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# 3D-Printed Satellite Brackets: Materials, Manufacturing and Applications

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**Citation:** Samal, S.K.; Vishwanatha, H.M.; Saxena, K.K.; Behera, A.; Nguyen, T.A.; Behera, A.; Prakash, C.; Dixit, S.; Mohammed, K.A. 3D-Printed Satellite Brackets: Materials, Manufacturing and Applications. *Crystals* **2022**, *12*, 1148. https://doi.org/10.3390/cryst12081148

Academic Editors: Huakang Bian, Weiwei Zhou and Andrei Vladimirovich Shevelkov

Received: 25 July 2022
Accepted: 13 August 2022
Published: 15 August 2022



**Abstract:** Brackets are the load-bearing components in a satellite. The current age of satellites comprises specific brackets that set out as a link between the bodies of the satellite, reflector parts, and feeder facilities mounted at its upper end. Brackets are used to carry loads of the satellite body frame, supporting elements, batteries, and electronic goods. The article explicates the various brackets used in satellites and aircrafts. The strength of the bracket is of utmost importance since it is an important load supporting member in several assemblies of aircraft and satellites. In addition to the mechanical strength, the weight of the bracket is a major concern as it adds to the total weight of the aircraft and satellite. Thus, weight savings of brackets can be of paramount importance and Additive Manufacturing (AM) is found as an overall solution to achieve the same. Hence, in addition to various brackets used in satellites, the article presents an exhaustive review of the processing of various advanced functional materials using various AM techniques to make high strength-to-weight ratio satellite brackets. The use of DFAM by various satellite manufacturers globally for optimizing the structure of the brackets resulting in a significant weight saving of the brackets is also presented in the article.

**Keywords:** additive manufacturing (AM); Selective Laser Melting (SLM); bracket; Ti-based materials; satellite; DFAM

## 1. Introduction

Brackets are the important components of space vehicles. Brackets serve the purpose of carrying loads and supporting the structures. Mounting brackets are found in large numbers in aerospace vehicles and satellites. Due to their lightweight and thermal conductivity, these are generally used in satellites. Various brackets are used to carry loads of electronic goods, cameras, batteries, antennas, and various satellite components. One of the applications of a bracket used on the outer surface of the satellite is shown in Figure 1. Depending on the application, the shapes of the mounting brackets can be hanging type or supporting type [1]. On the other hand, a suitable, sturdy bracket or stand is necessary for the proper functioning of the satellite dish [2]. A sturdy wall bracket prevents the structure from being damaged. The usage of a suitable bracket has advantages like ease of assembly, optimal reception, and easy alignment in the required direction. Although a sturdy and strong bracket is required for the applications, the weight of the bracket can be a major concern, especially in the case of aerospace and satellite applications. A high strength-to-weight ratio is essential as every kilogram carried into space will add to the total cost of the flight depending on the carrier system and the orbit to be reached. Weight minimization in every aspect adds great value to the design of bracket structures used in space vehicles. Weight reduction of the part can be addressed in three ways: material selection, material design, and material processing. The favorable choice of materials for making satellite and aircraft brackets are the advanced functional materials like Al-based, Ti-based, stainless steel, NiTi-based and composite materials. The material design is considered depending on the loading conditions and also on the structure, and thus, structure optimization of the part should is of great importance. Finally, the choice of material processing technology has a vital role to play as it decides the total cost of the project. For a finalized choice of material, the focus would be on the integration of structure optimization and processing of the material chosen. The resultant complex geometries are extremely difficult to process by conventional manufacturing techniques. Brackets constructed by conventional metal cutting do not fulfill the desire of achieving a high strength-to-weight ratio in parts produced because conventional metal cutting may not optimize the component's weight and stress factor [3]. Hence, there arises a need for efficient processing techniques that can accommodate complex geometries in addition to structural optimization. One of the best ways to achieve this is through Additive Manufacturing (AM). Owing to the design freedom and also the capability of processing complex geometries, the world is seeing greater interest in the processing of mounting brackets through additive manufacturing technologies [4].

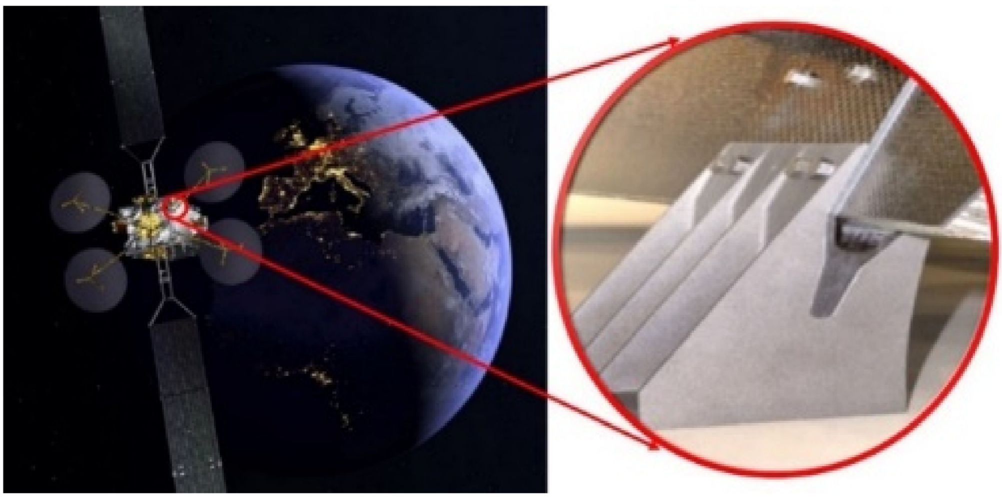

**Figure 1.** AM-made titanium brackets are used in satellites [5].

Additive Manufacturing (AM) is a process in which a 3D solid object is built by adding the material layer-over-layer [6–8]. The schematic of the AM steps is shown in Figure 2. A sliced 3D CAD model is directly converted into a solid model on the building platform of the machine. Hence, the process is also called 3D printing. During the making of the product, the material is added and consolidated into solid-phase layer-by-layer in the height direction. Hence the name layered manufacturing process. The most attractive aspect of AM is its ability to process complex geometries easily which is known as a solid free-form manufacturing process [9].

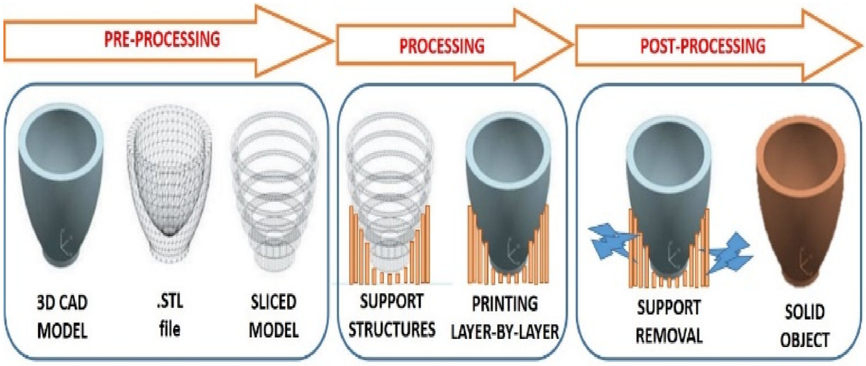


**Figure 2.** Schematic of AM process flow diagram.

AM is a recent technology and the alternatives to AM are the traditional manufacturing process that includes Subtractive Manufacturing (SM) and Formative Manufacturing. The SM uses a material removal approach, In contrast to AM, the part in SM is prepared out of the solid material block by removing the part of material using material removal processes like cutting, grinding, planing, shaping, drilling, milling, and slotting, etc. The AM technology was first attempted in 1981 by a Japanese Hideo Kodama for processing a photo-hardening polymer. Later in 1983, Charles W. Hull printed a teacup using the Stereolithography Apparatus SLA-1. In the initial days, the technology was imagined for making the prototypes of the products during the product development [10]. It was a solution for quickly making the products which otherwise consumed a huge amount of time and eventually added huge product development costs. With this technology, prototypes were quickly prepared and it was known as Rapid prototyping. The technology was evolving and attempts were made to process metals, ceramics, and other materials [11]. After about 12 years, the first powder bed has been developed by MIT using inkjet print heads and the term 3D printing began to be used [12]. In 1997, AeroMat produced a Metal 3D printer that used a laser to fuse Titanium powders, the process was called Laser Additive Manufacturing (LAM). As of today, the technology is matured to a greater extent and the world has witnessed the processing of almost all kinds of materials viz., polymers, metals and alloys, ceramics, composites, concrete, chocolates, sand, bio-materials, etc., using this technology. AM offers several advantages over traditional manufacturing technologies. The various advantages are explained below.

(I) Omission of smaller part assembly: During the designing procedure, various smaller parts can be replaced by a single part which allows us to print the complete part at once. Whereas in traditional manufacturing; first, all the components are manufactured individually and then assembled to create the final part [13].

(II) Minimization of Material waste: Advanced software like topology optimization calculates the best shape for a part and removes unnecessary material without compromising the structural integrity. This helps our engineers to design and produce a lightweight part by advancing the material distribution, which leads to minimizing material waste. For example, Siemens uses generative design software in 3D printing to develop its gas turbine blades. General Motors also uses 3D printing with generative design and topology optimization software, and it aims to reduce the weight of a vehicle by exploring various options for material distribution within a component [14].

(III) Can easily create highly complex parts: AM overcomes most of the traditional manufacturing limitations to create almost every complex part with enhanced functionality. For example, the cooling channel of injection moulds in the traditional manufacturing method is mostly straight, which leads to slow and inconsistent cooling of a moulded part. The cooling channel in 3D printing is more advanced and can be re-designed according to the requirement, which provides a more homogeneous heat transfer that results in enhanced cooling characteristics [15].

