NordDesign 2016
August 10 – 12, 2016
Trondheim, Norway

Opportunities and Challenges for Additive Manufacturing in Space Applications

Christo Dordlofva, Angelica Lindwall, Peter Törlind

Product Innovation, Luleå University of Technology, Sweden
Christo.Dordlofva@ltu.se, Angelica.Lindwall@ltu.se, Peter.Torlind@ltu.se

Abstract

Additive Manufacturing (AM) is a fast developing manufacturing technology that brings many opportunities for the design teams at companies working with product development. One industry that has embraced this is aerospace, and more specifically within space applications (satellites and launchers). Although there are huge possibilities with this technology, there are also several challenges that need to be overcome. This paper is based on interviews, study visits and a state of the art review from the current literature. The focus of this work has been to map the opportunities and challenges with AM in space applications and to highlight the research gaps that have been found. There are few documents available that address AM and/or innovation within space applications. The results show that design for AM, as well as product and process qualification, are areas that need to be further investigated.

Keywords: *Additive manufacturing, design processes, qualification of components, DfAM, innovation*

1 Introduction

Additive manufacturing (AM) has been heavily promoted over the last few years because of the success of cheap 3D printers and the emerging Maker Movement. In industry, AM has mainly been used for prototyping in the early phases of product development. Now companies are starting to use metal-based AM for more regular production of components. Three main manufacturing methods exist for metals – powder bed, wire feed and powder feed. Powder bed has the advantage of better tolerances, better surface finish, and it can also create more complex geometries, while the deposition rate of wire feed is unparalleled. The unit cost for metal-based AM is often very high and the business case has to be carefully chosen to beat the cost of traditional manufacturing methods. A sector that seems to be most suitable for AM applications is the space industry, which involves high performance parts with complex designs, specialised materials and very small series (the European expendable launch vehicle Ariane 5 has had roughly 80 launches in 20 years). With AM it is possible to introduce new optimised designs for increased functional performance (using geometries impossible to achieve with traditional manufacturing methods), short lead-times from concept to final product and independence from expensive castings. This paper highlights the opportunities for using AM in space applications and also points out challenges for engineering design research. The results given by this paper will give a direction for future research for design, innovation and qualification for AM within space applications. The paper is based on interviews with both manufacturers of AM machines, designers developing rocket engines and a state of the art review. These investigations result in a summary of the opportunities and challenges for AM that could emerge within space applications. Firstly, the method of the conducted research is presented in order to structure the information gathering. Later the state of the art and state of practice for AM are explained before the opportunities and challenges that come with AM are explored. Finally, the conclusions are presented, which target future research that needs to be conducted.

2 Method

The research has been performed in collaboration with GKN Aerospace and one of the authors is situated at GKN as an industrial PhD student and has several years of experience in design of space systems. The focus of the literature study has been on finding state of the art and state of practice of AM, specifically for space application.

The empirical data gathered in this project is based on interviews and visits to manufacturers of AM equipment and companies that use AM in their product development process. The interviews have been focused on identifying current design processes (focusing on rocket engine sub-components) and how AM can change this process. From the empirical data, opportunities and challenges have been identified, these findings have been presented to experts at the company in order to receive feedback and to ensure that the analysis is consistent with perceived problems, opportunities and existing processes.

Systematic literature studies have been conducted to investigate the current situation for AM within space applications with a focus on product design and innovation. The studies are limited to articles and conference papers. The literature study process is made through four steps: Identifying keywords, Screening, Filtering and Analysis of the document. Firstly the keywords are identified within the area of the study. In this case the keywords *Additive Manufacturing*, *Layered Manufacturing* and *Rapid Manufacturing* are at the centre of each search. Then a second keyword is added in order to direct the results towards documents that are of interest in this study. Examples of those keywords are *Product Development Process*, *Design Process*, *Challenges*, *Opportunities*, *Space*, *Space Applications*, *Qualification*, *Innovation* and *Design*. The search has been mainly made in Scopus.

The results are then screened through looking at the title of each document, if the title is within another area than preferred then the document is discarded from the study. In order to filter the results and to capture the relevant references, each document is investigated. Firstly the abstract is read, and if the document seems fit for the study then the results and discussion are read. If the document is still interesting for the study, the entire document is read and analysed.

