed Martin F-35 and the wing leading edge produced by GKN Aerospace for the Dassault Falcon 5X [71]. Dozens of brackets made from a titanium alloy using Electron Beam Melting by Lockheed Martin are already on-board the solar-powered Juno spacecraft, expected to arrive on Jupiter next year [68]. Lockheed Martin has set sights to employ 3D printing in other spacecraft programs. Some prototypes printed by them are the largest ever in aerospace industry, such as a 7-feet diameter forward bay cover for the Orion Multi-Purpose Crew Vehicle. A 3D printed Inconel pressure vent was used in the flight test of NASA's Orion capsule on 5th December 2014 [72]. To use AM, Lockheed Martin redesigned an antenna reflector from scratch and were able to reduce the antenna weight from 395 kg to 40 kg [72].

Boeing is also making use of 3D printing to fabricate plastic interior parts. The parts made from Ultem and nylon are mainly used for making prototypes and test coupons. It is also using this technology to fabricate tooling for producing composite parts [73].

PROJECTS IN EXTRA-TERRESTRIAL PRINTING

It is highly expensive to transport raw materials into space; for example, to ship one single brick to the moon would potentially cost USD 2 million [74]. Because of this high cost, both NASA and the European Space Agency (ESA) are trying to utilize the resources available on site (In-Situ Resource Utilization, ISRU). They are looking at respective regolith as the choice of construction material while on the moon or Mars. A separate research is being conducted by NASA and ESA for 3D printing structures on the moon and Mars. ESA is sponsoring D-Shape Technology while NASA is investigating the potential of a process called Contour Crafting.

The D-Shape technology is a system for 3D printing building or building blocks. The method allows printing entire building structures in-situ using regolith. The ultimate aim is for it to be used for building infrastructure on the moon [74, 75]. A preliminary feasibility study has shown promising results. This D-Shape technology could be further extended to Martian applications as it does not rely heavily on the base material used [75].

On the other hand, another construction technology is called Contour Crafting. Concrete is extruded through a computer guided nozzle, and thus helps fabricate components directly from computer models [74]. The nozzle flow is followed by a trowel, which smoothens the surface of the extrusion. A type of rapid-hardening cement is generally used as the build material. It requires very little time to acquire enough strength to be self-supporting. On the moon, the process can be easily adopted using locally available Sulphur as the binding agent instead of water.

System and Materials Research Consultant in Austin, Texas has been awarded a small grant by NASA to study the feasibility of 3D printing of food in space [58]. 3D printing food in space would help during long manned-missions. For example, during a manned-mission to Mars, the packed food would not survive the travel time. Using refrigerators to store food would require extremely high power consumptions. Besides, heavy packing of food for long distances reduces its nutritional value. Hence, 3D printing of food in space is a very important development for manned-missions into space.

CHALLENGES WITH 3D PRINTING IN SPACE

In Space, the feedstock used for 3D printing metals cannot be in the powder form, as it would float everywhere. Researchers at NASA's Langley Research Centre say that using Electron Beam Freeform Fabrication (EBF3) could solve this problem [58]. This technique uses an electron beam gun to melt two strands of wire into a 3D shape one layer at a time.

3D printing works by spraying thin layers of a material one-by-one that builds up to form a complete 3D part. But due to the little gravity in space, the material does not get held down, which results in unevenly thick layers of print [60]. Additionally, thermal issues could be tricky as the microgravity affects heat flow. While printing, this could potentially mean that the plastic parts will get either too hot or too cold, thus impacting the part quality.

FUTURE APPEARANCE OF AEROSPACE INDUSTRY WITH 3D PRINTING.

Nanocomposites are very attractive as materials because they combine the properties of nanomaterials as well as the host materials matrix [76]. Adding nanoparticles can improve mechanical properties, enhance electrical and thermal conductivity, decrease sintering temperature, and can have an impact on the dimensional accuracy [77]. One method to introduce nanomaterials in a 3D print object could be by having intermittent stoppages of the 3D print job and then adding the nanomaterials to the host matrix material either manually or automatically. The second method would be to pre-mix the nanomaterials with the host matrix and then 3D print using the mixture [76].