(IV) Flexibility of material choice: AM process can print almost using any material available; this opens up the possibilities for material innovation. Engineers can explore the limitless option for the better properties of the product. For example, 3D printing of high-performance thermoplastics can replace some metal parts, and it is also low cost and lightweight [16].
(V) Minimized support structure: Like material innovation, 3D printing also opens up the possibility for unique support structure design. By choosing the best part orientation, the post-processing time and cost can be reduced. Though the supporting system can't be removed completely, it is very much necessary that a minimum support system should be provided to the 3D model as it can reduce cost prominently. An optimized number of support systems should be provided while designing [17].
(VI) Lightweight product: Topology optimization provides the advantage to design and manufacture a product for a specific function, and with a made-to-measure feature, for example, unnecessary materials are removed by advanced design and complicated mathematical calculation; therefore, the product part is lightweight and cost is minimized [18].
(VII) Multimaterial Products can be manufactured: Another crucial advantage of 3D printing is multiple materials can be simultaneously printed into a solid. This solves one of the vital limitations of the conventional manufacturing method [19].

Although AM is evolving gradually, technology has gained tremendous interest in the last decade. As a part of industrial revolution 4.0, digital manufacturing involving AM appears to be the leading technology for manufacturing products on customized and mass levels. The current world is witnessing a revamp in manufacturing industries due to the implementation of AM [20]. The choice of suitable AM technique for making products mainly depends on (a) the material to be processed, (b) the size and shape of the product, and (c) the end characteristics of the product [21]. The success of making the product using AM technology requires greater experience in Design for Additive Manufacturing (DFAM) which makes use of the design of freedom of AM. DFAM mainly aims to optimize the product design by decreasing the total amount of support structures and the support material; decreasing the total mass of the product by incorporating lattice structures, print consolidation, and part orientation, eventually decreasing the total print time and total cost. Hence, the implementation of DFAM plays a vital role in making products using AM. Owing to the various advantages of AM and DFAM, it is easy to create high strength-to-weight ratio products. This is an important contribution to aerospace industries in meeting the unabated demand for lightweight and strong structural applications. Again, the applications of AM are spread on a large spectrum of industrial domains that include, automotive, healthcare, electronics, durable goods, cosmetics, architecture, etc.

## 2. Materials Used in Brackets

Material selection is a critical aspect of the aerospace component and system design cycle. It affects many of the performance factors of aircraft such as payload, flight performance, safety, reliability, structural efficiency, energy consumption, disability, lifecycle cost, and recyclability. The material for aerospace structural applications must consist of mechanical, physical, and chemical properties, such as rigidity, high strength, damage resistance, fatigue durability, high thermal stability, low density, excessive corrosion, and oxidation resistance. The material selection depends on various operating conditions like loading conditions, temperature, moisture, corrosion, noise, etc., of that particular component or system. For the brackets used in the wings of an aircraft that sustains bending during service along with torsion, vibration, tension, and fatigue, a material possessing high tensile and compressive strength, stiffness, vibration modes, and buckling strength will be suitable. Similarly, the combustion chamber always interacts with the fluid which is subjected to high temperature and pressure. So, the material for this should have oxidation resistance and principally thermal properties [22]. Despite matching the primary service requirements, the improvement of structural capability in aerospace structural design becomes remarkably important because the function of lightweight arrangement provides an exponential boost in aircraft performance wherein AM plays a significant role in meeting such unique demand. Another effective and more advanced way to achieve lightweight material is structural optimization. In this method, the material is distributed to reduce material, and structural performance is enhanced [23–25]. In addition to structural capability, improved acceleration performance, energy efficiency, flight endurance, payload, and decreased life cycle cost and greenhouse gas emissions can also be achieved by the application of DFAM [26]. The various materials used for making brackets and their processing using AM techniques are discussed below.

### *2.1. Al-Based Alloys*

Al6061 is a lightweight material yet high in strength as compared to other aluminum alloys. The important factors to be considered are deflection and stress distribution. In general, good ductility and corrosion resistance, relatively high basic strength and rigidity, low price, and simple manufacturability and durability make advanced aluminum alloys an excellent choice of lightweight materials in many aerospace structural applications such as upper and lower wing skins, wing stringers, and fuselage skin, etc. [27]. On their first human-crewed flight in 1903, Al was the first choice for the engine components and cylinder block for the Wright brothers. For the first time, an Al-alloy was heat-reinforced, a discovery that set Aluminium's dominance in aerospace engineering [28,29]. The aluminum added substance layer manufactured (ALM) section saves weight and decreases the making time. More prominent solidness gives better guiding exactness toward mounting receiving wires. Airbus Defence and Space in the UK attempted its first space-qualified aluminum 3D printed segments. The optimized antenna bracket for TMTC is shown in Figure 3. The 3D printed segments being created by the UK group are high-performance structures that cannot be manufactured by conventional techniques. The advanced structural bracket made of Al-alloy was installed in Eurostar E3000 broadcast communications satellites. The bracket is a single-piece laser liquefied part weighing 35% less than the conventionally manufactured part that consists of four sections and 44 rivets. In addition, the ALM section is 40% stiffer. Further, as compared to the part processed using conventional machining techniques, the least wastage is observed. The section is used for mounting the telemetry and telecommand (TMTC) reception apparatuses onto the satellite. From the flight qualification testing of the structure, it was found fit to be flown on an impending satellite [30]. The innovative design in the 8 U Cube Satellite included DFAM-based lattice structures to improve the protection. Some of the latest developments include alloying additions such as Gd, La, Sm, and Yb to improve the high-temperature performance and corrosion resistance of cast Mg alloys [31,32].

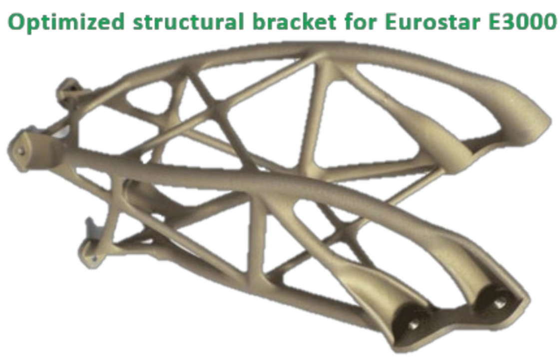


**Figure 3.** AM-made optimized bracket used for mounting the TMTC antennas onto the E3000 satellite [33].

### *2.2. Ti-Based Alloys*

Titanium alloy is a preferred choice of engineering material after aluminum to manufacture aircraft frames and engine components. Although It has paved its way into the aerospace industry manufacturing Ti products have challenges. Firstly, the high cost of alloy, which is nearly eight times that of Al-alloys used in industries. Secondly, machining Ti-alloy is quite a difficult and expensive process due to its high strength and hardness. Hence, an adaptation of Ti alloys is considered only in critical components of aircraft. They are preferred where high strength, corrosion resistance, and space constraint are the deciding parameters for designing components, and also cost of the product must not be that crucial. In general, Ti-alloys are used mainly in manufacturing engine components and the mechanical structure of aircraft. Titanium combinations have a boundless edge over different metals. It has high rigidity, great crack strength, and fatigue resistance, with some erosion resistance, heat resistance, cryogenic embrittlement restriction, and low thermal coefficient. This makes the Ti-alloy an appropriate alternate choice for steel and Al-based compounds used in aircraft applications. Figure 4 shows a simple design of the additively manufactured Ti-alloy bracket. The processing of Ti-alloy-based brackets using AM is also challenging. Benedetti et al. [34] found high porosity and surface roughness along with poor fatigue properties in the Ti-6Al-4V-alloy-made components processed by Selective Laser Melting (SLM). The relationship between porosity, microstructure, and mechanical properties is also analyzed in terms of process parameters and then improving the processing parameters to achieve 99.5% relative density in CP-Ti-made components [35]. Atar et al. [36] reported improvement in compressive strength, toughness, and tensile strength for SLMed structure. Sample production of Ti-6Al-4V alloy using Selective Laser Sintering (SLS) followed by hot pressing was attempted by Das et al. [37]. The Ti alloy structure processed by SLM provides the best strength-to-weight ratio and is about half as heavy-duty steels or Ni-based superalloys. The vast majority of aircraft frames today are made of Ti-alloys. These alloys have a very specific reinforcing body and can suppress the development of weakness on these grounds; they are considered an ideal replacement for steel and aluminum in frames. To prevent catastrophic fatigue, they are used as thin, narrow bracket rings around the aircraft fuselage of aluminum, similar to the belly bar. One of Ti alloys' main applications in the aerospace industry has been the use of (α + β) Ti3Al2.5V for hydraulic pipes, aircraft floors, piping systems, etc. [38]. Ti-6Al-2Zr-2Sn-2Mo-2Cr-0.25Si is being produced for US F-22 aircraft and joint strike missile projects. Ti alloys such as Ti-3Al-8V6Cr-4Mo-4Zr (β-C) and Ti-15V-3Cr-3Sn-3Al are preferred for generating sources for multi-aircraft activation systems [39]. Currently, Boeing has created 200 unique parts for ten aeroplane stages utilizing AM, and it has delivered around 20,000 sections for military and business aeroplanes, including 32 distinct segments for its 787 Dream liner planes. General Electric, the world's biggest fly motor provider, produces fuel spouts for a great many fly motors that are processed to have 25% less weight and multiple times more solidness than best-in-class parts, which were recently made by welding 20 unique parts. SLM is considered the most solid AM strategy that can deliver lightweight parts for aviation applications with diminished $CO_2$ discharge. Tomlin and Myer have demonstrated the useful suitability of the Electron Beam Melting (EBM) technique for making Airbus A320 nacelle pivot section segments. The utilization of Ti instead of steel brings about a 63% weight decrease. Table 1 shows the use of various Ti alloys in different sectors [40].