3 State of the Art for Additive Manufacturing in Space Applications

AM is a layer-upon-layer manufacturing method where a 3D CAD model is sliced into 2D layers that together produce a physical 3D model. The technology of AM has successfully been developed over the past 30 years, where the first machines were mainly used to rapidly produce prototypes (Gibson et al, 2015). Rapid prototyping still remains the main application for AM processes within polymer materials (Mellor S. et al, 2013) but within metallic AM the models are nowadays often used as an end-use part (Vayre et al., 2012).

Within space applications there seems to be a main focus on two AM processes: *Powder Bed Technologies* and *Deposition Technologies*. An overview of different AM methods suitable for space applications is shown in Figure 1.

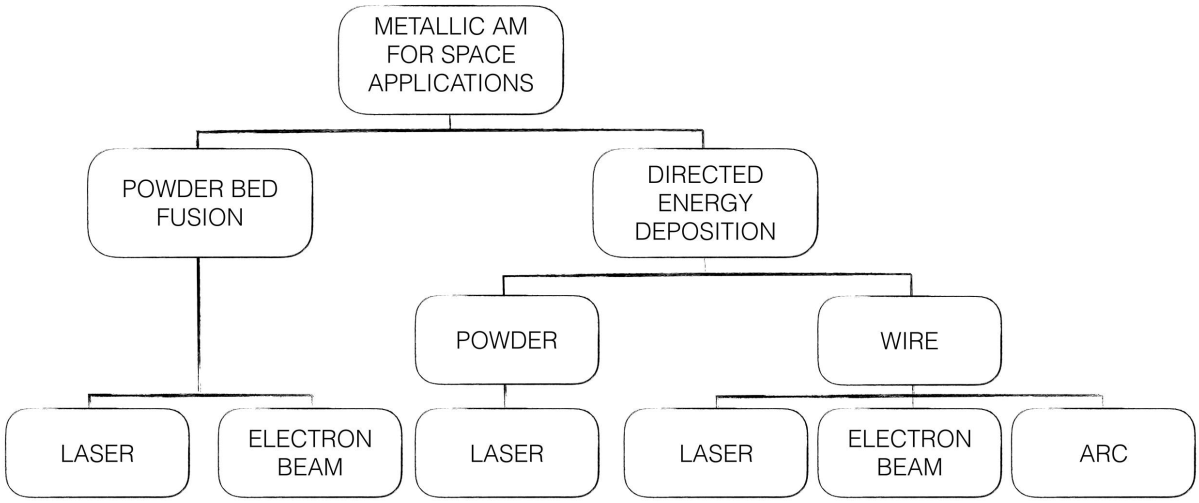

Figure 1. Overview of additive manufacturing methods for space applications

Uriondo et al. (2015) have made a review of the future of AM technologies in the aerospace sector. Their conclusion was that Powder Bed Fusion (PBF) and Directed Energy Deposition (DED) are the processes that are currently most suitable for the aerospace industry. Within PBF technologies they identified Electron Beam Melting (EBM) and Selective Laser Melting or Sintering (SLM/SLS). Within DED the technologies are Laser Metal Deposition (LMD) for powder and wire, and Wire and Arc Additive Manufacturing (WAAM). For space applications, and especially rocket engine applications, the most commonly used processes belong to the PBF category.

PBF is a method where powdered materials are applied on a platform, layer by layer. Then a thermal energy source induces fusion between the powder particles, where a controlling mechanism steers the fusion to a prescribed area of each layer. A rake or roller controls the adding and smoothing of the powder layers. As indicated, there are different fusion technologies, but the most common is laser (Gibson et al., 2015). Within the DED technologies there are the wire and powder processes where both have a fusion technology for building the part. The powder deposition uses a laser technology while wire deposition can use laser, electron beam or arc (plasma or gas) technology (Ding et al., 2015).

