A REVIEW ON PROPERTIES OF AEROSPACE MATERIALS THROUGH ADDITIVE MANUFACTURING

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Abstract- Additive Manufacturing (AM) process has been effective in producing materials that are being utilized by the aerospace industry in order to improve their performance by increasing their properties. Industry now opts for this technique over conventional methods as it has enormous advantages and applications. This Additive Manufacturing process is capable of producing complex near net shape of parts. The materials that are produced by this technique for aerospace industries are metal alloys, metal matrix composites, polymer matrix composites, ceramic matrix composites and nano-composites. Many of the composite materials are still under research and development.

In this study, a literature review on the mechanical properties of the materials that are used in the aerospace industry by AM process is discussed and these properties are also compared with the materials produced by conventional methods. The purpose of this review is to highlight the importance of Additive Manufacturing technique and also understand the effect of this process on the materials tested. During this work, the evolution of materials in the aerospace sector, the basic concept of AM technique, the application of the materials, the properties obtained when processing is done, the limitations and the scope for research are given.

Keywords- Additive Manufacturing, Selective Laser Melting, Aerospace materials, Mechanical properties.

I. INTRODUCTION

The Aerospace sector currently in the top of the technological industry, deals with tons of materials for testing and manufacturing. They demand a top notch set of materials that serve their very purpose. The quality of material opting for this industry has evolved since its inception in 1903, when the wright brothers built the first flight, building an engine block made up of Aluminium. But, today many metal alloys with different composition, metal matrix composites, polymer matrix composites, ceramic matrix composites, nano composites, serve the different functions. These materials are expected to showcase their physical and chemical strength, along with their least effect on the environment.

The First full metal airplane was built in 1915. The stainless steel production sought an attraction for aerospace industry in the early 1930’s. The application of plastics came into use in the mid of 1930’s, when manufacturers used plastics for designing pressurized cockpits and cabins. In 1942, the aircraft noses were built using Fibre glass, which provided housing for radar transmission and eased the radio frequencies. Later Titanium served as a potential material in this industry. Ti alloys were being used in airframes. Composite materials often contribute to 20-40% of airframe weight. In 1969, the Carbon fibre composites were used in the spacecraft and aero plane structures to provide high quality structures.

Ceramics were introduced in the year 1981. They played an important role in the making of space shuttle, ‘The Orbiter’. The bottom layer of shuttle made up of silica fibre composites provides an excellent thermal insulation during the re-entry time. Figure 1 shows a sectional view of space shuttle and its built up characteristics. In the late 90’s, the development of Al-li alloys combined with
Mn and Zr formulated. This synergic effect highlights the light weight characteristics along with high corrosion resistance and mechanical properties. Today Space X – Falcon 9 incorporates the advanced properties of this alloy for manufacturing its two stage reusable rockets. The Airbus implements a considerable amount of Aluminium-Lithium for the development of wings and fuselage. The Al-Li alloys have superior fatigue crack growth performance. The Airbus A380 airliner uses GLARE composites- “GLASS-Reinforced” Fiber Metal Laminate (FML).

![Figure 1. Sectional view of space shuttle and its built up characteristics](image)

The Boeing 787 Dreamliner uses specific composites along with combinations of metals and it alloys. Boeing787- Composites are also used extensively in both expendable launch vehicle and satellite structure.

### II. WHY ADDITIVE MANUFACTURING?

Additive manufacturing also called as “3D printing” or “Rapid prototyping” is the process of synthesizing three dimensional objects by adding materials successively with a help of computer-aided design model. Additive Manufacturing is being used for the production of series of components for the most demanding applications [1]. The use of additive manufacturing technology is developing in many industries: Aerospace engineering, Medical, Dental applications, Automotive and transportation etc. [2].

The advantages of using this technique over conventional methods are increased design freedom, structures that are light weight, near-net shape capability, production time being very less, environment sustainability and economic low volume production.

AM processes are divided into 7 groups: 1. Material extrusion, 2. Material jetting, 3. Binder jetting, 4. Sheet lamination, 5. Vat photo polymerization, 6. Powder bed fusion and 7. Direct energy deposition.

The three principle involved in the additive manufacturing technique are: Modeling, Printing and Finishing. In modeling, 3D models are created using computer-aided software via a scanner. The scanner looks for information regarding the shape and the appearance of real object and then creates
a digital model based on the information obtained. In the printing stage, the 3D model is printed using STL file (stereolithographic file). But before printing, it looks for errors. The errors are produced in output STL file such as holes, noise shells, manifold errors, etc. Once the scanning of the errors is done, the STL file is processed using a software called “SLICER”. This software creates series of thin layers of the designed model and produces a G-code file that contains the set of instructions for the 3D printer. Then the printing of the model is carried out by scanning layer by layer and the time required to create the object depends upon the type of material and also the complex nature of the object. In the finishing stage, surface finish, multiple colors for the objects, internal supports for overhanging objects, etc. of the printed part is carried out. The sequence of process carried out in additive manufacturing process is shown in Figure 2.

There are different additive manufacturing techniques to produce parts and it depends on the type of material to be used for manufacturing the product. Some of the processes includes:
1. Selective laser sintering
2. Selective laser melting
3. Fused deposition modeling
4. Stereolithography
5. Fused Filament Fabrication
6. Laminated object manufacturing
7. Solid ground curing.