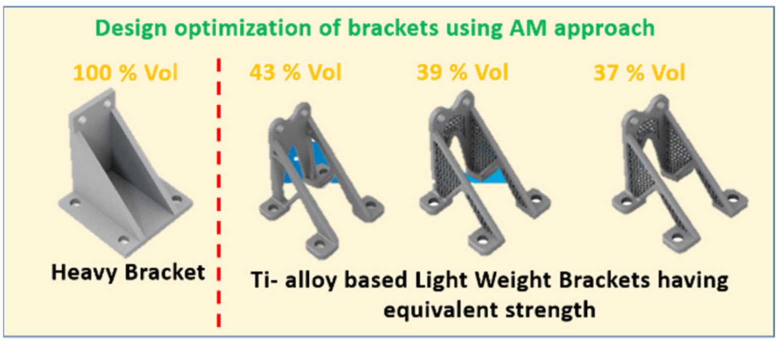


**Figure 4.** Schematic of Ti-alloy bracket processed by AM [5].

**Table 1.** Various types of Ti-alloys for aero-vehicle.

| Ti-Alloy | Application | Advantage |
|---|---|---|
| Ti-6Al-4V | • Aircraft window frame structure<br>• Fan and compressor of the gas turbine engine | • Lightweight (up to 40%)<br>• High strength and modulus<br>• Low density and coefficient of thermal expansion |
| Ti-3Al-2.5V (α Alloy) | • High-pressure hydraulic tubing<br>• Fuel structure in Airplanes | • Weight reduction (up to 40%)<br>• Replacement of structural steel<br>• High strength |
| Ti-3Al-10V-2Fe (β Alloy) | • Landing gears of Boeing<br>• High strength airframe components | • Weight reduction (up to 270 kg in Boeing aircraft)<br>• High strength (970 MPa) |
| γ-Ti | • Gas turbine engines | • Lower density as compared to other alloys of Ti<br>• High elastic modulus<br>• Oxidation resistance<br>• High creep and oxidation resistance<br>• Improved specific stiffness |

### 2.3. Stainless Steel

Steel is the most popular and commonly used material in almost every industry due to its easy availability and has high strength and stiffness, low cost, and good dimensional properties at high temperatures. It is still used in only 5% to 15% of the weights of a commercial aeroplane because of its limitation like high density and vulnerability to corrosion and embrittlement. For safety components where extremely high strength and stiffness are required, high-strength steel is the only choice. Another application of high-strength steel in aerospace is bearing, gearing, and undercarriage application [41]. All the AM-processed satellite wall brackets are made of high-quality stainless steel, making them resistant to all weather conditions and have a very high lifespan. The Cab Mount Bracket developed from powder-covered, heavy-gauge steel with vibration isolators offers the ideal solution for long-term outdoor use and is intended for robust support and durability [42].

### 2.4. NiTi-Based Alloys

NiTi smart materials are available in the form of a plate, thin film, or bar used to actuate the component whereas AM-made NiTi smart materials are available in any form [43]. In Figure 5a NiTi plate and an attachable flexible heater are part of the SMA damper module used to facilitate NiTi phase transformation. The SMA damper is also stowed together when the tape spring hinge is stowed in shape, as shown in Figure 5a. The tape spring is in an in-elastic condition at the stowed shape, but the NiTi plate is evidently in a plastic state; it recovers if its temperature is more than that of the austenite phase transformation temperature ($A_f$). Consequently, if the torque needed for NiTi plate plastic-like deformation is greater than the torque of a tape spring hinge, the deployment behavior could be regulated by the rate of NiTi phase transformation. The SMA damper module can minimize the accompanying latch-up shock without regard to functional requirements. The SMA damper module has no detrimental effect on the tape spring hinge and is a typical flexible deployment device for a satellite module's deployment torque since the phase transformation mechanism is similar to the steady release of the deployment angle restriction. Instead, when a deployed position (shown in Figure 5b) unexpectedly becomes stuck, the SMA damper module will serve as an emergency actuator because of its high recovery stress. Concerning deployed stiffness, it is clear that certain stiffness can be supplied by the SMA damper module [44].

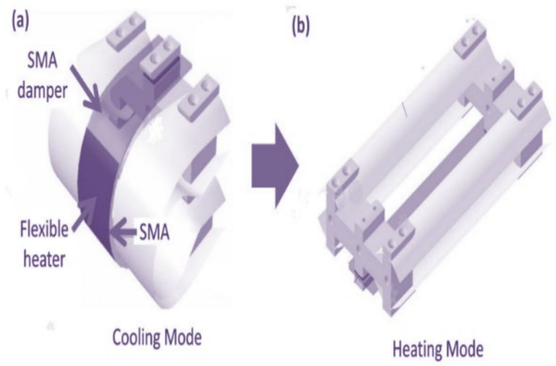


**Figure 5.** SMA damped tape spring hinge. (**a**) Stowed position; (**b**) Deployed position.

### 2.5. Composites

In honeycomb panels, metals and fiber-reinforced composites can be of great choice for making brackets. Using a sheet molding compound technique, the glass-reinforced polyester composite is formed which is used in making several aircraft components. A thruster bracket made up of composite material parts is used to join the thrusters to the satellite (spacecraft bus). The thrusters are designed such that cut-outs are provided to hold the thruster and to pass the cable of the thruster. A thruster bracket carries vibration loads during the launch phases and gives a necessary thruster mounting platform with essential precise angular direction. The designer follows inflexible technical requirements in making thrusters brackets for thrusters to function systematically [40]. Lightweight, angular tolerance, dimensional tolerance, and stiffness requirements are their specifications. There exist a competition between very high-performance composites (like fiber-reinforced polymer and fiber metal laminates) and lightweight aerospace materials (Al-alloys). In recent aircraft, aerospace composites having higher specific strength and specific stiffness at a moderate temperature are preferred over most metals [45]. Improved fatigue resistance, corrosion resistance, moisture resistance, and ability to tailor lay-ups for optimal strength and stiffness are required directions are some more benefits of composites. However, composites are costlier than metals and alloys, which is a major drawback of composites. Various applications of composites are listed in Table 2. All set of composites has been found successful in AM.

**Table 2.** Different composites and their applications.

| Composites | Aerospace Application |
|---|---|
| Carbon fiber reinforced polymer | • Fuselage and empennage<br>• Used in the wing box<br>• Used in control surfaces |
| Fibre metal laminates, especially glassfiber reinforced aluminum | • Fuselage skin<br>• Empennage |
| Aramid fiber polymers | • Used where high impact resistance is required |
| Glass fiber reinforced polymer | • Used in radomes and semi-structural components such as fairings |

Nanotechnology is found to improve the mechanical, physical, and chemical properties of materials [46]. Compared to conventional composites, nanocomposites provide the chance, without density increase and by addition of fewer amounts of nanoparticles like carbon nanotubes, layered silicate, etc., to enhance properties [47,48]. For example, nanoparticles such as silicate, CNTs, and polyhedral oligomeric silsesquioxane (POSS) can form passivation layers to increase the oxidation resistance of composites. In a composite matrix, the mixing of CNTs, silica, and layered silicate could lead to energy dissipation on structural failure [49]. Therefore, it could cause high damage tolerance structures when there is an increase in the toughness of the composite [50,51]. Figure 6 shows the mini-EUSO that is now flying in the International Space Station. 3D printed Ultem 9085 brackets made up of composite materials are used in the instrument (red colour mark shown in Figure 6a). The final unit with electronics included that is housed in the Mini-EUSO instrument is shown in Figure 6b.

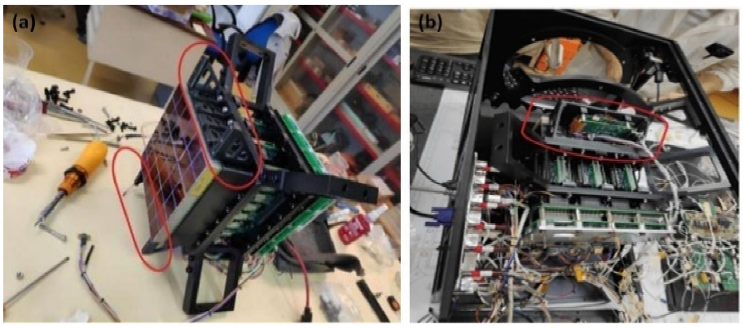


**Figure 6.** The Mini-EUSO used in the International Space Station: (**a**) 3D printed Ultem 9085 brackets (in red), and (**b**) The final unit with electronics included.

## 3. Manufacturing of Brackets

### *3.1. Selective Laser Melting (SLM)*

Selective Laser Melting (SLM), a powder bed fusion process, is a high-temperature part manufacturing technique similar to Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS). In the SLM process, the laser is used as a heat source to attain high temperatures to fuse powder particles in a layer. The process repeats on the consecutive layer that is periodically added to the bed. The schematic of the SLM process is shown in Figure 7. While printing a NiTi alloy-based bracket, a layer of NiTi alloy powder is spread over the build platform using the sweeper or the recoater blade. Typically, 0.1 mm thickness of the powder layer is spread out. The SLM machine preheats the NiTi powder material on the powder bed; then the laser scans the powder layer at the required points. As a result, the powder particles at all those points and a solid are formed at a rapid rate of melting and solidification. At the end of the scanning in the first layer, a new layer of powder is spread, and further layers or cross areas are fused and added; this practice continues until the whole model is printed layer-by-layer [52]. A large portion of SLM machines utilizes one fiber laser of 200 W to 1 KW ability to specifically intertwine the powder bed layer. During printing, the build chamber is filled with inactive argon gas for reactive materials and nitrogen gas for non-responsive materials. Similarly, these SLM machines can fabricate completely thick solid parts made up of a wide scope of metal composites like Ti-alloys, Inconel alloys, cobalt-chrome, Alloys, stainless steels, and tool steels. A large portion of the laser-based Powder Bed Fusion (PBF) frameworks have low form rates of 5000–20,000 $mm^3/h$, and the most extreme part size that can be created (construct volume) is restricted to ($250 \times 250 \times 325$ $mm^3$) which expands part cost and restricts its utilization just for the little sized parts. Various SLM manufacturers are aiming at printing bigger parts by increasing the build volume and fabrication rate. Germany-based SLM manufacturer, SLM solutions, developed the SLM 500HL machine in 2012, which uses two-fold shaft innovation to increase the development rate to 35,000 $mm^3/h$ and has a construct volume of ($500 \times 350 \times 300$ $mm^3$). Two arrangements of lasers are utilized in this machine, each set having two lasers (400 W and 1000 W) that amount to four lasers that scan the powder layer all the while. Another German maker EOS, developed the EOSINT M400 machine in 2013, which has a fabricate volume of ($400 \times 400 \times 400$ $mm^3$) and utilizes one 1 KW fiber laser to expand the construction rate. Idea laser and Fraunhofer establishment for laser innovation have created the biggest AM machine for metals (X line 1000R) with a construct volume of ($630 \times 400 \times 500$ $mm^3$) and assemble rate of up to 100,000 $mm^3/h$ [53].

