

PAPER • OPEN ACCESS

Metal additive manufacturing in aircraft: current application, opportunities and challenges

To cite this article: Xi Zhang and Enquan Liang 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **493** 012032

View the [article online](#) for updates and enhancements.

Metal additive manufacturing in aircraft: current application, opportunities and challenges

Xi Zhang * and Enquan Liang

Shanghai Aircraft Design and Research Institute, Shanghai, China

*Corresponding author e-mail: zhangxi@comac.cc

Abstract. Additive Manufacturing (AM) has huge advantages in prototyping and rapid manufacturing, also potentials in integrated design, cost and weight reduction, which are suitable for applications in aircraft. In recent years, aircraft manufactures as well as aviation authorities have made significant progress in Metal Additive Manufacturing components and structures, from materials and processes, to authority approval. Also, new AM technologies are still under rigid development, many of which have even more potentials than current favorite processes like selected laser melting (SLM), wire-arcing additive manufacturing (WAAM). However, as the first and overall requirement for aircraft, security level of AM components are still in question. Stability in mechanical properties, researches in fatigue and defect and issues in AM certification are major concerns for manufactures before AM technologies are really and widely used in aircraft design and manufacturing.

1. Introduction

Additive Manufacturing (AM)[1], or a public-friendly name, 3D printing, is challenging traditional industries with a revolution in full production life time, from design[2], prototyping, and even now mass production and quick repairing[3-5].

As for aircraft manufacturers, AM can shorten developing period for a new model, reduce weight and total cost for a single plane and increase economic efficiency and ECO performance. Metal Additive Manufacturing, referring to technologies using laser[6], electron beam[7], arcing[8] for metallic near-net-shape fabrications, are even more important for aircraft, since metals like aluminum, titanium are major components for most aircraft models.

This review shows current applications, introducing new opportunities as well as analyzing challenges for AM technologies in aircraft manufacturing industry.

2. Metal additive manufacturing in aircraft: current applications

Traditional metals that are widely used in aircraft is aluminium alloys as well as titanium alloys, due to their relatively low density, high resistance to fatigue and corrosion and high strength. The most popular material for AM processes is Titanium 6Al-4V alloy, which is already the most important titanium alloy in aviation industry. However, talking about metal additive manufacturing, due to the unfriendly nature of poor casting performance, aluminium alloys suitable for AM are still suffering from low strength and fatigue resistance [9-11].



Due to the safety regulations for aircraft, capability to fabricate full density metal structure is the priority consideration for the choice of AM processes. A lot of researches have been made on popular processes, like Selected Laser Melting (SLM), also named as Directly Metal Laser Sinter (DMLS), Electron Beam Melting (EBM), Wire-Arcing Additive Manufacturing (WAAM) are well studied, as well as commercially produced. Major machine suppliers and solution providers, like EOM, Renishaw, and GE Additive have developing a whole series of combines of different materials and machines. Some of the published mechanical properties of AMed Ti-6Al-4V are listed in Table 1.

Table 1. Mechanical Properties of Ti-6Al-4V additively manufactured.

Machine (Type)	Specimen Orientation	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Ref.
Arcam A1 (EBM)	XY	833 ± 22	783 ± 15	2.7 ± 0.4	[12]
	ZX	851 ± 19	812 ± 12	3.6 ± 0.9	
Arcam A2 (EBM)	Z	1011 ± 14.8	928 ± 13.3	13.6 ± 1.4	[13]
Arcam A2X (EBM)	XY	964 ± 0.3	851.8 ± 5.8	16.3 ± 0.8	[14]
Arcam S400 (EBM)	XY	917 ± 30.53	844 ± 21.6	8.8 ± 1.42	[15]
	Z	842 ± 13.84	782 ± 5.1	9.9 ± 1.02	
	Z	1237 ± 13	1098 ± 15	8.8 ± 0.6	[16]
EOS M280 (SLM)	ZX	1096 ± 7	1017 ± 7	12 ± 0.5	[17]
EOS M270 (SLM)	XY	1269 ± 9	1195 ± 19	5 ± 0.5	[18]
	ZX	1219 ± 20	1143 ± 30	4.89 ± 0.6	
Renishaw AM250 (SLM)	XZ	1143 ± 6	978 ± 5	11.8 ± 0.5	[19]
	ZX	1117 ± 3	967 ± 10	8.9 ± 0.4	
	XY	1199 ± 49	1075 ± 25	7.6 ± 0.5	
Casting	NA	≥ 871.8	≥ 772.2	≥ 5	[20]

Tests in Table 1 show that additive manufactured Ti-6Al-4V specimens generally have a better tensile performance in tensile properties than minimum requirement for those through casting. In aircraft industry, additive manufacturing, especially SLM, is considered to be one of the candidates replacing casting or wrought. Some of metal AM applications in certificated aircraft are listed below.

