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Additive Manufacturing Technologies in the Aviation Industry in Pursuit of Weight Optimization

Digitalization is an important evolution for the aviation industry. Implementation into the new technologies has many benefits such as reducing a company's overall costs and increasing revenue. In this manner, the report "Digital Transformation Monitor, Industry 4.0 in Aeronautics: IoT Applications" was released in June 2017 by the European Commission. In accordance with the mentioned report, in the aviation industry, the expected impact of digitalization is a reduction of - 3.7% in costs and an increase of + 2.7% in revenue annually (EC, 2017). Emphasizing the huge budgets of the aviation industry these percentages mean a lot in the name of savings. So, it can be said that digitalization is rapidly impacting the manufacturing world in the aviation industry and it will continue do so.

Regarding the International Civil Aviation Organization (ICAO) "2016 capacity and efficiency report" air traffic has doubled in size once every 15 years since 1977 and will continue with this trend in the future (ICAO, 2016). Also, the International Air Transport Association (IATA) declares that 8.2 Billion people will fly in 2037, which means that there's an increasing demand from customers to fly more frequently on a global level (IATA, 2019).

This customer demand will force the aviation industry to increase their budgets. As it was mentioned before, aviation grade materials are manufactured by using highly engineered techniques, hence these materials are generally not cheap. The issue of reducing wastage and decreasing the scrap ratio is crucial. Consequently, lower wastage and lower scrap ratios are essential for fierce competition. Traditional CNC machining processes are subtractive techniques, and the material wastage could be as high as 98% (Allen, 2006).

When we talk about waste, the term "Buy to fly ratio" must be known and understood. Buy to fly ratio is a term used in the aviation community, referring to the weight ratio between a finished component and the original raw material. The parts manufactured by traditional methods normally have buy to fly ratios at around 15-20 (Arcam, 2019). With AM technologies, the buy-to-fly ratio can be as low as 1:1. (Barz A., 2016). For example, with the Lockheed Martin engine bleed air leak detector bracket, the buy-to-fly ratio is reduced to 1:1 based on an electron beam melting method, as against the 33:1 ratio possible by traditional subtractive methods, leading to an overall 50% savings in the cost of the titanium alloy (Dehoff R, 2013).

Besides, scraps can be as low as 10%, part cost reductions can be as low as 50%, time-to-market can be as low as 64%, part weight reductions can be as low as 64% compared with traditional machining process (Deloitte, 2014).

These benefits make the additive manufacturing technologies unbeatable in the aviation industry. Since aviation grade materials are expensive, companies in the aircraft industry are under constant pressure to reduce wastage and develop manufacturing techniques that produce parts in near net shape (Alberto Garcia-Colomo, 2019). Additive manufacturing is a novel and disruptive technology which opens new windows in areas of weight reduction which is essential for the aviation industry. Additive Manufacturing Technologies are changing the paradigm of manufacturing techniques in the aviation industry.

The categorization of additive manufacturing techniques

AM techniques based on the conversion of three-dimensional geometries into simple two-dimensional layers and manufacturing them by using direct digital manufacturing (DDM) methods. It is possible to manufacture complex parts which may be too difficult or even impossible to produce by using conventional subtractive techniques such as turning and milling machines.

The additive manufacturing is accepted as a revolution in the manufacturing world. It has been extensively engineered and it enables the production of complex parts in a net shape. Including the assembled parts, the flexibility of additive manufacturing is expanding the boundaries of production.

A standard has been released by the American Society for Testing and Materials (ASTM) for categorizing AM techniques which is called "Standard Terminology for Additive Manufacturing Technologies, Designation: F2792 − 12a" (ASTM, 2013). This standard mainly classifies the AM techniques in 7 categories as binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photo-polymerization. It is worth noting that each additive manufacturing process has its own unique specifications as it is represented in Table 1. The materials differ from one AM technique to the other one. For example, wax-like materials can be processed with material jetting and binder jetting. Metals such as nickel-based alloys and aluminum can be processed with directed energy deposition. Thermoplastic filaments can be processed with Material Extrusion. With powder bed fusion, polymers, maraging steel, stainless steel 316 L, 15-5PH, 17-4PH, nickel-based superalloys, Inconel 718, Inconel 625, Hastelloy X, Titanium TA6V, chrome-cobalt, aluminum ALSi10Mg can be used as raw materials. Adhesive coated papers, metal tapes and foils, plastic sheet material can be processed with sheet lamination and light curable resin and photopolymers can be processed with Vat Photo-polymerization.

The material selection is based on the customer requirements and there are some hybrid methods as well.