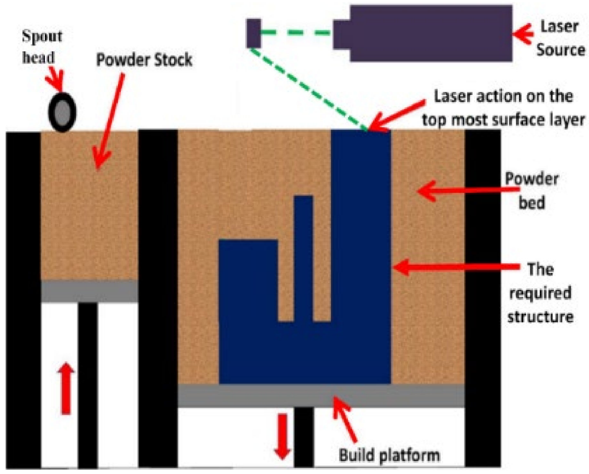


**Figure 7.** Schematic of SLM process.

### 3.2. Influencing Parameters during the Processing of Ti-Based Satellite Bracket by SLM

Table 1 shows the various type of Ti-alloys used for making brackets used in satellite and other aerospace vehicle parts along with the advantages. In general, the main objective of SLM or other AM processes is to create a part with almost zero defects and having full density structure. A large number of precisely calculated processing parameters are involved during the SLM process. Hence there arises a need for proper control of every parameter to get a high-quality product. Parameters like the wavelength of laser and laser working mode are determined by the device [54]. Critical parameters like process parameters and manufacturing parameters should be taken care of during optimization. For a given material, the energy density of the laser (E) applied to a certain volume of powder during SLM is given by [55]:

$$E = P/((v \times t \times s)) \quad (1)$$

where P is laser power (W), v is scanning speed (mm/s), t is the thickness of layer (mm), and s is the spacing of scan (mm). The laser energy density is defined as the function of these important factors which affect the quality and densification of fabricated parts. As inferred in the above equation, the increase of the power of the laser and/or a decrease of the scan speed or thickness of layer or spacing of scan would elevate the density of the laser and hence the powder temperature also increases. A higher amount of energy density of an incident laser results in increased melting of powder and so the material will have a higher final density. The complete melting of powder resulting in a melt pool is essential for producing fully dense parts and hence adequate laser energy is required to obtain the fully dense part. During SLM, the laser beam having a constant speed (scan speed) travels across the powder bed, which decides the production time in SLM [56]. In simple terms, the higher the scan speed shorter is the production time. However, the maximum laser power of a particular SLM device should be taken care of while increasing scan speed. The thickness of layer (t) is another parameter that determines the amount of energy as well as the production time required to melt a given layer of powder. The thickness of a layer is much crucial parameter as good bonding between two given layers is possible when previously processed layers undergo re-melting. The production time decreases if a higher thickness of a layer is formed. However, to melt thick layers completely during the successive scan, higher energy input is also required which may cause a reduction in dimensional accuracy and an increase in surface roughness. The hatch spacing of scan(s) is normally taken as parallel lines in SLM [57]. In SLM, it has been observed that spacing of scan promotes the overlapping of adjacent solidified tracks, thereby contributing to the surface roughness and porosities of produced parts. For proper bonding of adjacent tracks during the SLM process, the scan spacing should be determined carefully (should vary between the half and the full width of the melt pool). Other important parameters in this process are the length and pattern of the laser scanning vectors. The length of the scanning vector is determined by scanning geometry. This scanning also known as manufacturing pattern can be designed in several ways. The laser scanning pattern typically consists of straight and parallel lines with the possibility of spiral or circular coverage. The direction of scan patterns can also be changed between consecutive layers or inside a single layer [58], as presented in Figure 8a–d. The variants in Figure 8a,b are named unidirectional and bi-directional (zig-zag) scan patterns, respectively. Also, scan directions can be angularly adjusted from section to section, similar to inter-layer scanning, as shown in Figure 8c. The scanning direction can be rotated by providing different rotation angles between consecutive layers as shown in Figure 8d. The SLM processed parts' quality is greatly influenced by the design of the manufacturing pattern [59].

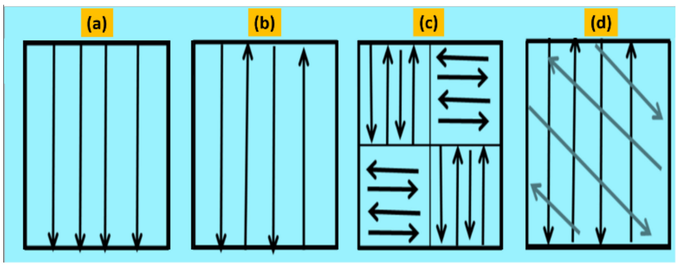


**Figure 8.** Various scan patterns used in SLM: (**a**) unidirectional, (**b**) bi-directional (zig-zag), (**c**) angularly adjusted from section to section, and (**d**) different rotation angles between consecutive layers.

In addition to the above-discussed parameters, the type of laser and powder characteristics are also important for achieving the desired microstructure, density, and surface quality of the final product. The melting of metallic powder occurs by heat energy accumulation during the SLM procedure. So, the powder characteristics and properties of starting material are important for melt pool generation and absorption of the laser. SLM process is significantly affected by the size, shape, and type of the powder; the interaction between laser and powder material; powder flowability; etc. The starting powder characteristics play a crucial role in determining the quality and density of the final SLM-produced sample. Powder morphology determines to what extent the particles are packed together when a fresh layer of powder is spread over the previously formed layer of solid. Thus, powder morphology is critical in determining the surface roughness and layer thickness during the SLM process. Generally, spherical-shaped powder materials are desirable for the SLM process. Spherical-shaped powder materials are prepared by atomization technique. However, the chemical composition of feedstock powder is limited as applicable to SLM. Currently, the SLM process uses 29 common metal powders from all the available materials, and Ti-6Al-7Nb, CP-Ti, and Ti-6Al-4V are the most commonly used Ti-alloys. The smaller the powder particle size better the packing density and hence, there is a strong demand for efficient and economical powder processing techniques as well. Ball milling is comparatively an economical way of processing near-spherical powder materials. However, ball milling of powders is in general inconsistent with the size of the particles produced. It is commonly observed that ball milling for a longer duration produces irregularly shaped powder particles, which result in lesser compaction during processing in SLM and thus result in increased porosity in the laser-fabricated parts. In contrast, a short milling time could produce near-spherical shape powders of oxide dispersion strengthened steel and titanium matrix composites for the SLM process. Another important aspect of processing parameters is the optimization of all the influencing parameters. Optimization plays a great role in producing high-quality and high-density products.

### 3.3. Defects in SLM Processed Brackets

The typical defects observed in SLM processed brackets are residual stress, cracking, melt ball, swelling, delamination, substrate adherence, and wrapping. It is important to detect these defects and analyze and rectify them to enhance the life span and quality of the SLM-associated parts [60]. These defects may be eliminated by adjusting the processing parameters like laser energy, scan speed, hatching distance, balling effect, etc. As laser energy is vital in the densification of parts, defects such as porosity and unmelted areas might be created during SLM due to reduced solubility and improper powder bed density of some elements during solidification shown in Figure 9 [61]. It may also be formed due to localized irregularities due to the Heat-Affected Zone (HAZ). During SLM, increased laser energy results in high power density, which melts the powder particles when the laser source scans line by line. It forms a continuous cylindrical path. Surface energy keeps on decreasing until equilibrium exists, which occurs when cylinder break-up occurs. It forms several metallic agglomerates of spherical shape.

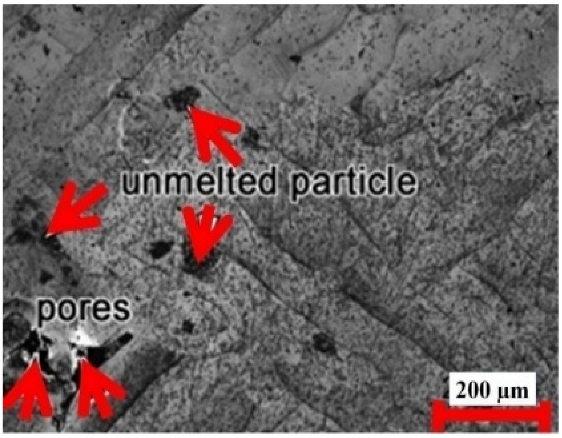


**Figure 9.** Pores and unmelted particles in the SLM processed Ti-24Nb-4Zr-8Sn sample.

Increasing scan speed can influence the stability of the melt pool as the balling effect is experienced in the elongated liquid pool during SLM. The balling effect leads to the formation of weak interline bonding during the laser scanning process. Due to the non-uniform spreading and fusing of powder particles, porosity will occur in the solid part, and delamination of layers will be caused by weak interlayer bonding and thermal stress. Balling effect may also lead to a poor surface finish. Balling effect can be eliminated by improving the stability of the melt pool, increasing the width of contact, decreasing the length/width ratio, reducing the speed of scanning, or increasing laser power. The microstructure is altered in the HAZ due to temperature-induced and high exposure time. Hence large variation in cooling gradients, temperature, and retention time leads to changes in the composition and microstructure of HAZ. Due to large cooling rates in SLM, a large temperature gradient and a very narrow HAZ are formed. To decrease non-homogeneity in the parts, HAZ must be minimized. For example, SLM-produced parts consist of reduced wear resistance due to large HAZ. Optimal adjustment of laser processing parameters could produce minimum HAZ. SLM-produced parts should not contain any type of cracks. In general, cracks produced in laser-processed samples are classified into two types, i.e., macroscopic cracks and microscopic cracks. Microscopic cracks are formed due to quick solidification. Crack is initiated in the solidification temperature range as high energy liquid film interruption at grain boundary takes place. Macroscopic cracks, otherwise known as cold cracking, are formed due to stress-induced crack propagation and low material ductility. In general, the formation of cracks significantly reduces the mechanical properties and dimensional accuracy of SLM-produced parts. For example, the presence of defects in SLM-produced CP-Ti significantly decreases its tensile properties. In SLM high heating and cooling rate occurs; therefore, residual stress in the produced part is comparatively high. It may result in interlayer de-bonding also in stress cracking. In the SLM processed part, the residual stress profile includes high tensile stress at both the top and bottom of the part and intermediate compressive stress in between. The property of material, sample height, and laser processing conditions changes the magnitude and shape of residual stress. Material properties like the elastic modulus and thermal expansion coefficient determine the level of residual stress. Laser processing parameters should be handled carefully to reduce the level of residual stress. Usually, higher residual stress is perpendicular to the scan direction; by preheating the building substrate, the temperature gradient decreases, which controls the residual stress. We need to understand the laser behavior on the weld zone and specifically on residual stress development. It is evident that by using post-weld treatment, residual stress can be decreased [62]. During the SLM process, most metallic materials are highly reactive to the atmosphere. Hence the process should be carried out in a protective atmosphere, generally in a closed chamber in which inert gas is provided. Generally, the argon environment is used with high pressure to avoid the possibility of contamination. The improper control of gas pressure and its physical and thermal properties will affect the process of SLM, and so oxidation cannot be completely prevented. The minor oxidation on the surface of the particles reduces wettability as the surface is decreased due to atmospheric conditions. Pore formation happens when the oxide is added to the weld pool. This also leads to the formation of a weak interlayer formation [63].