2.1. Boeing 787 structural components provided by Norsk Titanium

In 2017, Norsk Titanium AS reported their first delivery of Federal Aviation Administration (FAA) approved structural components for installation on the Boeing 787[21], which is also the first FAA-certified AM Ti-6Al-4V components [21]. Norsk Titanium uses a relatively new technology, the Rapid Plasma Deposition (RPD), which is believed to have better mechanical performance and less defects than other AM processes[22].

2.2. 3D printing fuel nozzles in GE9X Engine

In 2017, GE started certification testing plan for its newest high-bypass turbofan aircraft engine, GE9X [24]. Designed for Boeing 777X-8/9, the world's largest jet engine has shocked the industry with its 3D printing fuel nozzles[23]. Certificated by FAA in middle of 2015, this nozzle is only a part of GE's effort in bringing AM to jet engines. Reports shows GE is also pushing AM technology to its new turboprop engine and other models[23].



Figure 1. FAA-Certificated Ti-6Al-4V component made by Norsk Titanium (left), and the fuel nozzle of GE9X (right)

2.3. Airbus, APworks and scalmalloy

Different from Boeing, Airbus is focusing on high strength aluminium AM technology. Its subsidiary APWorks had announced an aluminium-scandium alloy Scalmalloy, providing a better strength-weight ratio than titanium alloys[25, 26]. APWorks is also playing the leading role in the industrial revolution of “Design for Additive Manufacturing”, concerning a full innovation from design to fabrication.

2.4. SAE standardization in AM specifications.

Among international specifications, Aerospace Material Specifications (AMS) issued by SAE international are the most important ones, admit by aviation authorities. SAE has been working for years on their AMS on AM technologies, that is, AMS 700X series. In June 2018, first four specifications were issued, as well as many others developed. SAE standardization in AM specification will have a huge pushing impact towards AM applications in aerospace and aviation.

3. Metal additive manufacturing in aircraft: opportunities

AM technologies are still improving, innovating and changing. There is no answer to “Which AM process is best for aircraft”. There is neither no definitive conclusion on “Which component cannot be fabricated by AM after all”. Researchers, aircraft manufacturer and authorities are all making effort on opportunities lies in the future of AM.

3.1. FAA additive manufacturing roadmap

FAA has been the leading force in applying AM into aircraft industry. They introduce a workshop towards AM parts every year since 2015 as a joint of FAA and U.S. Air Force[27]. Recently, FAA announced an eight-year roadmap for AM is under development, covering training and education, regulations and documentations, R&D plans and interagency communication[28]. This roadmap is believed to give guidance on AM non-standardized situation and its application on aircraft. Furthermore, the roadmap will set up examples on how authorities should approve and certificate AM parts.

Table 2. AMS specifications on AM.

Standards	Name	Status
AMS7000	Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion and Heat-Resistant, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed	Issued
AMS7001	Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb	Issued
AMS7002	Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts	Issued
AMS7003	Laser Powder Bed Fusion Process	Issued
AMS7004	Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate-Ti6Al4V-Stress Relieved	WIP
AMS7005	Plasma Arc Directed Energy Deposition Additive Manufacturing Process	WIP
AMS7006	Alloy 718 Powder	WIP
AMS7007	Electron Beam Powder Bed Fusion Process	WIP
AMS7008	Powder, Hastelloy X	WIP
AMS7009	Additive Manufacturing of Titanium 6Al4V with Laser-Wire Deposition - Annealed and Aged	WIP
AMS7010	Laser-Wire Directed Energy Deposition Additive Manufacturing Process	WIP
AMS7011	Additive Manufacturing of aerospace parts from T-6Al-4V using the Electron Beam powder bed fusion EB-PBF) process.	WIP
AMS7012	17-4PH Powder for Additive Manufacturing	WIP

3.2. *New technologies*

Technology is improving every day. Take Norsk Titanium AS mentioned above as an example, they choose RPD rather than popular SLM or WAAM. There is no perfect process now, opportunities and possibilities are still waiting for researchers. New materials and processes, like nanoparticle reinforced poudner[29-31], layered metal-polymer composites[32], micro-forging[33], are under robust development, and may one day be applied on a commercial aircraft.