Table 1 shows different processes, materials and also the layer deposition technique for the state of starting material [3, 4]. In-situ Fraunhofer ILT (German research institute) uses AM technology (Laser Metal Deposition) to repair aerospace components. In addition to several advantages, additive manufacturing technique has certain limitations which include:
- The part size is limited to the powder bed size, such as 250*250*250mm
- Usually suitable for small series productions and not mass production
- Parts made by additive manufacturing technique tend to show anisotropy in the Z-axis.

Figure 2. Process sequence in Additive Manufacturing
Table 1. Different AM processes, materials and the layer deposition technique for the state of starting material [3,4]

| State of starting material | Process | Material preparation | Layer creation method | Typical materials | Applications |
|---------------------------|---------|----------------------|----------------------|------------------|--------------|
| Filament                  | FDM     | Melted in nozzle      | Continuous extrusion & deposition | Thermoplastics, waxes | Prototypes, Casting patterns |
|                           | Robocasting | Paste in nozzle      | Continuous extrusion | Ceramic paste     | Functional parts |
| Liquid                    | SLA     | Resin in vat         | Laser scanning       | UV curable resin  | Prototypes, Casting patterns |
|                           | MJM     | Polymer in jet       | Ink-Jet printing     | Acrylic plastics, wax | Prototypes, Casting patterns |
| Powder                    | SLS     | Powder in bed        | Laser Scanning       | Thermoplastics, waxes, Metal powder, ceramics powder | Prototypes, Casting patterns, Metal and ceramic |
|                           | SLM     | Powder in bed        | Laser scanning       | Metal             | Tooling, Functional parts |
|                           | EBM     | Powder in bed        | Electron beam scanning | Metal          | Tooling, Functional parts |
|                           | 3DP     | Powder in bed        | Drop-on-demand binder printing | Polymer, Metal, ceramic, other powders | Prototypes, Casting shells, Tooling |
| Solid Sheet               | LOM     | Laser Cutting        | Feeding and binding of sheets with adhesives | Paper, Plastic, Metal | Prototypes, Casting Models |

III. METAL ALLOYS USING ADDITIVE MANUFACTURING

The metal alloys are chosen because they satisfy the standards of quality, resistant to corrosion, lightweight, excellent physical and chemical properties. These alloys have the primary elements as Aluminium, Titanium, Stainless steel and Nickel.

3.1. Aluminium alloys: Aluminium was first put into use in 1903, when wright brothers developed an engine with a light weight Aluminium engine block. In 1930, the demand for Aluminium became meteoric. Its unique characteristics of being a light weight metal, high strength and high workability make it a potential material for aerospace industry. Today, there are over 27,000 commercial aircraft flying in the world and many thousands of light aircraft and helicopters. The fuselage, seats and internal fittings are made using Al, for light weight and reducing payload purposes. Currently material property enhancement technique such as Additive Manufacturing is used to develop the same parts/tools (as the conventional methods) for aerospace industry with better material property.

3.1.1. Aluminium 7075: Al7075 being the primary alloy, its properties were tested after being additively manufactured. Reschetnik et al. [5] investigated the fatigue crack behaviour & mechanical property of Additively manufactured, EN AW 7075 Al alloy. SLM process was used to process the manufacturing of Al7075 and some of the manufacturing specimens were subjected to heat treatment. The fatigue crack growth remained same for both the heat treated and those which weren’t and the mechanical property remained lower than conventionally produced ones. Now, changing the alloy composition lead to favourable results. Maria L. Montero Sistiaga et al. [6] have conducted the experiment by the addition of Si into Al7075. Si was added under different compositions. The effect
of Si addition created crack free parts. The process parameters for the SLM process (carried out by LM-Q: Laser melting with quality control machine, Germany) were: 1) Power = 200w-300w, 2) Scan speed = 100-1600 m/s, 3) Hatching = 110µm, and 4) Layer thickness = 30µm. The specimens were subject to heat treatment at different temperatures. After etching, SEM images were taken and crystallographic orientation was determined by X-ray Diffraction. It was concluded that only applying aging treatment following SLM provided better hardness results. A Vickers hardness tester FV-700 (0.5 kg load for 15s with five repetitions per sample) was selected for conducting the test. When Al7075+4% Si was processed by SLM along with subsequent aging treatment, it resulted in hardness values (171±4 HV) comparable to the conventionally produced Al7075 with T6 treatment (175 HV) [7]. It was noted that the ultimate compressive strength and the ultimate compressive strain were inferior to conventional Al7075. It is seen that there is certain amount of decrease in MgZn₂ and Mg₂Si (The presence of Si, Mg can also form Mg₂Si, a hardening phase observed for casting aluminium alloys) phase. X- Ray Fluorescence results show that there is decrease in percentage in Zn and Mg. Table 2 shows this property of SLM manufactured component [8]. The fine dispersion of MgZn₂ particles is known to be partly responsible for the high strength of Al7075. Further research is needed for metallurgical effects of this Si addition and the subsequent mechanical properties.