Areas where 3D printing could be adopted quickly would be unmanned air vehicles and experimental aircrafts, as these require the least regulatory scrutiny [71]. 3D printing could also be adopted in operational aircrafts still in service long after their production has stopped. The parts for such aircrafts are difficult to support, but with 3D printing, this is no longer a problem. For example, the cockpit of the Panavia Tornado is now equipped with protective covers on radio switches produced by 3D printers while a similar device makes support structures for cabin crew seats on the Airbus A310 [71].

Despite on-going intense research works, the adoption rate of AM in aerospace manufacturing industry is still slow. This can be attributed to a couple of reasons. The primary concern is the strict certification requirements that are inherent to the safety of air and space crafts. Testing and safety standards for AM in aerospace are still under development. Also, it is not easy to identify a set of certification rules given that different AM technologies are still on their way to being fully matured. Another reason for the slow AM adoption is the high energy demand; it is sometimes many folds greater than the traditional manufacturing. These issues need to be addressed before aerospace industry fully adopts AM.

But in general, AM is a promising proposition in terms of hard benefits as depicted in Figure 2.

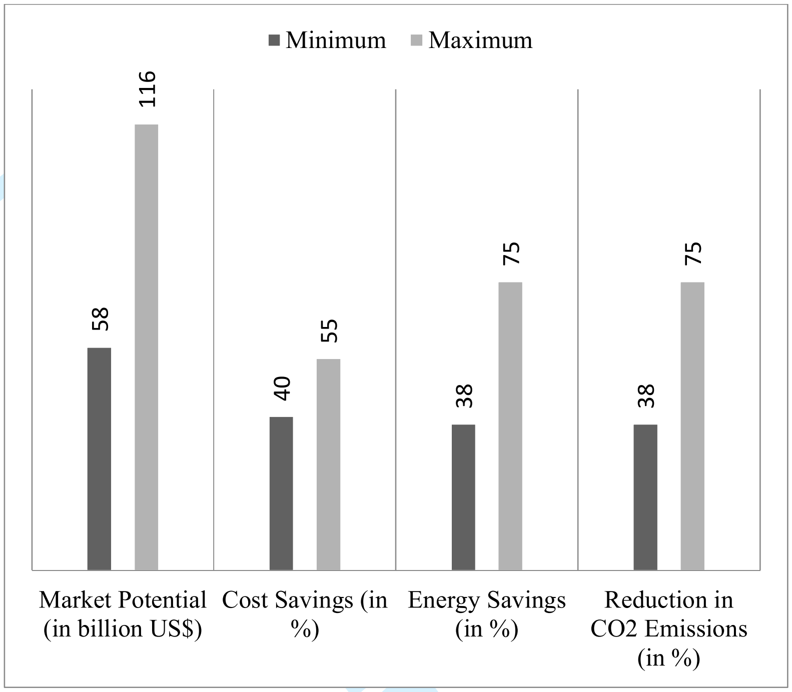

Figure 2: Projected Effects of 3D Printing in Aerospace Industry by 2025 [16].

CERTIFICATION ON THE AEROSPACE MARKET

The European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) are the organizations responsible for safety and environmental protection standards in civil aviation [24]. A joint committee was formed by ISO/TC 261 and ASTM F42 to identify a list of topic for AM standardization. A few of them are coordination of ISO 17296-1 and ASTM 52912 terminology standards, standard test artifacts, requirement for purchased AM parts and design guidelines among many others [78]. Some standards are already in circulation [e.g.79].

CONCLUDING REMARKS

3D printing is definitely revolutionizing the world of manufacturing, even in a most advanced and sophisticated industry like aerospace industry. This industry works around 2 basic principle requirements – low weight and high safety. 3D printing has been able to aid reduction in weight through complex and net shape manufacturing with less number of joints and intricate geometry. However, from the safety aspect, it is still a long way before being the reliable standard. Many challenges such as, printing patterns, porosity built-up, uneven print flow, etc. need to be solved and eliminated completely. It is just a matter of time. Once that happens, 3D printing would replace more and more traditional manufacturing techniques currently used in the aerospace industry and will definitely have a sustained adaptation and growth.

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