3.3. *Trend of mass customization*

Aviation is changing. In 1950s, it is common that one manufacturer only provides limited models of aircraft. But nowadays, the need for customization is becoming more and more urgent, from capacity, weight, speed, engine options of a single model, to cabin arrangement, specialized decorations, or even military and business models. The cost and time advantages for AM parts are considered to be one of the best solutions to handle mass the upcoming mass customization trend.

4. **Metal additive manufacturing in aircraft: challenges**

Although in other industries like automobile, AM technologies has been applied much widely, in aircraft manufacturing however, things are different. Security is always the first red line for aviation. AM still has a long way to go before proved to be safe enough.

4.1. *Stability of mechanical properties*

In aircraft design and manufacturing, stability is the first requirement on mechanical properties. A material with fair but stable strength is considered much better than one with outstanding but fluctuating strength. In Table 1 for example, it can be seen UTS performance varies at most 20% for a particular combination of material and process, which is not acceptable for any approved part. Also, the anisotropy nature of AM decides the fluctuations of mechanical performance in different directions. Further works must be done before the stability of the mechanical properties of AM part fit the requirement of aviation authorities.

4.2. *Studies on defects and fatigue*

There is no AM technology that can promise a 100% building. Defects like porosity, voids, cracks and inclusions are still troubling the industry, limiting some crucial performances like fatigue. Though there have been a lot researching works on defects[34], fatigue[11, 35] and their relationships[16, 36], there is still no conclusion on inspection methods or acceptance standards of defected parts. Fatigue performance is the key item for a process to be applied on an aircraft, since it directly limits the flight life and possibility of failure for a single part.

4.3. *Approval and certification*

Any part that is installed on a commercial aircraft need to be approved and certificated by authorities like FAA, EASA. However, to get certificated, especially for the applications on bearing components or main structure of an aircraft, AM process needs much more testing items other than tensile and fatigue, like compress, rupture, shear, bearing, impact and creep, and all testing items need to fulfil number requirement to setup aircraft design allowable[37]. Anisotropic issue for AM also decides tests should be taken according to different directions, making the certification expense 2-3 times larger than those for traditional processes.

4.4. *Paradox between safety margin and weight reduction*

It is generally believed that mechanical properties for tested specimens do not always represent the performance of real components and structures. Process details for mass production cannot stay the same as those during specimen fabrication. To make things worse, mechanical properties of AM parts also varies according to dimensions of design and building scenario[38]. To promise the safety of components and structures, sufficient safety margin must be held beyond specification limits, especially for new technologies like AM. Though these margins are necessary and part of requirements by aviation regulations, they do add up to total weight of AM parts, reducing their potential in weight reduction. Further works need to be done to reduce minimum margin before fully liberate possibilities for AM materials and processes.

5. Conclusion

Metal additive manufacturing has been considered a new solution in the aim of weight, cost and time reductions for aircraft manufacturing industry. Main manufacturers like Boeing and Airbus, as well as main suppliers like GE aviation have made great progress according to their own plans; authorities like FAA have also put much efforts to bring the whole AM area into the world of aviation. International standardization organizations like SAE has been issuing aerospace specifications for AM materials and processes. With new technologies improved, AM is expected to anticipate much more in aircraft manufacturing. However, much more works is still needed to be done to improve production stability and understanding of every aspect of mechanical properties required by aircraft components before certificated by authorities. Future for AM is bright, yet the possibility is still beyond our imagination.

References

- [1] B. Mueller, Additive manufacturing technologies–Rapid prototyping to direct digital manufacturing, *Assembly Automation* 32(2) (2012).
- [2] D.W. Rosen, Computer-aided design for additive manufacturing of cellular structures, *Computer-Aided Design and Applications* 4(5) (2007) 585-594.
- [3] B.P. Conner, G.P. Manogharan, A.N. Martof, L.M. Rodomsky, C.M. Rodomsky, D.C. Jordan, J.W. Limperos, Making sense of 3-D printing: Creating a map of additive manufacturing products and services, *Additive Manufacturing* 1 (2014) 64-76.
- [4] V. Petrovic, J. Vicente Haro Gonzalez, O. Jordá Ferrando, J. Delgado Gordillo, J. Ramón Blasco Puchades, L. Portolés Griñan, Additive layered manufacturing: sectors of industrial application shown through case studies, *International Journal of Production Research* 49(4) (2011) 1061-1079.