### *3.4. Advantages and Limitations of SLM*

Layering error or the staircase effect observed in the samples processed by all layer manufacturing techniques including the SLM process is a limitation. It depends on various factors such as inclination angle as well as the layer thickness [60]. Due to this effect, shafts and holes are manufactured with their circular cross-section in the plan rather than elevation. Otherwise, the roundness of the piece would not be acceptable. Besides roundness, the positioning of the piece is another contributing factor, and depending on the application; it would be interesting to manufacture an overturned sliding axis so that no interlocking occurs [64]. Further, the mass production of components by SLM in many cases is a limitation and traditional manufacturing methods are preferred for mass production. However, it depends on the size and quantity of the components to be made. For example, Citim, GmbH a German-based company reports that it was an easy job for the company to produce 30 tensile test pieces, two antennas, and various test items in a construction volume of 400 $mm^3$, in a single setting [65]. In addition, the layer-by-layer deposition sometimes leads to anisotropic materials. Most industrial components are generally subjected to various forces, which put the component under stress conditions, and they always require minimum material for their components. Though the SLM provides a high advantage here, the performance result of the component while in service is inadequate. The tolerance of SLM components is still higher than other conventionally manufactured components [66,67]. Providing support structures during the printing of the brackets is another limitation of the process. Support material is a part of the build process that is a caveat of many AM processes. Support structures are unwanted in many a way. Firstly, the support structure is built using the same material as that of the component and it gets wasted during post-processing. Secondly, support structure adds to the total build material, total print time, total post-processing time, and eventually to the total print cost. Hence the support structures have to be reduced as much as possible. However, the support material is required in the design where there are steep overhangs or unsupported areas where they would support the mass of the part as it is being printed out. Using DFAM the design can be optimized for having the least support structures in the part design. Parts that follow the DFAM principles, during the design phase limit overhangs and build angles to less than 45° to the build platform. Compared to the conventional approach, DFAM offers a wealth of advantages, particularly when it comes to design freedom and quality.

## 4. Emerging Applications of Satellite Brackets

### 4.1. Antenna Brackets

The German Center for Aerospace reports in the year 2016 that the space exploration mission's costs per kg of the payload are above €20,000 [68]. The variation in each gram of a load of a component may lead to a significant rise in the cost of launching the vehicle. Although optimization of process parameters for conventional manufacturing methods is possible, it is very difficult to reduce the load of the components [69]. AM provides greater freedom for the design of the bracket [70]. A Swiss research group, RUAG, investigated the optimization of the antenna bracket design using AM process and found that by adopting AM process, the optimum combination of strength and weight is achieved for the structure of its antenna bracket [65]. Similarly, using EOS M400, a 40 cm long antenna bracket was fabricated by Citim, GmbH a German-based company. Using the AM process, 60 µm layer thickness was formed within 80 h. In general, 80% of the total scope of a project in the aerospace industry, is implemented in comprehensive tests (Figure 10) [71]. The EOS's AlSi10Mg material is found to exhibit high strength and strong resistance to dynamic stress, making it the material of choice for printing high-stress components.

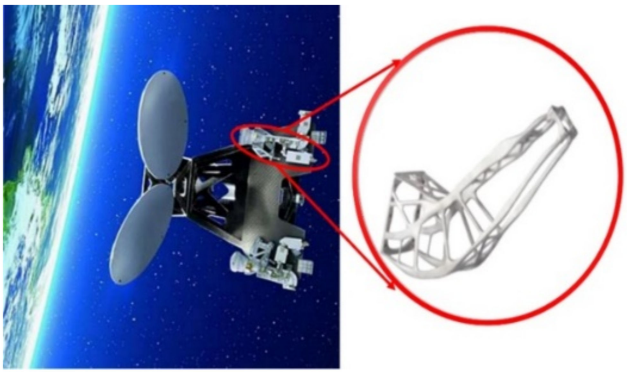

**Figure 10.** 3D printed Antenna bracket for reflector panel used on the Sentinel-1B satellite [71].

Several manufacturers have adopted AM for making brackets and have found positive results upon implementation. Surrey Satellite Technology, a British satellite company, says that AM has a significant role in changing the economics of space. The main reason behind that observation is the ability of AM for achieving optimization of the strength-to-weight ratio. In space flight, weight reduction indicates the savage of fuel, the crucial entity. The space antenna FusiA which is a 3D printed part possesses reduced weight. By the implementation of AM techniques, MDA Ltd., Brampton, Ontario, Canada, a Canadian space technology company, designed the space-bound part, a spacecraft interface antenna bracket optimized for a flight which has made it easy for the company to process the complex structures [72]. Nowadays, mesh structures are used, which doesn't add density to the structure but rather reduces weight. Similarly, Airbus also uses AM to fabricate brackets that hold reflectors. The company reports that the innovative design of the bracket as a result of DFAM reduces the weight of the satellite by 1 kg [71]. The 3D printed antenna bracket used in the Sentinel-1 B satellite is shown in Figure 6. A similar attempt by Juno wherein the aircraft is housed with AM-made support structures has been of great advantage in weight reduction in their mission to Jupiter.

### 4.2. Reaction Wheel Brackets

The reaction wheel is a type of flywheel and is also a momentum wheel that is used primarily by space crafts and satellites. Brackets are used in the reaction wheel to hold a machine and they are also designed for the basic control of the spacecraft to rotate and to use the inertia time to adjust the satellite's position in place. Direct Manufacturing Research Center at Paderborn University carried out a study to determine the feasibility of AM to manufacture reaction brackets for satellites. The main focus of the work was to show the potential of AM for reducing waste, weight, cost, and time for producing reaction brackets [73]. A huge bracket that was used four times per satellite was chosen for analysis. The important aspect of AM is the provision for topology optimization. To achieve the biomimic shape on the bracket, a highly time-efficient semi-automatic voxel-based technique for topology optimization was applied. The developed model is shown in Figure 11. This allows the model to be built quickly and without stress. In addition, the value of the product shows the differences in the design of the product besides the products in the larger process, even in terms of cost. Wheel bracket made by AM process can reduce waste by 98% (from 56 kg to 0.8 kg), weight by 60% (from 1100 g to 450 g), time by 32% (from 59 h to 40 h), price by 53% (from 8000 € to 3800 €).

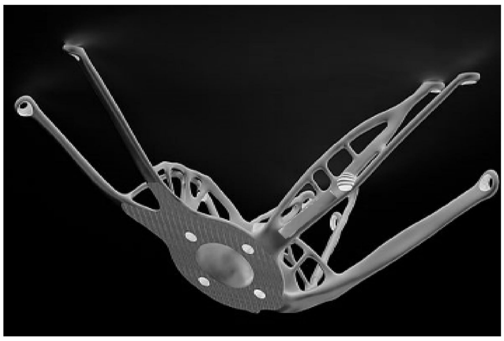

**Figure 11.** AM made reaction wheel bracket [73].

On the other hand, 3D printed reaction wheel brackets made of aluminum were housed in Space bus Neo [74]. The satellite also consists of sixteen antenna transmission brackets and ADPM (Antenna Deployment and Pointing Mechanism) of which, four are Al made and twelve are made of Ti, all of them were 3D printed. These 3D-printed wheel arches were designed to meet market demand for a low-cost antenna. As a result, the cost was reduced by 10% and the production time was also reduced by 1–2 months. Thales Alenia Space reports that. the biggest powder bed fusion-based printer was installed in Europe that has a build volume of (800 × 400 × 800 mm$^3$) to produce the large reaction wheel brackets, Similarly, Thales Alenia Space also includes plugs and cable connectors directly into the overall design, which is printed as a unit, avoiding additional installation requirements. To produce this large reaction wheel bracket (466 × 367 × 403 mm$^3$), the largest 3D powder printer-the Xline 2000R metal laser printer from the concept laser with (800 × 400 × 500 mm$^3$) building space-was installed [75].

### *4.3. Thruster Mount Bracket*

A thruster is a propulsive device used by spacecraft for important activities like altitude control and station keeping in the reaction control system. Mounting of thrusters inside the spacecraft requires extensive care and the thrusters are mounted using brackets. The design of the mount bracket is an important aspect to be considered. Taking the advantage of design freedom in AM, the mount bracket has been modified on a larger scale. Kevin Chris Yakacki et al. [76] carried out work on Lockheed Martin GPS Satellite Bracket and developed an optimized model for manufacturing the thruster mount bracket using AM. The final generatively designed bracket included a thruster mount bracket that has been optimized for minimum possible support structure. Using DFAM for the topological optimization, the amount of support material required was reduced considerably. Before applying DFAM, the orientation of the part on the build plate from various surfaces of the part was chosen as the one with the least support needed [77]. The optimized thruster mount bracket built using AM is shown in Figure 12. The part was built using Aluminum material. Furthermore, the top left corner seen in Figure 12 was an infill added to the design with those angles and geometry purely to eliminate the need for support materials on that corner of the bracket.