3.1 State of Practice for Additive Manufacturing

AM for metallic materials is highly protected by patents and trademarks and different technologies are often unique to each manufacturer (e.g. powder bed using electron beam is only used by Arcam AB). For aerospace the number of applications are rapidly increasing and some examples of current implementations are the 3D printed bionic partition for Airbus A320, manufactured using direct metal laser sintering in Scalmalloy (3Ders.org, 2015). The partition is not only stronger than the existing model, but also about 25 kg lighter. Perhaps the most well-known aerospace application is the fuel nozzle designed by GE Aviation for the LEAP engine, planned to be produced in quantities of 30,000 parts per year. The specifically AM-designed fuel nozzle will have intricate solutions such as internal cooling channels and will combine 18 parts into 1 while reducing the weight of the part by 25% (Wohlers Report, 2015). For space applications there are fewer reports of implementations, however several secondary structures and demonstrators have recently been evaluated. Examples include the Main Oxidizer Valve (MOV) body in one of the nine Merlin 1D engines in the Falcon 9 rocket launched by SpaceX. The mission marked the first time SpaceX had ever flown a 3D-printed part (SpaceX, 2014). NASA (2015) demonstrated a SLM printed breadboard engine (where all parts are connected so that they work the same as they do in a real engine but not packaged together in a flight configuration) in December 2015. GKN Aerospace in Sweden (formerly Volvo Aero) has manufactured and proven a nozzle extension demonstrator for a possible upgrade of the Vulcain 2 engine (used on the Ariane 5 launch vehicle). LMD using wire as material feed was used to produce 3D features on the outside of the nozzle wall with the intention of structural strengthening and producing weld preparation areas. The complete nozzle was eventually tested and proven in a full-scale demonstrator engine test (Honoré et al., 2012).

3.2 Current Design and Manufacturing Processes

Many rocket engine parts today are manufactured using traditional processes such as casting, with subsequent machining and finishing. Once the detailed product design is set by the design team responsible, a 3D CAD-model is communicated to the material supplier (the foundry in the case of casting) and an iteration loop is started between the design team and the supplier to make minor changes to improve the producibility (often including casting trials and/or process simulation). When a final design is agreed, a first article is produced for verification, usually through a cut-up including material testing and microstructure evaluation. Gating and feeding systems are often problematic to design and there are usually several iterations until an acceptable process is found. Once the article is approved, the first batch for part testing is made, and even at this point there is usually additional rework (grinding and welding) needed for defects found using non-destructive testing (NDT). Due to the long lead-time involved, it is not uncommon that the first batch is produced simultaneously with the first article used for verification (cut-up). This means that if process difficulties are not captured in process simulation or casting trials, finished parts might become useless if a problem comes up at a late stage, bringing about additional costs. Furthermore, late updates in load specifications from the end customer might also lead to already-produced castings becoming useless. In the case of casted products, the casting process is characterised by long lead-times, 10-12 months is not unusual for aerospace applications, just for the casting. A typical design and manufacturing process is pictured in Figure 2.

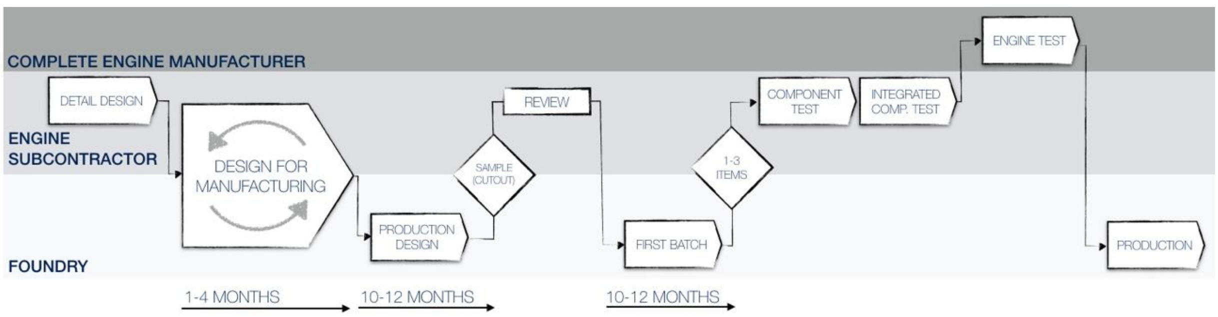

Figure 2. Overview of a general casting process.