3.1.2. Aluminium AlSi10Mg: It comprises of Aluminium alloy with 10%Si along with minor amount of Mg, Fe and other elements. The material is characterised by a very high hardness, corrosion resistance, low density (good for light weight components), high stability and high specific strength (strength to mass ratio). The presence of silicon makes the alloy both harder and stronger than pure aluminium due to the formation of Mg₂Si precipitate. Due to the high cooling rates during the construction process, the mechanical properties of the additively manufactured components are better than the corresponding casting process. The production of these components is done by Selective Laser Melting (SLM). The components show a homogeneous and almost pore-free structure. Selective laser melting process is carried out on the alloy with the process parameters (Power = 400W, layer thickness 25µm) following which heat treatment is carried on. It is plausible to modify the mechanical properties of the manufactured components by applying T6 heat treatment and elongation can be improved. Further, the anisotropic properties are reduced as result of the layered structure. It is used in Aircraft and Space applications. The Mechanical property of additively manufactures AlSi10Mg components is shown in Table 3 [9].

| Experiment | Zn (weight %) | Mg (weight %) |
|------------|---------------|----------------|
| Before SLM | 6.52%         | 2.48%          |
| After SLM  | 3.06%         | 1.86%          |

Table 2. Property of SLM manufactured component[8]

Table 3. Mechanical properties of Additively manufactured AlSi10Mg component [9]

| MECHANICAL PROPERTIES OF AM COMPONENTS                      | As Built                     | Stress relieved (note 2*) |
|------------------------------------------------------------|------------------------------|----------------------------|
| Tensile Strength (UTS) (note 1*)                            | 442 MPa ± 6 MPa              | 334 MPa ± 1Mpa             |
| Horizontal direction (XY)                                  | 417 MPa ± 27 Mpa             | 339 MPa ± 6 Mpa            |
| Vertical direction (Z)                                     | 264 MPa ± 2 Mpa              | 211 MPa ± 2Mpa             |
| Yield Strength (note 3*)                                   | 206 MPa ± 6 Mpa              | 174MPa ± 4Mpa              |
| Horizontal direction (XY)                                  | 9% ± 1%                      | 9%  2%                     |
| Vertical direction (Z)                                     | 6% ± 2%                      | 4%  1%                     |
| Elongation at break (note 3*)                              | 71 GPa ± 5 GPa               | 71 GPa ± 2 Gpa             |
| Horizontal direction (XY)                                  | 68 GPa ± 2 GPa               | 66 GPa ±3 Gpa              |
| Modulus of elasticity (note 3*)                             | 68 GPa ± 2 Gpa               | 66 GPa ±3 Gpa              |
| Hardness (Vickers) (note 4*)                                | 68 GPa ± 2 Gpa               | 66 GPa ±3 Gpa              |
Horizontal direction (XY) | 119 HV0.5 ± 5HV0.5 | 103HV0.5 ± 5 HV0.5
Vertical direction (Z) | 123HV 0.5  ± 2 HV0.5 | 103 HV0.5 ± 5 HV0.5

Surface roughness (note 5*)

| Horizontal direction (XY) | 5 µm to 9 µm |
| Vertical direction (Z) | 7 µm to 9µm |

* Note 1: In the range of 20 ºC to 100 ºC.
Note 2: Stress relieved at 300 ºC ±10 ºC for 2 hr, air cooled.
Note 3: Tested at ambient temperature by Nadcap and UKAS accredited independent laboratory. Test ASTM E8 Machined before testing.
Note 4: Tested to ASTM E384 -11, after polishing.
Note 5: Tested to JIS B 0601-2001 (ISO 97), as built after bead blasting[9]

3.1.3. Aluminium AlSi9Cu3: The primary constituent is Aluminium, 7.5-9.5% of Si, 2-3.5% of Cu and less than 0.55% of Fe is present in the composition. It has excellent chemical resistance and Thermal conductivity. It is Preferred in gears and engine manufacturing. Cu provides high temperature strength. Si and Cu provide mechanical strength. The Mechanical properties of additively manufactured AlSi9Cu3 are listed in Table 4 [10].

| Material Characteristics | Unit | As Built | Testing at Elevated Temperature 250ºC |
|--------------------------|------|----------|--------------------------------------|
| Tensile Strength         | MPa  | 350±40   | 160±10                               |
| Yield Strength           | MPa  | 200±40   | 130±10                               |
| Elongation               | %    | 2.5±10   | 28±5                                 |
| E-Modulus                | GPa  | 62±10    | 62±10                                |
| Density                  | g/cm³|          | Approximately 2.7                   |

3.1.4. Scandium-Aluminium Alloy: It is a Quintessential aerospace alloy. Schmidtke et al. [11] investigated the properties of laser additive manufactured Al-Sc Alloy. Aluminium scandium master alloy (2 wt. % Sc) was molten and magnesium, manganese and zirconium were added. Sc composition was reduced to 0.66% and Mg to 4.5%. The process parameters were chosen at 195W power and 25µm layer thickness. Product was obtained at different orientations [0º, 45º, 90º]. The material was subjected to ageing at 325ºC for 4hours. Surface texture properties were put under examination [12].The specimens were subjected to mechanical testing. Yield strength was achieved at over 500MPa, Tensile strength at over 520MP which is comparable with Aluminium 2090 [13]. It was concluded that the addition of scandium enhanced the strength properties and effect on ductility. Vickers hardness test resulted at an average hardness value of 177HV. Average elongation was 14% and fracture was predominant at 45º orientation.