- [5] S.J. Hu, Evolving paradigms of manufacturing: from mass production to mass customization and personalization, *Procedia CIRP* 7 (2013) 3-8.
- [6] D. Buchbinder, H. Schleifenbaum, S. Heidrich, W. Meiners, J. Bültmann, High power selective laser melting (HP SLM) of aluminum parts, *Physics Procedia* 12 (2011) 271-278.
- [7] L.E. Murr, S.M. Gaytan, D.A. Ramirez, E. Martinez, J. Hernandez, K.N. Amato, P.W. Shindo, F.R. Medina, R.B. Wicker, Metal fabrication by additive manufacturing using laser and electron beam melting technologies, *Journal of Materials Science & Technology* 28(1) (2012) 1-14.
- [8] D. Ding, Z. Pan, D. Cuiuri, H. Li, Wire-feed additive manufacturing of metal components: technologies, developments and future interests, *The International Journal of Advanced Manufacturing Technology* 81(1-4) (2015) 465-481.
- [9] N.T. Aboulkhair, N.M. Everitt, I. Maskery, I. Ashcroft, C. Tuck, Selective laser melting of aluminum alloys, *MRS Bulletin* 42(4) (2017) 311-319.
- [10] N. Kaufmann, M. Imran, T. Wischeropp, C. Emmelmann, S. Siddique, F. Walther, Influence of process parameters on the quality of aluminium alloy EN AW 7075 using selective laser melting (SLM), *Physics Procedia* 83 (2016) 918-926.
- [11] W. Reschtnik, J.-P. Brüggemann, M. Aydinöz, O. Grydin, K.-P. Hoyer, G. Kullmer, H. Richard, Fatigue crack growth behavior and mechanical properties of additively processed EN AW-7075 aluminium alloy, *Procedia Structural Integrity* 2 (2016) 3040-3048.
- [12] P. Edwards, A. O'conner, M. Ramulu, Electron beam additive manufacturing of titanium components: properties and performance, *Journal of Manufacturing Science and Engineering* 135(6) (2013) 061016.
- [13] [13] S. Lu, H. Tang, Y. Ning, N. Liu, D. StJohn, M. Qian, Microstructure and mechanical properties of long Ti-6Al-4V rods additively manufactured by selective electron beam melting out of a deep powder bed and the effect of subsequent hot isostatic pressing, *Metallurgical and Materials Transactions A* 46(9) (2015) 3824-3834.
- [14] X. Tan, Y. Kok, Y.J. Tan, M. Descoins, D. Mangelinck, S.B. Tor, K.F. Leong, C.K. Chua, Graded microstructure and mechanical properties of additive manufactured Ti-6Al-4V via electron beam melting, *Acta Materialia* 97 (2015) 1-16.
- [15] H.K. Rafi, N. Karthik, T.L. Starr, B.E. Stucker, Mechanical property evaluation of Ti-6Al-4V parts made using electron beam melting, *Proceedings of the Solid Freeform Fabrication Symposium*, 2012, pp. 526-535.
- [16] H. Gong, K. Rafi, H. Gu, G.J. Ram, T. Starr, B. Stucker, Influence of defects on mechanical properties of Ti-6Al-4 V components produced by selective laser melting and electron beam melting, *Materials & Design* 86 (2015) 545-554.
- [17] D. Greitemeier, C. Dalle Donne, F. Syassen, J. Eufinger, T. Melz, Effect of surface roughness on fatigue performance of additive manufactured Ti-6Al-4V, *Materials Science and Technology* 32(7) (2016) 629-634.
- [18] H. Rafi, N. Karthik, H. Gong, T.L. Starr, B.E. Stucker, Microstructures and mechanical properties of Ti6Al4V parts fabricated by selective laser melting and electron beam melting, *Journal of materials engineering and performance* 22(12) (2013) 3872-3883.
- [19] M. Simonelli, Y.Y. Tse, C. Tuck, Effect of the build orientation on the mechanical properties and fracture modes of SLM Ti-6Al-4V, *Materials Science and Engineering: A* 616 (2014) 1-11.
- [20] SAE, AMS 4992 (Rev.B): Casting, Structural Investment, Titanium Alloy 6Al - 4V, Hot Isostatically Pressed, 2014.
- [21] Norsk Titanium Delivers First FAA-Certified, Additive Manufactured Ti64 Structural Aviation Components. <http://www.norsktitanium.com/media/press/norsk-titanium-delivers-first-faa-certified-additive-manufactured-ti64-structural-aviation-components>.
- [22] F. Martina, J. Mehnen, S.W. Williams, P. Colegrove, F. Wang, Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V, *Journal of Materials Processing Technology* 212(6) (2012) 1377-1386.