Apart from the long lead-time when dealing with casting suppliers, the low series of production in the space industry (e.g. 6-10 parts per year) might be a disadvantage when looking for suppliers. The business case is normally small in comparison with e.g. the automotive industry, or even civil aerospace, leading to expensive castings.

The casting process is well established with standards and specifications setting the minimum requirements for acceptance of products and materials. The process parameters are known and some simulation models also take microstructure, residual stress and phase transformations into account. Once the part-specific casting process has been shown to fulfil the requirements set by the customer (who has responsibility for the design), the process is frozen. Ideally it then gives similar results for each subsequent batch (with small variations), but there is usually still a need for rework after NDT.

4 Opportunities and Challenges

AM in general has huge potential – it is possible to control the distribution of materials within objects with a high degree of precision (Hiller & Lipson, 2009) which leads to the possibility of improving performance and also adding new functionality (Hammetter et al., 2013). However, the potential benefits aside, AM for metallic materials is still evolving, and there are still challenges to overcome. In fact, the biggest hurdle to implementation of AM into “main stream manufacturing” is quality and consistency (Yeong, 2013). The following sections highlight the identified opportunities and challenges with AM in general but also specifically for space applications.

4.1 Opportunities

There are four main reasons to use AM: customise products for the requirements of individuals; improve product functionality with adoption of complex geometries; reduce part numbers through consolidation; increase the value to the customer with specific design features (Campbell et al., 2012). Many products that are available today are an assembly of several parts and are often divided into more parts than necessary due to manufacturing methods (Yang et al., 2015). When using AM instead of traditional manufacturing methods there is a greater possibility to merge these parts into more complex parts and assemblies which could reduce the time for the manufacturing process.

Aerospace, and more specifically space, is one industry that could benefit from introducing AM into the production process. The space industry is characterised by complex products in low volumes which is an ideal match for AM (Gibson et al., 2015). It gives the opportunity to optimise product design for increased functionality - internal cooling solutions that are not feasible with traditional manufacturing methods and part consolidation are some examples. Weight has always been a driver in space applications due to cost and practical reasons. Lower launcher weight will ultimately allow for increased payload weight and increased value for each launch. The estimated cost for each kg into orbit is in the order of $10,000. Light-weight materials, such as titanium, are available for AM and more net-shaped, weight-optimised products can be produced. Furthermore, traditional manufacturing processes such as casting are characterised by long lead-times (4-12 months, as mentioned above). AM has the potential to both substantially decrease the lead-time (3-6 weeks), and possibly (if desired) move manufacturing in-house. An example of this is from SpaceX development of the engine chamber for the Super Draco launch escape system. The chamber, printed in Inconel, resulted in an order of magnitude reduction in lead-time compared with traditional machining – the path from the initial concept to the first hotfire was just over three months (SpaceX, 2014). Another example is Lockheed Martin Space Systems in the U.S.A. which has used the Sciaky electron beam wire system (EBAM®) to manufacture a satellite propellant tank in titanium, consisting of two hemispherical halves of roughly 150 cm in diameter. Allegedly, product cost could be reduced by 55% and total manufacturing time by as much as 80% using the EBAM process. The tank has not been used in service yet, but Lockheed Martin sees the process to be a viable option in the future (Lockheed Martin, 2015; Sciaky, 2016). New actors in the space industry are also changing the industry in a disruptive way, *"Traditionally space applications had an extreme focus on weight and performance, but today the emergence of new actors in the market (e.g. SpaceX) has driven the focus towards competitiveness in cost"* (senior project leader at engine sub-component development). AM gives opportunities to decrease cost since the need for expensive tooling is removed and the possibility to make late changes in the design is added (without changing an already set manufacturing process) (Gibson et al., 2015). Both Cronskär M. et al. (2013) and Baumers M. et al. (2016) also state that AM technology will enable reduced unit cost, especially for low and medium production scale (Mellor et al., 2014).