3.1.5. Aluminium-Lithium alloy: Al-Li 2099 and Al-Li 2199 is primarily used for aerospace applications. It has high corrosion resistance, good spectrum fatigue crack growth, strength & toughness. Rioja [14] investigated the use of new Al-Li alloys. They are used for (2199) lower wing skins and (2099) stringers and (2199) for fuselage skin. Alloy 2199 provides 18% weight improvement. Buy/Fly ratios are higher and also there is anisotropy in the material property and additive manufacturing will vary results.

3.1.6. Aluminium 7475: The main composition is Al(90.3%) ,Zn(5.7%),Mg(2.3%),Si(1.5%) and remaining by other elements. The presence of Zn and Mg in the alloys imparts higher strength to the alloy [15]. Aluminium 7475 alloy is not usually welded. Additive manufacturing of Aluminium 7475 can be done and subjected to heat treatment. The fatigue crack growth of Al7475 was studied by Chemin et al. [16]. Only few experiments have been conducted on additive manufacturing of Al7475.
3.2. Inconel IN718: Inconel 718 when subjected to selective laser sintering, effects on good tensile strength and fatigue strength. It is easy to weld and can be subjected to heat treatment. Alejandro hinojos et al. [17] investigated the property of 316 stainless steel and Inconel 718 after joining using electron beam melting. Metal powders used were, Inconel and 316 Stainless steel. Fabrication was achieved by EBM S12 System (from ARCAM AB) and it follows five routine step: Preheating of layer, melting of contour, melting of internal parts, lowering the Table, raking of powder to deposit uniform layer. Fabrication parameters for Inconel: laser beam v = 918mm/s, beam current = 12mA, beam focus = 22mA; Beam temp = 920ºC. Process Parameters for 316 Stainless Steel = 4350mm/s, Beam current = 17mA, Beam focus = 1mA, Beam temperature = 950ºC. Vickers test carried out with micro indentation at 300 g force at dwell of 15sec. Resulted in184HV ±11HV for 316 SS and 296HV for Inconel 718 substrate. Hardness remained at uniform value throughout in the HAZ (Heat Affected Zone). After post fabrication, microstructure did not reveal carbide’s presence [18].

3.3. Copper Alloy CuNi2SiCr: This alloy is known for its unique property for its role in electrical and thermal conductivity and has high stiffness. It has high corrosion resistance and mostly put into use for wear and sliding applications, also used in tooling because of its high strength. This alloy when prepared using SLM additive manufacturing showed great results. Table 5 shows the mechanical properties of additively processed CuNi2SiCr [19]. It has applications in electromechanical components, valves, tools etc.

| Material Characteristics | Unit | As Built | Precipitation Hardened |
|--------------------------|------|----------|------------------------|
| Tensile Strength         | MPa  | 251±10   | 595±10                 |
| Yield Strength           | MPa  | 192±10   | 508±10                 |
| Elongation               | %    | 34±5     | 15±5                   |
| E-Modulus                | GPa  | 89±5     | 97±10                  |

3.4. Stainless Steel 1.4542: Stainless steel when processed through additive manufacturing results in high strength. The material is corrosion resistant and has excellent ductility. This material possesses some good mechanical properties. The tensile strength has a range of 930MPa, but when heat treated it can go up to 1040-1100MPa. However there is no significant change in yield stress (450MPa) when heat treated and when not heat treated [20].

3.5. Titanium alloys: The first application of Titanium began early in the 1950’s and since then demand increased. The titanium satisfies all the required aircraft material properties. It has high corrosion resistance and excellent strength to weight ratio. Most of the titanium produced assist in the development of the aircraft engine. Titanium occupies the disk, blades, shafts, and casing of the aircraft engine. They are capable of operating at sub-zero conditions till600ºC[21].Currently, titanium makes up to 10% of empty weight of aircraft such as the Boeing 777. It has high strength up to 1200MPa. Titanium alloys with its application and attributes are listed in the Table 6. Ikuhiro Inagaki et al. (2014) discussed the property and applications of Ti alloys in aerospace industries [22].

3.5.1. Ti6Al4V: Eckart Uhlmann et al. [23] investigated the properties of additively manufactured Titanium alloy for aircraft components. The additive process is carried out by using SLM technique. The metal powder of Ti6Al4V is prepared and percentage composition tests are carried out on the metal powder, after which additive manufacturing process is carried out. An inert gas (Ar) environment is setup in the experiment to avoid oxidation phenomenon. The layer thickness during the process is maintained at 50μm. Post processing is done on the culmination stage of the product and results are compared with similar products at different experimental conditions.
Table 6. Titanium alloy application and attributes (Source: Titanium information group)

| Alloy                  | Application/Attributes                                      |
|-----------------------|-------------------------------------------------------------|
| Ti6Al4V               | Workhorse, General purpose high strength alloy               |
| Ti6Al2Sn4Zr2M0 (6-2-4-2) | Creep and oxidation resistant engine alloy                   |
| Ti6Al2Sn4Zr6M0 (6-2-4-6) | Creep and oxidation resistant alloy                         |
| Ti3AlV6Cu4Zr4 (Beta C) | Beta alloy with established spring applications             |
| Ti10V2Fe3Al           | Beta forging alloy used for 777 landing gear                 |
| Ti15V3Cr3Sn3Al        | High strength heat treatable beta sheet alloy                |
| Ti3Al2.5V             | Medium strength used in hydraulic tubing                    |
| Ti4Al4Mo2Sn           | Higher strength heat treatable airframe and engine alloy     |
| Ti5.5Al3.5Sn3Zr1Nb    | Advanced engine alloy, creep and oxidation resistant         |
| Ti5.8Al4Sn3.5Zr0.7Nb  | Advanced engine alloy, creep and oxidation resistant         |
| Ti5Al2SnMo2Zr4Cr (Ti17)| Advanced engine alloy, creep and oxidation resistant       |
| Ti15Mo3NbAl0.2Si (21S)| Oxidation and corrosion resistant beta sheet alloy          |

In the pre-processing stages, The chemical composition of the powder is checked using a chemical composition testing unit: SEM LEP 1455VP which uses energy dispersive X-rays, analysed using SEM [23]. One more parameter that is measured is the packed filling density. As packing density increases, the blow holes decreases. The tests results show that with packed filling density of 53%, the raw material has a density of 4.43g/cm³ [24].