Conventional methods prior to additive manufacturing

Aviation is a highly engineered industry with strict manufacturing requirements. The materials used in the aviation industry are complex and high-tech matrix materials. As such, generally even one chip left after a machining process has a valuable price. Because of its high-tech requirements, aviation has been forced to become a pioneer for the implementation of novel manufacturing techniques and newly developed materials. For example, Computer Aided Design-Computer Aided Manufacturing (CAD-CAM), and carbon fiber composites were initially adopted by the aviation industry (Stratasys, 2017).

On the other hand, as a disruptive and innovative technology additive manufacturing is rapidly impacting the manufacturing world. Additive manufacturing can be seen as the "Great Renaissance" of industry, with its no tooling, no cutting, no heat affected zone (HAZ) and relatively less wastage and less scraps comparing with subtractive manufacturing technologies.

It is worth emphasizing that there are four main types of manufacturing. First are the subtractive and chip-away techniques like milling and turning. Humankind is very familiar with subtractive technologies since the producing of chipped-stone tools like axes, cleavers etc. Because voluminous metal parts are designed for CNC machining operations, the traditional machining processes such as milling and turning are still in the aviation industry.

The second is the forming process which a block or sheet that is formed by force. The forming process starts with a block or sheet of material, but this time a force is applied in order to shape the block or sheets. Forging, sheet metal forming, rubber-pad forming are the typical forming processes.

The third one is casting. In this process a raw material which is in solid form is transformed to liquid, generally by applying heat. Then the liquid material is poured into a shaping device which is called a mold.

Additive manufacturing technologies are changing the paradigm in the aviation industry

Airplanes can only fly with airworthy and airborne parts. Airworthy part certification is granted by airworthiness authorities only. Because of the design freedom upon complex parts available with AM techniques of the airworthy parts which are used on the airplanes are perfect applications (Matthew Tomlin, 2011).

Additive manufacturing gives advantages of weight reduction and process time savings. For example as an iconic part, the Leading Edge Aviation Propulsion (LEAP) fuel nozzle which was manufactured by GE was made combining 20 parts into one, manufactured in a single machine and weighed 25% less than the conventionally produced (3dprintingmedia, 2019). It is reported that these nozzles are 5 times more durable than those were manufactured by using legacy manufacturing technologies such as milling and turning processes (GE, 2019). Until now approximately 35.000 nozzles have been manufactured and it is announced by GE sources that the total number of manufactured nozzles will be around 40.000 by 2020 (Gorelik, 2019). The mentioned nozzles are used in CFM 56 engine. These engines are powering the almost the half of the Boeing 737 and Airbus A320 family. In other words, since the Boeing 737 and / or Airbus A320 are widely used in the fleets, in recent years many airplanes are flown with an additively manufactured fuel nozzle. It is worth emphasizing that the additively manufactured airworthy parts are penetrating into the aviation industry rapidly.

The Structure of Additive Manufacturing Process

Additive manufacturing technologies are allowing the manufacturers to go from CAD file to end-part. While using AM techniques, the core of the whole process is creating a CAD model. The CAD model, initiates the whole process (Liou, 2007). In Figure 6, the CAD model (as an initiator) and the following steps of AM process are shown in consecutive steps.

The AM Technologies require a solid CAD model of the part or assembly to be produced, the companies had to introduce solid modeling systems for creating the CAD files into the production process. CAD model is always ready for to be manipulated for fine-tuning. STL file can be described as “triangle-mesh” of a solid CAD design. Each triangle consists of 3 vertices and 1 normal. A CAD file differs from STL file in several ways. A CAD file is defined by it parameters whereas an STL file is defined by triangles made of vertices and normals. A CAD file therefore is more precise while an STL file is more or less a lose approximation of the original design. Since CAD files are focused on traditional manufacturing it does not include any information about inside or outside of the part to be produced while an STL file does contain this crucial information (Materialise, 2019).

Later on STL file is converted for layer-by-layer manufacturing technique. After manufacturing sometimes post-process activities may be required for having precise surface and heat treatments etc. The one of the main subject must be emphasizing that during these steps there's no support tooling and there's no fixtures either.

The weight reduction studies using additive manufacturing applications

While reducing the weight of a part, maintaining the same mechanical features as its traditionally produced predecessors is vital. Additive manufacturing is relatively new technology in the aviation industry comparing with traditional manufacturing techniques. ICAO as an airworthiness authority, takes attention for emerging technologies may impact the aviation safety negatively (ICAO, 2018).

Redesign is the core of weight reduction etudes, such as GE's nozzle which was mentioned previously. Redesigning of the nozzle gave chances to reduce operational man and machine hours and simplifying the manufacturing process, thanks to AM techniques (Mélanie Despeisse, 2015). Another redesigning project is the "SAVING" project. By redesigning the seat buckles using AM techniques, the "SAVING" project elucidated that 55% weight reduction is possible compared with original design. Weight reduction was almost a total 72,5 kg can be saved if all the seat buckles of the Airbus 380 which 853 seats were to adopt the optimum designs, amounting to 3.3 million liters of fuel savings over the service life of the aircraft.