- [23] GE9X, the Largest and Most 3D Printed Jet Engine Ever, Is Flying. <https://www.3dprintingmedia.network/ge9-largest-3d-printed-jet-engine-ever-now-flying/>.
- [24] Boeing 777X: Everything you need to know about the world's biggest passenger airliner. <https://www.ibtimes.co.uk/boeing-777x-everything-you-need-know-about-worlds-biggest-passenger-airliner-1557537>.
- [25] APWorks, Material Data Sheet - Scalmalloy®. http://www.apworks.de/en/wp-content/uploads/sites/2/2017/08/20170626_SCALMALLOY_REV0010.pdf, 2017.
- [26] APWorks, Scalmalloy® - APWorks (Product Page). <http://www.apworks.de/en/scalmalloy/>.
- [27] DOT/FAA/TC-16/15, Summary Report: Joint Federal Aviation Administration–Air Force Workshop on Qualification/Certification of Additively Manufactured Parts.
- [28] Research, Engineering and Development Advisory Committee (REDAC) Guidance on the FY 2019 Research and Development Portfolio. https://www.faa.gov/about/office_org/headquarters_offices/ang/office_s/tc/about/campus/faa_host/RDM/media/pdf/Guidance-FY2019.pdf.
- [29] B. AlMangour, D. Grzesiak, J.-M. Yang, Nanocrystalline TiC-reinforced H13 steel matrix nanocomposites fabricated by selective laser melting, *Materials & Design* 96 (2016) 150-161.
- [30] Q. Han, R. Setchi, S.L. Evans, Synthesis and characterisation of advanced ball-milled Al-Al₂O₃ nanocomposites for selective laser melting, *Powder Technology* 297 (2016) 183-192.
- [31] J.H. Martin, B.D. Yahata, J.M. Hundley, J.A. Mayer, T.A. Schaedler, T.M. Pollock, 3D printing of high-strength aluminium alloys, *Nature* 549(7672) (2017) 365.
- [32] R. Falck, S. Goushegir, J. dos Santos, S. Amancio-Filho, AddJoining: A novel additive manufacturing approach for layered metal-polymer hybrid structures, *Materials Letters* 217 (2018) 211-214.
- [33] X.-T. Luo, M.-L. Yao, N. Ma, M. Takahashi, C.-J. Li, Deposition behavior, microstructure and mechanical properties of an in-situ micro-forging assisted cold spray enabled additively manufactured Inconel 718 alloy, *Materials & Design* (2018).
- [34] S.A. Khairallah, A.T. Anderson, A. Rubenchik, W.E. King, Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones, *Acta Materialia* 108 (2016) 36-45.
- [35] S. Leuders, T. Lieneske, S. Lammers, T. Tröster, T. Niendorf, On the fatigue properties of metals manufactured by selective laser melting–The role of ductility, *Journal of Materials Research* 29(17) (2014) 1911-1919.
- [36] J.N.D. Ngnekou, Y. Nadot, G. Henaff, J. Nicolai, L. Ridosz, Influence of defect size on the fatigue resistance of AlSi10Mg alloy elaborated by selective laser melting (SLM), *Procedia Structural Integrity* 7 (2017) 75-83.
- [37] R.C. Rice, *Metallic Materials Properties Development and Standardization (MMPDS): Chapters 1-9*, National Technical Information Service 2003.
- [38] A. Yadollahi, N. Shamsaei, S.M. Thompson, D.W. Seely, Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel, *Materials Science and Engineering: A* 644 (2015) 171-183.