The additive manufacturing process is carried using SLM technique and post processing activities are done on the specimen [25]: 1. Thermal post processing is carried out for reducing high residual stress and close micro cracks [26, 27]. 2. Hot isostatic pressing is carried out after the thermal post processing. Hot isostatic pressing is used to reduce micro blowholes through annealing at high temperature, It also reduces porosity, increases density, improves fatigue property, increases elongation [27]. Apart from mechanical properties, other properties are also tested. 3. Density is calculated using Archimedes principle. The results obtained show a value of 4.35g/cm³ [28, 29]. 4. Micro hardness is determined along XY as 316H30 and along XZ as 320H30 [30, 31].

IV. METAL MATRIX COMPOSITES USING ADDITIVE MANUFACTURING

Critical spacecraft missions involving dynamic and thermal disturbances require spacecraft structures to be of high pointing accuracy and dimensional stability. Composite materials with their high specific stiffness, light weight characteristics and low coefficient of thermal expansion, prove to be an essential contributor for this purpose. The continuous-fiber reinforced MMC was first used in tubular struts. It is used as frame and rib truss members in the mid-fuselage section and also for the landing gear drag link of the space shuttle orbiter[32, 33]. Therefore, the development of MCMs was primarily directed toward diffusion-bonding processing[34]. Metal matrix imparts ductility and thermal stability for the composites whereas the fiber increases strength and stiffness, also enhances the resistance to creep. The most commonly used MMC’s are Aluminium and its alloy such as Copper, Titanium and Magnesium. MMC can be categorized based on type of reinforcements- fibre or particulate. Powder metallurgy, squeeze casting, spray deposition are the most common fabrication processes of MMC’s. The constitutive models of the NiTi element and Al matrix have investigated average interface shear strength of 7.28 MPa and an effective coefficient of thermal expansion of zero at 135°C. Ultrasonic additive manufacturing uses ultrasonic metal welding to develop aluminium matrix composites [35, 36]. This composite comprises of aluminium matrices and embedded shape memory NiTi magnetostrictive, Galfenol and electro-active phases (Polyvinylidene fluoride phases). Advantage of this technique is that the working temperature is low as 25°C during
fabrication when compared with fabrication of other metal matrix fabrication which occurs at temperature as high as 500°C [37].

V. POLYMER MATRIX COMPOSITES USING ADDITIVE MANUFACTURING

Polymer matrix composites (PMCs) are comprised of a variety of short or continuous fibres bound together by an organic polymer matrix. It consists of polymer resin as the matrix phase and fibre as the reinforcement medium. The matrix phase of commercial PMCs can be classified as either thermoplastic or thermosetting. Thermoplastic polymers includes ABS, polyether-etherketone (PEEK) and liquid crystal polymers. Thermosetting polymers include polyesters, vinyl ester, epoxies and polyamides. Thermoplastic polymers are preferred over thermosetting polymers since they have extreme toughness, no toxicity and great hydraulic stability. Hence nowadays for most of the aerospace components, thermoplastic fibre reinforced composites are preferred over thermosetting polymer matrix composites. Polymerisation and poly-addition are some of the methods for the preparation of polymers for fibre reinforced composites. Reinforcing fibres are usually carbon, glass or aramids. PMCs usually contain about 60% reinforcing fibres by volume. The properties of fibre reinforced polymers are high strength at low weight, good impact, compression, fatigue properties, non-magnetic properties, and good thermal insulation. These properties usually depend upon the mechanical properties of fibre and matrix (polymer), their volume relative to one another, fibre length and also orientation within matrix. The addition of fibres improves the properties[38,39]. The primary matrix material in aerospace applications is epoxies and the most common reinforcements are carbon/graphite, aramid and glass. However high temperature thermoplastics such as PEEK, ABS are considered as preferable matrix materials for future aerospace applications. Structural weight of 3% composites is usually present in commercial aircrafts such as BOEING767. By the year 2000, PMCs made up 65% of structural weight of commercial transport aircrafts.

The manufacturing of polymer matrix composites through additive manufacturing for aerospace applications is increasing, since additive manufacturing of these PMCs tends to increase their mechanical properties when compared to conventional methods. Also additive manufacturing has been effective in processing these polymer composites as it has the ability to handle complex shapes with great design flexibility. But there are certain limitations that limit the use of additive manufacturing technology for polymer matrix composites. They are low production rate, small physical size of parts and mechanical property limitations [40].