**Figure 12.** Optimized mount bracket using DFAM [76].

*4.4. Camera Head Unit Bracket*

The Camera Head Unit (CHU) forms an input vision unit of the spacecraft. A typical CHU developed by conventional manufacturing techniques like milling would account for 90% of material wastage. In this regard, it is worth considering making brackets for CHU using AM approach [78]. The star tracker is part of the Flying Laptop, a satellite, which was developed in 2014 by the Institute of Space Systems at the University of Stuttgart. The satellite was sent into space to reliably calculate the position and alignment of satellites in outer space. The satellite star tracker consists of a combination of two optical cameras (star cameras), aligned to one another at an angle of approximately 15°. The CHU bracket was reimagined for biomimic structure using topology optimization in AM. Such CHU was to be mounted on the bracket. The 3D printed CHU bracket is shown in Figure 9. The 3D printing of such brackets was attempted on a TruPrint 3000 system. Three bracket structures were printed simultaneously and the process lasted for about 6 h. The total print time was reduced to 2.5 h using TruPrint 5000 machine. Camera Head Unit bracket components were printed simultaneously on the substrate plate. The process of manufacturing a component using the TruPrint 3000 lasts approximately 6 h. Using this system, the build time was further reduced to around 2.5 h. On the other hand, the bracket used in the star tracker was also designed and printed using an AM technique called Laser Metal Fusion (LMF). The bracket design has been tailored to the stresses to which it will be subjected, resulting in a 48% reduction in peak stresses compared to its conventionally manufactured counterpart [79]. Compared to conventional mechanical production, the production costs for a bracket produced using AM are up to 70% lower (Figure 13). At the same time, its lower weight enables significant cost savings when launching the rocket [80].

**Figure 13.** Camera Head Unit (CHU) bracket [80].

### 4.5. The Hinge Brackets

The hinge brackets are the vital parts of the aircraft and satellite structures. The hinge bracket possesses a peculiar design to have flexible point in its structure. The bracket processed by conventional technique consisting of unoptimized design consumes more material in mass and hence adds more weight to the assembly in which it is used. Hence the optimization of the design of the hinge bracket is crucial. A study by EOS Innovation Centre in Warwick, UK, in collaboration with EADS Innovation Works (IW), UK on making hinge brackets for Airbus A320 has reported interesting observations [81]. An attempt to replace heavy steel hinges with Titanium made hinges processed on DMLS has been successful. The optimization using DFAM has resulted in considerable weight savings of 10 kg for an aircraft. The optimized design of the nacelle hinge bracket made by additive manufacturing technology is shown in Figure 14. In addition to the weight savings, the processing of components is comparatively eco-friendly due to the least emissions observed during processing [82].

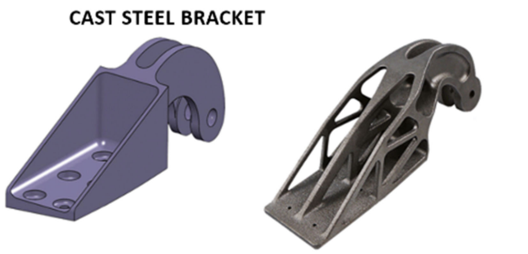


**Figure 14.** Optimized design of Nacelle hinge bracket using AM approach [82].

### 4.6. Wire Bundle Clamps

The traditional methods used for clamping electrical cables and air duct bundles require skilled labor and more installation time. Generally, loop and square types of clamps are used for wire bundles, and the structure is fastened with a tailpiece. Such clamps are made up of metallic strips. A rubber housing is facilitated at the wire's mating surface to prevent the wire from breaking. The clamps are attached to the outer layer in different directions, depending on the position. The brush rods can also avoid interference, such as drilling holes in the supporting structure and drilling the insulation cover. The fence is a small fitting or support used to hold sections of the system such as blankets, cables, plugs, and packages in place. Rigid sheets are usually made of cut steel strips and cut to size before bending. The necessary material for the surface is obtained by heat treatment of the rods. Currently, AM parts are found to replace several mechanical components that are used in the overall assembly of wire bundling and clamping. Figure 15 shows various AMed structures, such as A-bracket (connected directly to the main model using a fixed connection button), B-bracket (removable markers connected to A-brackets or directly to the model), C-brackets (attached to either A or B; they are usually connected to brackets A and B) [83].

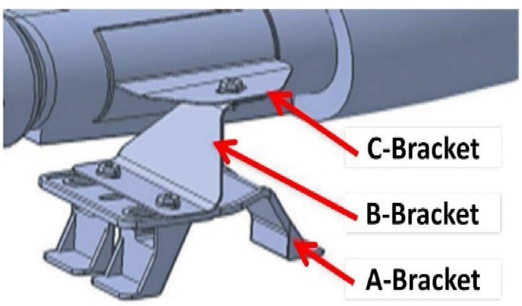


**Figure 15.** Types of A-, B-, and C-bracket [84].

### 4.7. Thales Alenia Space Antenna Brackets

Thales Alenia Space incorporated AM in 2015. Initially, the company printed Aluminum made brackets for TurkmenAlem/MonacoSAT satellite that was launched in 2015, and for the Iridium® NEXT constellation, the company made polymer tube supports using AM approach [75]. The collaboration between the 3D system and Thales Alenia Space demonstrated the production of an antenna bracket (190 × 230 × 290 mm$^3$) for a geostationary telecommunications satellite [85] (Figure 16). Metal printing is now fully affordable and suitable for use in Thales Alenia Space titanium aviation. Thales Alenia Space works closely with the 3D Systems Manufacturing on-demand team in Belgium to design and print the Ti Gr5 (A) laser holder and meet the requirements for all aspects of quality and tolerance [77]. Allowable space, loads, boundary conditions, and other major engineering factors are always taken into account. The design of each of the four individual brackets is different because they are mounted on the edge of the antenna reflector and screwed to the mould surface. The antenna holder is manufactured by the 3D system in the ProX DMP 320 3D System engine. ProX DMP 320 is designed for the production of heavy metal parts. It uses a completely new architecture that simplifies setup and allows for adaptability in the production of all types of internal geometries of titanium (grades 1, 5, and 23), super alloyed nickel, and 316L stainless steel. By combining the advanced capabilities of the ProX DMP 320 and the 3D system experience, Thales Alenia Space can get the parts made in half the time required for normal production. Titanium brackets that DMP manufactures are lighter than brackets produced through the conventional process. Also, DMP-produced brackets have a higher strength-to-weight ratio. In comparison, the file preparation, heat treatment, CNC milling, quality-control analysis, and data acquisition take about 4–5 weeks compared to 10 weeks in a conventional process. In 2015, for three Thales Alenia Space geostationary satcoms 3D Systems manufactured more than 50 different space components. Adoption of DMP was more beneficial as both Thales Alenia Space and 3D Systems collaborated. The adoption of DMP stimulates the aerospace and defense industry worldwide [77]. The Thales Alenia Space antenna brackets are shown in Figure 16.

**Figure 16.** Thales Alenia Space antenna brackets [85].

## 5. Conclusions

The importance of satellite brackets, various types of satellite brackets, the advanced materials used, and their processing using AM have been extensively discussed in the article. The bracket is a structural support component used in a satellite. Assembling a satellite is a complicated process that includes the use of several brackets. In addition to support providing, brackets add self-weight to the satellite which can be of major concern. Hence, weight reduction of brackets without comprising the strength of the bracket can be of paramount importance.

Processing of brackets using AM has resulted in lightweight yet strong brackets. In addition to the processing, significant structural changes that can serve the demand for a high strength-to-weight ratio are also achieved as a result of DFAM. The structural optimization using DFAM is an important aspect of AM that has brought tremendous changes in the way the brackets are processed as compared to conventional processing. Several bracket manufacturers globally have adopted AM for processing aircraft and satellite brackets. Several types of AM processed brackets including angle brackets, antenna brackets, reaction wheel brackets, Thales Alenia space antenna brackets, mounting brackets of the thruster, and the camera head unit bracket manufactured by various manufacturers are in real-time applications in the satellites.

Materials such as Al-based, Ti-based, stainless steel, NiTi-based, and composites have been successfully processed by AM for making high-performance brackets with unique designs. The advanced materials used in space vehicles are replacing conventional materials and are capable of retaining the most important properties of strength, rigidity, and incredibly lightweight. A single kilogram of mass reduction can reduce the cost of initiation by several thousand dollars. Techniques like SLM, DMLS, SLS, etc. are used by the majority of manufacturers for making brackets. Several manufacturers around the globe have successfully made satellite brackets using AM approach. Such AM processed brackets are found to be efficient and light in weight which is desired in aerospace applications.

The current age-supporting brackets are much different from those produced by conventional manufacturing techniques. The versatility of AM including DFAM can result in reformations in the design, size, shape, weight, and performance of the brackets. As a result, the world is witnessing tremendous newness in the manufacturing of brackets. Although the results and success may vary from case to case, on a whole, AM appears to be a promising technique for producing high strength-to-weight ratio brackets for aircraft and satellite applications.