Reportedly, total saving is $3 million while the cost of making the buckles using Direct Metal Laser Sintering (DMLS) is only $256,000 ((Sarat Singamneni, 2019), (B. Dutta, 2017)).

The reduction of one kg built-in aircraft weight is able to reduce carbon emissions by 0.94 kg for the case of the Boeing 747-400 whose Maximum-Take-Off-Weight (MTOW) is 396,890 kg and by 0.475 kg in the Airbus A330-300 whose MTOW is 242,000 kg.

(Wen-Hsien Tsai, 2014). The lighter aircraft means less carbon footprint. At the conclusion, the weight, the carbon emissions, the fuel consumption, and the operational cost are interrelated with each other. e.g., reducing one pound of weight from each aircraft in American Airlines' fleet could save about 11,000 gallons of fuel annually (Lyons, 2011).

Thanks to AM and TO studies, European Aeronautic Defense and Space Company (EADS) redesigned the nacelle hinge brackets of Airbus A320 the brackets weight saved up to 64% while keeping the mechanical features satisfactory (Weihong Zhang, 2016).

Besides weight reduction AM technologies are always-ready for maintenance periods in Part 145 certified shops. That's why there are collaborations in the aviation maintenance, repair, and overhaul (MRO) area. During MRO stages aircrafts don't fly and whenever an aircraft is not flying, it means wasting money for airline companies. Aircraft-On-the-Ground (AoG) is an unwanted situation as it is said "aircraft in the sky makes money, aircraft on the ground takes money". Airbus China estimated that a grounded A380 Airbus costs $1,250,000 every day; and when you consider the implications of this for an entire fleet, the scale of the issue is significant (itproportal, 2019). For shortening the ground-time and preventing waste of money, there are some collaborations in the MRO field. e.g. Etihad Airways Engineering, which is the largest aircraft MRO services provider in the Middle East and EOS which is a leading innovation supplier in the field of industrial AM have agreed on a strategic partnership which is a significant mutual relation (EOS, 2019). Shortening the maintenance intervals is a target and in the MRO area, and some other collaborations are underway such as the collaboration between Emirates Engineering and 3D Systems. The Airbus and Boeing aircrafts' video monitor shrouds are printed by 3D Systems using flame-retardant nylon-12 thermoplastic material. Shrouds are now 9-13% lighter than the original ones. The other examples of MRO area are the Airbus and Belgium based Materialise company (Materialise, 2019), Airbus and Singapore based SIA Engineering Company (SIAEC) (Airbus, 2019), and Airbus and Stratasys (Stratasys, 2019) collaborations. In the military side, LM and Sciaky manufactured a flaperon spar made through AM Electro-Beam Direct Melting (EBDM) process could save about 100 $ million thru the lifetime of F-35 (Fabricator, 2019). Research collaborations between aerospace institutes and universities such as LM and ORNL, BAE System and Cranfield University, NASA, Honeywell, and Ohio Aerospace Institute, and many others are currently active and evaluating various possibilities for the application of additive manufacturing for the aviation industry (Sarat Singamneni, 2019). In August 2012, the USA AM Innovation Institute was established in Youngstown, Ohio, with the participation of 46 large business and 62 small businesses companies, 40 academic organizations (universities, community colleges, and research institutions), 14 government organizations, 11 non-profit organizations and 4 Manufacturing Extension Partnership (MEP) centers (Manufacturing USA, 2016). Since aforementioned collaborations will assure the part consolidation, reduced inventory and less storage fee, on-demand manufacturing, light-weighting reduced costs, lower fuel consumption and eventually smaller carbon footprints, it seems that in the future there will be more all-parts-win collaborations in the aviation industry.

Although it may seem that additive manufacturing technology is a neutral extension of the rapid prototyping, nowadays it is not the case. Many additional considerations and requirements have come into the theater for manufacturing that are not important for prototyping.

Additive manufacturing technology has a history of almost three decades, starting with rapid prototyping studies (Jakus, 2019).Up to date, many parts have been additively manufactured in the aviation industry. Many of them are flying on the military aircraft, commercial aircraft and even space shuttles.

Conclusionally, the capability of processing the aviation grade material in an additive manner will disruptively change the industries and produce new parts that could not be manufactured using traditional techniques. This will have a lasting and profound impact upon the way that the parts and assemblies are manufactured and distributed, and thus on society as a whole.

The aviation industry has been sparked by the imagination of the aviators and now opportunities for development are bounded only by the creativity of those using additive manufacturing technologies