5.1. Carbon Fiber Reinforced composites: Carbon fiber reinforced composites are composites that contain carbon fibre as the reinforcement medium and polymer resin as the matrix medium. Carbon fibre has been described as a fibre containing at least 90% carbon obtained by the complete pyrolysis of appropriate fibre. Carbon fibre is the most widely used fibre in the aerospace industry. It is produced from precursors including Polyacronitrile (PAN), rayon and pitch. PAN based carbon fibres are more versatile and widely used. It has less impact resistance. They have high specific modulus and specific strength of all reinforcing fibre materials, non affected by moisture at room temperature and retaining their high tensile modulus and high strength at elevated temperatures. To increase the load bearing capacity of the composite, carbon fibre can be added to the polymer matrix. The polymer matrix can be used to bind and protect the fibre and transfer the load to the reinforcing fibre.

Fuda Ning et al. [41] investigated the manufacturing of carbon fibre reinforced thermoplastic composites using fused deposition modeling. They used ABS thermoplastic pellets as polymer matrix and carbon fibre as reinforcement medium. Both the fibre and the pellets were mixed together in a blender and then extrusion process is carried out. Then the additive manufacturing product was made by Fused deopsition modeling process. The process was carried out at an extrusion temperature of 220°C, filament yield speed of 2m/min and nozzle diameter of 2.85mm. They came to the conclusion that when the carbon fibre was added to the plastic material, then increase in tensile strength and young’s modulus were observed and decrease in toughness, yield strength and ductility were observed. Also they have observed that the tensile strength and young’s modulus values were
large while the toughness and ductility values were small and there was no change in the yield strength value for the increasing length of the carbon fibre. The properties obtained are shown in Figure 3 and Figure 4 [41].

![Figure 3](image3.png)

Figure 3. Typical tensile Strain-Stress curves for specimens with different carbon fiber contents (carbon fiber length is 150µm) [41]

![Figure 4](image4.png)

Figure 4. Typical Stress-Strain curves for the effects of carbon fiber length (carbon fiber content is 5wt%) [41]

Flexural property changes were also observed. It was seen that adding 5% weight of carbon fibre improved all the flexural property except flexural yield strength. With 5% carbon fibre content, the flexural stress, flexural modulus and flexural toughness of carbon fibre reinforced polymer composite specimen were increased by 11.82%, 16.82%, 21.86% respectively, as compared with pure plastic specimen. The flexural stress-strain properties obtained are shown in Figure 5 [41].

![Figure 5](image5.png)

Figure 5. Flexural Stress –Strain curve and properties [41]
The testing of the material parts in FDM was carried out according to ASTM standard [42,43]. This carbon fibre reinforced thermoplastic matrix (ABS) is widely used in many applications in aerospace including fuselage of Airbus A350 aircraft.

Bade et al. [44] investigated the mechanical property of PLA filament made by additive manufacturing with and without the addition of carbon fibre and compared with conventional manufactured PLA filament specimen. They observed that the tensile strength of printed (AM) filament was 42MPa in the absence of carbon fibre, while the tensile strength of melted (conventional) specimen was 45MPa. But when carbon fibre is added, they noticed 38% increase in tensile strength (66% better performance) with printed filament while 73% increase in tensile performance with melted specimen. The tensile strength comparison obtained is shown in Figure 6.

![Figure 6. Tensile strength comparison of PLA, PLA-CF specimens [44]](image)

Hall tekinalp et al. [45] investigated the property of short carbon fibre (0.2mm-0.4mm) reinforced arcylonitrile-butadiene (ABS) composite and compared with traditional compression molded composite. The tensile strength and young’s modulus of 3D printed samples increased ~115% and ~700% respectively. The property is as shown in Figure 7.

![Figure 7. Effect of fiber content and preparation process on tensile strength and modulus of ABS/CF composites[45]](image)

Ryosuke matsuzaki et al. [46] conducted a test on thermoplastic composite (polylactic acid) reinforced with carbon fibre by fused deposition modeling (FDM). They came to conclusion that those reinforced with unidirectional carbon fibre showed mechanical properties superior to those unreinforced thermoplastic. Also continuous fibre reinforcement improved tensile strength of printed composite relative to the values shown by conventional 3D printed polymer matrix composite.
Quasistatic tensile tests were performed using universal testing machine. The 3D printer used is FDM blade-1, produced by Hotproceed, Japan.

5.2. Glass Fiber Reinforced composites: Fibre glass is simply a composite consisting of glass fibre either continuous or discontinuous, contained within a polymeric matrix. Glass is a popular reinforcing material for several reasons: 1. It can be easily drawn into high strength fibre from molten state, 2. It produces a composite having a high specific strength, and 3. It has high corrosion resistance. It also has certain limitations: 1. It is less stiff and has poor rigidity. But when compared to carbon fibre, it has high impact resistance and greater elongation to break.