**Author Contributions:** Conceptualization, A.B. (Ajit Behera); methodology, A.B. (Ajit Behera), A.B. (Asit Behera) and T.A.N.; writing—original draft preparation, S.K.S., K.A.M. and C.P.; writing—review and editing, H.M.V.; funding acquisition, K.K.S. and S.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** Ministry of Science and Higher Education of the Russian Federation under the strategic academic leadership program 'Priority 2030': Agreement 075-15-2021-1333 dated 30 September 2021.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Yongxin, G.; Lihua, Z.; Zhijia, L.; Yimin, G.; Ling-xi, M. Optimization Design of Star Tracker Bracket of Small Satellite for 3D Printing. In Proceedings of the 2019 5th International Conference on Control, Automation and Robotics (ICCAR), Beijing, China, 19–22 April 2019; pp. 808–811.
2. Haase, C.; Bültmann, J.; Hof, J.; Ziegler, S.; Bremen, S.; Hinke, C.; Schwedt, A.; Prahl, U.; Bleck, W. Exploiting Process-Related Advantages of Selective Laser Melting for the Production of High-Manganese Steel. *Materials* **2017**, *10*, 56. [CrossRef]
3. Orme, M.; Madera, I.; Gschweitl, M.; Ferrari, M. Topology Optimization for Additive Manufacturing as an Enabler for Light Weight Flight Hardware. *Designs* **2018**, *2*, 51. [CrossRef]
4. Sinha, A.; Swain, B.; Behera, A.; Mallick, P.; Samal, S.K.; Vishwanatha, H.M.; Behera, A. A Review on the Processing of Aero-Turbine Blade Using 3D Print Techniques. *J. Manuf. Mater. Process.* **2022**, *6*, 16. [CrossRef]
5. Lighter Titanium Aerospace Part. Available online: https://www.materialise.com/en/cases/a-63-lighter-titanium-aerospace-part (accessed on 17 July 2022).
6. Poomathi, N.; Singh, S.; Prakash, C.; Subramanian, A.; Sahay, R.; Cinappan, A.; Ramakrishna, S. 3D Printing in Tissue Engineering: A State of the Art Review of Technologies and Biomaterials. *Rapid Prototyp. J.* **2020**, *26*, 1313–1334. [CrossRef]
7. Singh, H.; Kumar, R.; Prakash, C.; Singh, S. HA-Based Coating by Plasma Spray Techniques on Titanium Alloy for Orthopedic Applications. *Mater. Today Proc.* **2022**, *50*, 612–628. [CrossRef]
8. Gibson, I.; Rosen, D.; Stucker, B. *Additive Manufacturing Technologies*, 2nd ed.; Springer: New York, NY, USA, 2015; ISBN 978-1-4939-2112-6.
9. Korotchenko, A.Y.; Khilkov, D.E.; Tverskoy, M.V. The Development of New Materials and Modes of Casting Metal Powder Mixtures (MIM Technology). *Mater. Sci. Forum* **2019**, *945*, 538–542. [CrossRef]
10. Ramanath, H.S.; Chua, C.K.; Leong, K.F.; Shah, K.D. Melt Flow Behaviour of Poly-ε-Caprolactone in Fused Deposition Modelling. *J. Mater. Sci. Mater. Med.* **2008**, *19*, 2541–2550. [CrossRef] [PubMed]

11. Singh, A.; Singh, H. Metal Additive Manufacturing: From History to Applications. In *Innovations in Additive Manufacturing: Springer Tracts in Additive Manufacturing*; Khan, M.A., Jappes, J.T.W., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 3–32; ISBN 978-3-030-89401-6.
12. Matias, E.; Rao, B. 3D Printing: On Its Historical Evolution and the Implications for Business. In Proceedings of the 2015 Portland International Conference on Management of Engineering and Technology (PICMET), Portland, OR, USA, 2–6 August 2015; pp. 551–558.
13. Cuellar, J.S.; Smit, G.; Plettenburg, D.; Zadpoor, A. Additive Manufacturing of Non-Assembly Mechanisms. *Addit. Manuf.* **2018**, *21*, 150–158. [CrossRef]
14. Ford, S.; Despeisse, M. Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges. *J. Clean. Prod.* **2016**, *137*, 1573–1587. [CrossRef]
15. Gardan, J. Additive Manufacturing Technologies: State of the Art and Trends. *Int. J. Prod. Res.* **2016**, *54*, 3118–3132. [CrossRef]
16. Huang, Y.; Leu, M.C.; Mazumder, J.; Donmez, A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. *J. Manuf. Sci. Eng.* **2015**, *137*. [CrossRef]
17. Strano, G.; Hao, L.; Everson, R.M.; Evans, K.E. A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing. *Int. J. Adv. Manuf. Technol.* **2013**, *66*, 1247–1254. [CrossRef]
18. Emmelmann, C.; Sander, P.; Kranz, J.; Wycisk, E. Laser Additive Manufacturing and Bionics: Redefining Lightweight Design. *Phys. Procedia* **2011**, *12*, 364–368. [CrossRef]
19. Bandyopadhyay, A.; Heer, B. Additive Manufacturing of Multi-Material Structures. *Mater. Sci. Eng. R Rep.* **2018**, *129*, 1–16. [CrossRef]
20. Dilberoglu, U.M.; Gharehpapagh, B.; Yaman, U.; Dolen, M. The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manuf.* **2017**, *11*, 545–554. [CrossRef]
21. Singh, S.; Prakash, C.; Antil, P.; Singh, R.; Królczyk, G.; Pruncu, C.I. Dimensionless Analysis for Investigating the Quality Characteristics of Aluminium Matrix Composites Prepared through Fused Deposition Modelling Assisted Investment Casting. *Materials* **2019**, *12*, 1907. [CrossRef]
22. Ruan, G.; Wang, Z.; Long, C.; Zhang, Y. A Study on Thermal Stability of Star-Sensitive Brackets Made up of Different Material Based on Precision Measurement. *J. Phys. Conf. Ser.* **2020**, *1650*, 022045.
23. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
24. Khalid, M.Y.; Arif, Z.U.; Ahmed, W. 4D Printing: Technological and Manufacturing Renaissance. *Macromol. Mater. Eng.* **2022**, *307*, 2200003. [CrossRef]
25. Orme, M.E.; Gschweitl, M.; Ferrari, M.; Vernon, R.; Madera, I.J.; Yancey, R.; Mouriaux, F. Additive Manufacturing of Lightweight, Optimized, Metallic Components Suitable for Space Flight. *J. Spacecr. Rocket.* **2017**, *54*, 1050–1059. [CrossRef]
26. Brevault, L.; Balesdent, M.; Morio, J. *Aerospace System Analysis and Optimization in Uncertainty*; Springer: Cham, Switzerland, 2020; ISBN 978-3-030-39125-6.
27. Booth, P.; Gilmore, J.; Lluch, E.V.; Harvey, M. Enhancements to Satellite Feed Chain Performance, Testing and Lead-Times Using Additive Manufacturing. In Proceedings of the 2016 10th European Conference on Antennas and Propagation (EuCAP), Davos, Switzerland, 10–15 April 2016; pp. 1–5.
28. Zhu, L.; Li, N.; Childs, P.R.N. Light-Weighting in Aerospace Component and System Design. *Propuls. Power Res.* **2018**, *7*, 103–119. [CrossRef]
29. Al Alloys for Aerospace Applications. Available online: http://www.dierk-raabe.com/aluminium-alloys-for-aerospace-applications/ (accessed on 2 November 2021).
30. Metal Additive Manufacturing: Download the Current Issue .... Available online: https://www.metal-am.com/metal-additive-manufacturing-magazine/ (accessed on 2 November 2021).
31. Xia, X.; Xiao, L.; Chen, Q.; Li, H.; Tan, Y. Hot Forging Process Design, Microstructure, and Mechanical Properties of Cast Mg–Zn–Y–Zr Magnesium Alloy Tank Cover. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 4199–4208. [CrossRef]
32. Suseelan Nair, K.; Mittal, M.C. Rare Earths in Magnesium Alloys. *Mater. Sci. Forum* **1991**, *30*, 89–104. [CrossRef]
33. Aluminium Bracket for New Eurostar E3000 Satellite Platforms. Available online: https://www.metal-am.com/airbus-defence-and-space-develops-aluminium-bracket-for-new-eurostar-e3000-satellite-platforms/ (accessed on 17 July 2022).
34. Benedetti, M.; Cazzolli, M.; Fontanari, V.; Leoni, M. Fatigue Limit of Ti6Al4V Alloy Produced by Selective Laser Sintering. *Procedia Struct. Integr.* **2016**, *2*, 3158–3167. [CrossRef]
35. Singh, N.; Hameed, P.; Ummethala, R.; Manivasagam, G.; Prashanth, K.G.; Eckert, J. Selective Laser Manufacturing of Ti-Based Alloys and Composites: Impact of Process Parameters, Application Trends, and Future Prospects. *Mater. Today Adv.* **2020**, *8*, 100097. [CrossRef]
36. Attar, H.; Calin, M.; Zhang, L.C.; Scudino, S.; Eckert, J. Manufacture by Selective Laser Melting and Mechanical Behavior of Commercially Pure Titanium. *Mater. Sci. Eng. A* **2014**, *593*, 170–177. [CrossRef]
37. Das, S.; Wohlert, M.; Beaman, J.J.; Bourell, D.L. Processing of Titanium Net Shapes by SLS/HIP. *Mater. Des.* **1999**, *20*, 115–121. [CrossRef]
38. Monogarov, K.A.; Pivkina, A.N.; Grishin, L.I.; Frolov, Y.V.; Dilhan, D. Uncontrolled Re-Entry of Satellite Parts after Finishing Their Mission in LEO: Titanium Alloy Degradation by Thermite Reaction Energy. *Acta Astronaut.* **2017**, *135*, 69–75. [CrossRef]