4.2 Challenges

The AM processes, as they are today, show a variation in the printed products, which can be seen on a part-to-part basis as well as machine-to-machine (Frazier, 2014). It is vital to understand this process variation, since it could otherwise be a limiting factor in the use of AM in mission critical components (Seifi et al., 2016). Parameters such as internal defects, surface roughness and geometry tolerance are all important to master. For example, to be able to utilise the design freedom enabling complex shapes within aerospace, one driver is to use "as deposited" surfaces (Seifi et al., 2016). This however sets requirements on what surface roughness is acceptable from a fatigue resistance perspective (risk of crack initiation due to rough surface structure) and possibly a functional perspective for internal flow surfaces. Process control, material characterisation, part inspection through NDT and post-processing are areas that need development for qualification of AM (Uriondo et al., 2015). The design freedom increases with AM since the designer is able to to create geometries that have not been feasible with traditional manufacturing methods. However, this also means that the designer has to adapt to the AM process and take new factors into account in the design process, i.e. Design for Additive Manufacturing (DfAM) (Yang & Zhao, 2015). Part orientation, support structure, topology optimisation and multi-functional features for increased performance are some examples of design aspects that need to be included (Gibson et al., 2015; Vayre et al., 2012). However, it is hard for the designer to take full advantage of the AM capabilities due to the new design framework (Yang & Zhao, 2015).

4.2.1 Design for Additive Manufacturing

It might be hard for the designer to take in all the possibilities of the design freedom that AM comes with, and one challenge is to identify the parts and assemblies with which AM can bring value to the customer (Klahn et al., 2015). AM can often be more expensive per part compared to traditional manufacturing methods if printed in a higher volume, but parts in a low volume are often less expensive (Mellor et al., 2014). Therefore, many designers see several areas where customised products have potential. It is necessary to understand when the use of AM is beneficial from both a cost and geometrical perspective.

There are several different approaches available for DfAM but, as yet, none of them have been deeply investigated yet. Emmelmann et al. (2011), Gao et al. (2015) and Gibson et al. (2015) state that the designer is limited to the CAD tools and the holistic design guidelines available. The possibilities of today's CAD systems for AM usage are not ideal due to the limitations the solid-modelling-based systems have (Gibson et al., 2015). Yang & Zhao (2015) state that CAD systems have difficulties in precise geometric modelling and have problems with complex constraints and modelling information. This might also affect the possibilities of using CAD systems for AM. Klahn et al. (2015) propose that there are two types natures of design strategies. The first one is manufacturing driven which gives the designer the option to be cautious and design for any manufacturing method. This makes it easy to use AM as a confirmation method, where the product is tested on a customer base and altered into the perfect shape before the selection of all manufacturing methods in relation to cost per part. The second one is function driven where the designer uses any shape possible for AM in order to optimise the function of the product. This could be seen as a more insecure approach where there is only one manufacturing method available for the design. Yang & Zhao (2015) propose that to find an optimal design, a new method should be developed from an upstream point of view where the first step is to optimise the existing part. However, there is also a need to find a method for optimal design while designing a new product.

4.2.2 Qualification

Qualification and verification of AM materials and products is a topic subject to intensive research by universities and industry, and there is still a need for technology development in this field. Ways of qualifying the processes need to be found (Frazier, 2014) in the establishment of sufficient TRL-levels (Mankins, 1995). It is not possible to use conventional NDT methods due to the characteristics of the material (internal and at surface) (Uriondo et al., 2015). Furthermore, the conventional qualification processes for metallic materials require extensive testing that may take up to 15 years and considerable amounts of money, and are not suitable for variable processes like AM (Seifi et al., 2016). Therefore, alternative methods need to be developed to be able to qualify AM if it is to be applied as a “de facto” manufacturing process in the industry in the coming years. Standards are being developed (e.g. ISO/ASTM) but are not yet available for the qualification requirements on parts (Monzón et al., 2015).

To be able to qualify AM products and also to establish AM technology as a competitive manufacturing process, there is a need for in-process control systems (Frazier, 2014). The nature of the layer-by-layer process makes it possible to inspect each of the layers while they are created. In this way, defects could be identified while the part is being built, and product quality assured in-situ. The machine manufacturers have understood this need and several systems are under development. Some examples are Concept Laser (QM meltpool 3D), Arcam (LayerQam) and EOS (EOState) (Everton et al., 2016). Simulation of the AM process is also still quite rudimentary but is an important step towards understanding and qualifying the process (Gockel et al., 2014; Martukanitz et al., 2014).