Kate Pitt et al. [47] compared the mechanical properties of formulation of wood waste (wood flour) and thermosetting binder (urea formaldehyde) produced by conventional technique and additive manufacturing technique with and without glass fibre reinforcement. Conventional method of formulation of wood waste and thermosetting binder can be either injection molding [48] or compression molding [49] and the additive manufacturing method is extrusion based [50]. Extrusion allows net shape components to be manufactured additively. The reinforcement filler in thermoplastic composite material was wood flour and thermosetting resin was used as the binder material. The advantage of using thermosetting resin over thermoplastic resin is that they have improved temperature resistance, resistance to deformation, superior mechanical property [51, 52]. The additive manufacturing technique offers the advantage of inducing the alignment of fibrous material within a product to enhance the mechanical strength. Glass fibre of 100micrometer length was used. Tensile strength measurement was carried out using same TA500 texture analysis for both the methods of manufacturing (additive manufacturing and conventional method). Both the tensile and flexural data’s were calculated. It was concluded that there was improved mechanical properties in printed samples compared to Non-printed samples manufactured. The reason is being due to the densification in case of printed samples (additive manufacturing) as it is extruded through nozzle and of the fibre alignment in the sample. Also it has been observed that when glass fibre was added, there was an increase in tensile strength of printed samples by 30% when compared to when glass fibre is absent in the sample. The schematic diagram of extrusion based additive manufacturing
technique is shown in Figure 8 and the mechanical properties of the printed and non-printed parts are shown in Figure 9 [47].

![Comparison of mechanical properties of printed and non-printed products](image)

Figure 9. Comparison of mechanical properties of printed and non-printed products (a) flexural and (b) tensile Stress-Strain curves for urea formaldehyde-wood flour only (c) flexural and (d) tensile Stress-Strain curves for urea formaldehyde-wood flour-glass fiber samples [47]

5.3. Aramide Fibre Reinforced composites: These are the fibre which are formed from aromatic polyamides. They have high strength and high modulus. They are introduced in the early 1970’s. Most common aramide materials are kevlar and nomex. They have the advantage of having good impact resistance and good elongation. Their application finds in the helicopter blades. They are mainly used for components that are subjected to high stresses. For example, they are needed for the construction of gliders. When compared to carbon fibre reinforced plastics, they have lower compression resistance. However, they have higher impact resistance. Due to this reason they are used very often as safety shields for engine cowls. Lot of research work is being carried out on additive manufacturing of composites reinforced with aramide fibre for their application in aerospace engineering [53].

VI. CERAMIC MATRIX COMPOSITES USING ADDITIVE MANUFACTURING

These are the composites in which the particulates, fibres or whiskers of one ceramic material are embedded into the matrix of another ceramic. They are reinforced with fibres that add mechanical strength. In these composites, mechanical stresses are transferred from weaker matrix to strong internal fibres where forces are dispersed and mitigated through bulk of the composite. They are also added with one or more additional property modifying components like SiC or Zirconia to modify the surface and bulk properties. These composites may be fabricated by hot pressing, hot isostatic pressing and liquid phase sintering techniques. However, the fabrication of ceramic matrix composites by conventional techniques is difficult. But additive manufacturing (AM) technique has ability to deal with those type of materials without need for molds or part specific tools. This ceramic matrix composites by additive manufacturing are produced by either Selective Laser Sintering (SLS),
Fused Deposition Modelling (FDM), Stereolithography (STL) and Direct inkjet printing [54]. These composites can be fabricated by a layer manufacturing technology called selective laser gelation (SLG), combining SLS and sol-gel technique. Material comprises of stainless steel powder and silica solution at a proportion of 65-35wt%. The gelled silica matrix with embedded metal particles was used to form 3D composite part and it is distributed over the silica gelled layer using ND:YAG laser technique. By carrying out many experiments, a 50 micrometer smallest layer thickness has been created by this rapid prototyping technique. A bending strength of 45MPa and 10% dimensional variation was observed under 0.4J/mm² laser energy density. It was also confirmed that the energy required for SLG was less compared to as SLS for ceramic matrix composites production [55,56]. CMCs can benefit aerospace in propulsion and exhaust systems and it can also give thermal protection to the components. SiC based composites can handle temperature upto 1200ºC while reducing weight and cooling required. Also ceramic nozzle will reduce weight, engine noise and increase component lifetime[57]. CMCs has potential for a) high fracture toughness, b) high strength, c) low thermal expansion and d) resistance to catastrophic failure[58]. A new additive manufacturing technique called LCM (lithography based ceramic manufacturing) is adopted to produce CMCs by using a photo-curable ceramic suspension that is hardened via a photolithographic process. This technique not only produces parts that are highly accurate but can reach high densities for sintered parts. In case of alumina, a relative density of over 99.4% and a 4 point bending strength of almost 430MPa was obtained [59]. The advantages of using this method are: no geometric limitations, no demolding, no tooling costs and faster time to market.AM technology was used to fabricate and develop fully dense ceramic freeform-components through high-strength oxide ceramics (ZrO2-Al2O3 ceramic) with improved mechanical properties. SLM (Selective laser melting) process can be used to melt completely ZrO2-Al2O3. 100% density and 500 MPa of flexural strength have been observed. In this experimental process, no sintering is done and crack free specimen is obtained. So it has many advantages compared to laser sintering processes. However there are some limitations in the surface quality of manufactured component and the mechanical strength [60]. The CMC part produced by SLG process is shown in Figure 10 [56, 61, 62].

VII. NANOCOMPOSITES USING ADDITIVE MANUFACTURING

Nanocomposites are nothing but composites in which nano (one-billionth of a meter) fillers is dispersed in the matrix. Typically, the structure is a matrix-filler combination where the fillers like particles, fibers, or fragments surrounds and binds together as discrete units in the matrix. Nowadays, polymer nanocomposites are being widely used in aerospace applications because they result in significant weight reductions and increased barrier performance. Thermoplastics and thermosetting polymers are the common polymers in these polymer matrix nanocomposites. These nanocomposites also include nano-particles as reinforcement material. The commonly used nano-particles are carbon nanofibers, nano silica, nano Al₂O₃, nano TiO₂ and others. The commonly used thermoplastics and thermosetting polymers include nylons, polystyrene, polypropylene and epoxy resins. One of the
major disadvantages of polymeric nanocomposite is that there are damages in these composites that are non-visible. So in order to prevent this non-visible damage and to enhance its characteristics, materials like carbon nano-fibers, nano-clays, carbon nanotubes are incorporated in these nana composites.