39. Chowdhury, S.; Yadaiah, N.; Prakash, C.; Ramakrishna, S.; Dixit, S.; Gulta, L.R.; Buddhi, D. Laser Powder Bed Fusion: A State-of-the-Art Review of the Technology, Materials, Properties & Defects, and Numerical Modelling. *J. Mater. Res. Technol.* 2022, *in press*. [CrossRef]
40. Mohd Yusuf, S.; Cutler, S.; Gao, N. Review: The Impact of Metal Additive Manufacturing on the Aerospace Industry. *Metals* **2019**, *9*, 1286. [CrossRef]
41. Karayel, E.; Bozkurt, Y. Additive Manufacturing Method and Different Welding Applications. *J. Mater. Res. Technol.* **2020**, *9*, 11424–11438. [CrossRef]
42. Antenna Mount Bracket. Available online: https://www.kuschle.com/top-antenna-mounting-brackets-car/ (accessed on 2 November 2021).
43. Behera, A. *Advanced Materials—An Introduction to Modern Materials Science*, 1st ed.; Springer: Cham, Switzerland, 2022; ISBN 978-3-030-80359-9.
44. Jeong, J.W.; Shin, K.C.; Kim, K.W.; Lim, J.H.; Lee, J.J. SMA Damped Tape Spring Hinge for Quasi-Static Deployment of a Satellite Solar Array. *Appl. Mech. Mater.* **2015**, *705*, 96–100. [CrossRef]
45. Uozumi, T.; Kito, A. Carbon Fibre-Reinforced Plastic Truss Structures for Satellite Using Braiding/Resin Transfer Moulding Process. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2007**, *221*, 93–101. [CrossRef]
46. Singh, B.; Chandel, S.; Singhal, P. Investigation of Mechanical Properties of Synthesized AA2024-T351/$SiO_2$ Metal Matrix Nano-Composite. *Mater. Today Proc.* **2020**, *26*, 1082–1086. [CrossRef]
47. Vishwanatha, H.M.; Eravelly, J.; Kumar, C.S.; Ghosh, S. Microstructure and Mechanical Properties of Aluminum-Alumina Bulk Nanocomposite Produced by a Novel Two-Step Ultrasonic Casting Technique. *Metall. Mater. Trans. A* **2016**, *47*, 5630–5640. [CrossRef]
48. Vishwanatha, H.M.; Eravelly, J.; Kumar, C.S.; Ghosh, S. Dispersion of Ceramic Nano-Particles in the Al-Cu Alloy Matrix Using Two-Step Ultrasonic Casting and Resultant Strengthening. *Mater. Sci. Eng. A* **2017**, *708*, 222–229. [CrossRef]
49. Rajak, D.K.; Wagh, P.H.; Kumar, A.; Behera, A.; Pruncu, C.I. Advanced Polymers in Aircraft Structures. In *Materials, Structures and Manufacturing for Aircraft*; Kuşhan, M.C., Gürgen, S., Sofuoğlu, M.A., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 65–88; ISBN 978-3-030-91873-6.
50. Waterman, P. 3D Printing for Space: FDM Materials on Real Missions. Available online: https://www.padtinc.com/blog/3d-printing-for-space-fdm-materials-on-real-missions/ (accessed on 2 November 2021).
51. Tech Briefs. Available online: https://www.techbriefs.com/component/content/article/tb/pub/features/articles/33914 (accessed on 2 November 2021).
52. Xiao, Z.; Yang, Y.; Wang, D.; Song, C.; Bai, Y. Structural Optimization Design for Antenna Bracket Manufactured by Selective Laser Melting. *Rapid Prototyp. J.* **2018**, *24*, 539–547. [CrossRef]
53. Razvan, P.; Ancuta, P. Applications of the Selective Laser Melting Technology in the Industrial and Medical Fields. In *New Trends in 3D Printing*; IntechOpen Limited: London, UK, 2016; ISBN 978-953-51-2480.
54. Jafari, D.; Wits, W.W. The Utilization of Selective Laser Melting Technology on Heat Transfer Devices for Thermal Energy Conversion Applications: A Review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 420–442. [CrossRef]
55. Prashanth, K.G.; Scudino, S.; Maity, T.; Das, J.; Eckert, J. Is the Energy Density a Reliable Parameter for Materials Synthesis by Selective Laser Melting? *Mater. Res. Lett.* **2017**, *5*, 386–390. [CrossRef]
56. Ansari, M.J.; Nguyen, D.-S.; Park, H.S. Investigation of SLM Process in Terms of Temperature Distribution and Melting Pool Size: Modeling and Experimental Approaches. *Materials* **2019**, *12*, 1272. [CrossRef]
57. Greco, S.; Gutzeit, K.; Hotz, H.; Kirsch, B.; Aurich, J.C. Selective Laser Melting (SLM) of AISI 316L—Impact of Laser Power, Layer Thickness, and Hatch Spacing on Roughness, Density, and Microhardness at Constant Input Energy Density. *Int. J. Adv. Manuf. Technol.* **2020**, *108*, 1551–1562. [CrossRef]
58. Trevisan, F.; Calignano, F.; Lorusso, M.; Pakkanen, J.; Aversa, A.; Ambrosio, E.P.; Lombardi, M.; Fino, P.; Manfredi, D. On the Selective Laser Melting (SLM) of the AlSi10Mg Alloy: Process, Microstructure, and Mechanical Properties. *Materials* **2017**, *10*, 76. [CrossRef] [PubMed]
59. Zhang, Y.; Wu, L.; Guo, X.; Kane, S.; Deng, Y.; Jung, Y.-G.; Lee, J.-H.; Zhang, J. Additive Manufacturing of Metallic Materials: A Review. *J. Mater. Eng. Perform.* **2018**, *27*, 1–13. [CrossRef]
60. Abdulhameed, O.; Al-Ahmari, A.; Ameen, W.; Mian, S.H. Additive Manufacturing: Challenges, Trends, and Applications. *Adv. Mech. Eng.* **2019**, *11*, 1687814018822880. [CrossRef]
61. Zhang, B.; Li, Y.; Bai, Q. Defect Formation Mechanisms in Selective Laser Melting: A Review. *Chin. J. Mech. Eng.* **2017**, *30*, 515–527. [CrossRef]
62. Ali, H.; Ghadbeigi, H.; Mumtaz, K. Processing Parameter Effects on Residual Stress and Mechanical Properties of Selective Laser Melted Ti6Al4V. *J. Mater. Eng. Perform.* **2018**, *27*, 4059–4068. [CrossRef]
63. Aboulkhair, N.T.; Everitt, N.M.; Ashcroft, I.; Tuck, C. Reducing Porosity in AlSi10Mg Parts Processed by Selective Laser Melting. *Addit. Manuf.* **2014**, *1–4*, 77–86. [CrossRef]
64. Ardila, L.C.; Garciandia, F.; González-Díaz, J.B.; Álvarez, P.; Echeverria, A.; Petite, M.M.; Deffley, R.; Ochoa, J. Effect of IN718 Recycled Powder Reuse on Properties of Parts Manufactured by Means of Selective Laser Melting. *Phys. Procedia* **2014**, *56*, 99–107. [CrossRef]

65. Space-Propulsion-Satellites@Www.Eos.Info. Available online: https://www.eos.info/en/3d-printing-examples-applications/aerospace-3d-printing/space-propulsion-satellites (accessed on 2 November 2021).
66. Khorasani, A.; Gibson, I.; Goldberg, M.; Littlefair, G. Production of Ti-6Al-4V Acetabular Shell Using Selective Laser Melting: Possible Limitations in Fabrication. *Rapid Prototyp. J.* **2017**, *23*, 110–121. [CrossRef]
67. Pauly, S.; Löber, L.; Petters, R.; Stoica, M.; Scudino, S.; Kühn, U.; Eckert, J. Processing Metallic Glasses by Selective Laser Melting. *Mater. Today* **2013**, *16*, 37–41. [CrossRef]
68. SpaceX Reduced Costs. Available online: https://theconversation.com/how-spacex-lowered-costs-and-reduced-barriers-tospace-112586 (accessed on 1 January 2021).
69. Marshall Space NASA. Available online: https://www.nasa.gov/centers/marshall/news/background/facts/astp.html (accessed on 1 January 2021).
70. Altair RUAG Bracket. Available online: https://www.altair.com/resource/ruag-space-satellite-antenna-bracket (accessed on 1 January 2021).
71. Du Plessis, A.; Yadroitsev, I.; Yadroitsava, I.; Le Roux, S.G. X-ray Microcomputed Tomography in Additive Manufacturing: A Review of the Current Technology and Applications. *3D Print. Addit. Manuf.* **2018**, *5*, 227–247. [CrossRef]
72. European Space Agency. Available online: http://www.esa.int/Enabling_Support/Space_Engineering_Technology/Europe_s_3D_printer_set_for_Space_Station (accessed on 1 January 2021).
73. DMRC PADERBORN. Available online: https://dmrc.uni-paderborn.de/content/innovation/am-for-satellites-reaction-wheel-bracket (accessed on 16 November 2021).
74. 3d Systems Space Bus. Available online: https://www.3dsystems.com/customer-stories/design-and-additive-manufacturing-expertise-3d-systems-serve-thales-alenia-space (accessed on 6 November 2021).
75. Thales Alenia Space. Available online: https://www.thalesgroup.com/en/worldwide/space/press-release/thales-alenia-space-takes-3d-printing-series-production (accessed on 6 November 2021).
76. Yakacki, C. Lockheed Martin GPS Satellite Bracket—Manufacturing Team at University of Corlodo, Denver. Available online: https://engineering.ucdenver.edu/current-students/capstone-expo/archived-expos/spring-2020/mechanical-engineering-1/mech7-lockheed-martin-gps-satellite-bracket-manufacturing-team (accessed on 2 November 2021).
77. 3d-Me. Available online: https://www.3d-me.com/thales-alenia-space-and-3d-systems (accessed on 2 November 2021).
78. Chen, M.H.; Wang, C.H.; Huang, J.D.; Chen, C.R. Thermal Control on the Sensitive Star Tracker of FORMOSAT-5 Satellite: Design, Modeling and Validation. In Proceedings of the 11th International Energy Conversion Engineering Conference, San Jose, CA, USA, 14–17 July 2013; pp. 1–8.
79. Jain, T.K.B.; G, B.R.; Sundaram, M. Stress Analysis for Wing Attachment Brackets. *Int. J. Eng. Res. Technol.* **2016**, *5*, 568–571. [CrossRef]
80. CHU. Available online: https://www.trumpf.com/en_INT/solutions/applications/additive-manufacturing/laser-metal-fusion/use-case-star-tracker/ (accessed on 2 November 2021).
81. Blakey-Milner, B.; Gradl, P.; Snedden, G.; Brooks, M.; Pitot, J.; Lopez, E.; Leary, M.; Berto, F.; du Plessis, A. Metal Additive Manufacturing in Aerospace: A Review. *Mater. Des.* **2021**, *209*, 110008. [CrossRef]
82. Additive Manufacturing Study Shows Cuts in Material Consumption and Reduced $CO_2$ Emissions. Available online: https://www.pm-review.com/articles/additive-manufacturing-study-shows-cuts-in-material-consumption-and-reduced-co%E2%82%82-emissions/ (accessed on 17 July 2022).
83. WIRE. Available online: https://www.aircraftsystemstech.com/2017/05/wiring-installation.html (accessed on 2 November 2021).
84. Sivaiah, A. Innovative Bracket Design Concepts for the Installation of Aircraft Systems. *J. Aerosp. Technol. Manag.* **2012**, *4*, 289–295. [CrossRef]
85. 3D Systems. Available online: https://www.3dsystems.com/learning-center/case-studies/tipping-point (accessed on 3 November 2021).