AM is a process where the material is “created” in the process getting properties that are linked to the thermal environment in the building process. E.g. cooling rate and temperature history has a direct connection with the achieved microstructure (Gu et al., 2012; Murr, 2014). Although a challenge, since this means that the new material has to be characterised, it also brings about opportunities. Mastering the process and understanding the microstructure would mean that it is possible to adapt the material characteristics within the build towards the part’s geometry and function. Furthermore, new alloys can be created that are specifically developed for AM (Seifi et al., 2016).

Yeong et al. (2013) have suggested a quality management framework for implementing AM into the biomedical industry. The framework highlights the deficiencies of AM and suggests activities throughout the industrial chain for assuring product and process quality. Although being suggested for biomedical use, the principles are the same for other industries with high demands on product quality. The essence is that the complete industrial chain is involved in assuring product and process quality, from the generation of the STL file to understanding the product requirements and verifying process and material characteristics.

5 Conclusions and Discussion

Traditionally space component development has focused on performance and robustness, often developed in large international consortiums with governmental support. The product development process is very detailed and complex because of all the stakeholders involved. With the introduction of new commercial players there has been a radical shift to innovation, rapid iteration and cost. Traditionally, many details of rocket engines have been developed for casting or other conventional processes, with subsequent machining where the manufacturing time from finished geometry of the first component can be more than six months. Therefore, components are developed incrementally; designers do not dare to introduce radical new solutions.

This paper has identified several opportunities and challenges that are of importance for future research. AM in general has huge potential – it is technically possible to produce components with varying stiffness (by altering the internal structure of the component), build anisotropic components or mix materials in a solid component (for certain AM processes). Also, compared to traditional processes the manufacturing of a single component can be reduced from 6 months to less than a week. This could give the opportunity to create a more explorative iterative design cycle and explore more radical design solutions.

AM also introduces challenges, firstly the whole product development process is affected. Design for Additive Manufacturing is a complex approach due to the few design tools and CAD packages that exist for AM. There are few support tools and methods that help the engineers to adopt AM in the design process. Traditional CAD tools are designed for conventional manufacturing methods such as drilling and lathing (features like holes/pockets/ etc). This forces the engineer into design in a traditional way, instead of encouraging the wider geometrical possibilities that AM brings. A new tool should fit the new possibilities and encourage engineers (especially engineers who are inexperienced with AM) to think in an AM perspective. In a proposed CAE system the engineer could design in a top-down approach, describing functional requirements (e.g. interfaces, cooling, embedded electronics, structural requirements) and let the system perform topology optimisation (similar to existing FE programs for structural topology optimisation). There is also little experience of AM within companies, which results in a more cautious approach as regards embracing new solutions with low TRL. These uncertainties can both lead to a longer design process and a lower level of innovation within companies and processes.

Qualification is another important area for space applications – products should not fail. Traditionally design simulations are verified and complemented with empirical testing of both material and products. This would be time consuming and imply large costs for the qualification of each AM process and machine. Therefore, it is a great challenge to develop simulation models for the manufacturing process in order to understand how process parameters influence the final products. Also the verification and qualification processes need to be assessed and developed for AM.

Future work includes more detailed studies of the current design and qualification processes, and also how design and qualification processes have been implemented when introducing new manufacturing methods. A broad perspective needs to be taken to understand how the product development process as such will change to allow for new innovative designs and solutions. Several breakthroughs in AM for space applications have been reported in news channels (NASA, 2015; SpaceX, 2014; 3Ders.org, 2015) but cannot yet be found in research papers. Also the literature studies indicate a lack of research regarding both additive manufacturing and innovation within space applications, which gives a clear indication of where further investigations and research should be conducted.

Acknowledgement

The work presented in this paper is a collaboration between GKN Aerospace and Luleå University of Technology. The work is part of the RIT project (Space for Innovation and Growth), funded by the European Regional Development Fund. The Swedish National Space Board is also involved through NRFP, Swedish National Space Research Programme.

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