Polymer nanocomposites has good thermal performance and increased modulus compared to carbon fibre reinforced polymeric composites. The reinforcing phase of the nanocomposites are grouped into 3 main categories: 1. Nanoparticles (0-D), 2. Nanotubes (1-D), and 3. Nanoplates (2-D). The interaction between the particle and polymer affects the modulus and the strength of the nanocomposites. Addition of nano materials to additive manufacturing printing media has the ability to create composites that have unique mechanical properties. It is thus a promising approach to alleviating some of the limitations. Athreya et al. [63,64] performed laser sintering of nanosized carbon black powder blended with nylon-12 powder. It has been observed that nylon - 12 composites possessed flexural modulus lower than that of pure nylon-12 composites depending upon the laser power and scan speed. They also compared nylon-12/carbon black parts made by laser sintering with objects that are made by extrusion-injection molding. It has been observed that for both laser sintering and molding, the impact strength was decreased due to the addition of carbon black to nylon-12. Further they found that the laser sintering produced parts having porosity of ~10% while extrusion produced parts having porosity of less than 5%. Lao et al. [65] investigated by using multi-walled carbon nanotubes (MWCNTs) melt blended with polyamide-11. Specimens were prepared by injection and compression molding. Their mechanical characteristics were studied. Addition of MWCNTs has increased tensile strength and fracture stress by 5.7% and 26% (approx.) respectively. When 0.1wt% MWCNTs resin was used, tensile strength increased by 7.5% while the fracture stress increased by 33%. Bai et al. [66] investigated an experiment on metal nanoparticles. They created a silver nano suspension by mixing silver nanoparticles of diameter 30nm and binder solution. Due to the addition of these silver nanoparticles, the sintering characteristic of the final product is improved. It has been seen that sintering temperature of 300ºC is sufficient to print the parts with nanosilver suspension. It is also seen that the shrinkage and distortion of the product is less when compared with that of a pure binder system.

Shofner et al. [67,68] performed an experiment using Fused Filament Fabrication (FFF) to study the properties of carbon reinforced composites. They used ABS copolymer by adding carbon nanofibers and single walled carbon nanotubes (SWCNTs) and they were mixed in banbury type mixer. Feed rods for FFF were produced and extruded using 0.6mm nozzle. They concluded from the results that carbon-nanofibers and SWCNTs were evenly distributed in the ABS matrix and aligned with respect to the direction of extrusion. There was an improvement in tensile strength and tensile modulus due to the addition of these two materials when compared with that of unfilled ABS. SWCNTs reinforced ABS had an increase in tensile strength of 31% and increase in tensile modulus of 93% when compared to pure ABS. However there was a decrease in elongation at break from 175% for pure ABS to 28%-3% for carbon-nanofiber and SWCNTs reinforced materials respectively. Research work were also carried out on ceramic nanoparticles. Zheng et al. [69] performed an experiment by laser sintering on Al2O3 nanoparticles in combination with polystyrene and their properties were studied. It was found that there was 50% increase in tensile strength and 300% increase in impact strength for Al2O3 core shell specimens compared to Al2O3 polystyrene mixture and pure polystyrene. Also Al2O3 / polystyrene core shell samples showed higher ductility and toughness value. Semiconductor nanocomposites are nowadays being produced in large amounts due to their application and their property behaviour. Duan et al. [70] studied the mechanical property of the fabricated parts by using semiconductor nanoparticles in selective laser sintering process. It has been observed that the addition of TiO2 nanoparticles improved the tensile strength by 89%, tensile modulus by 18%, flexural strength by 6% and hardness by 5%. It is observed that use of semiconductor and ceramic nanoparticles as additives to laser sintering had shown promising results in enhancing mechanical properties of final printed parts.
VIII. LIMITATIONS AND SCOPE FOR RESEARCH

There are certain limitations that limit the use of AM technique

- Nozzle clogging and higher Bly-Fly ratio.
- Limit on the thickness of the samples and also strength of the final product.
- Agglomeration of nano-materials which affect mechanical properties of the final product.
- Higher AM cost.

Number of Research and Developments can be made in this field. Some of them are:

- SLS can be used for the fabrication of Polymer composites with sufficient mechanical properties.
- Research can be done on layer thickness optimization to achieve sufficient thickness and also processing time.
- Capability of processing multiple materials within same AM system [71].
- Speed of processing can be increased to achieve efficient design process [72].

IX. CONCLUSION

As the research works discussed in this paper about additive manufacturing, it is seen as a viable option for manufacturing in the coming years. Since its inception 25 years ago, AM has found applications in industrial sectors ranging from aerospace to dentistry and orthodontics. Currently AM is being used for maintenance and repair of damaged parts, wherever traditional method of manufacturing cannot be applied, additive manufacturing comes into action. Although AM is an excellent choice for productive manufacturing it has certain drawbacks ranging from machine, material, design of tools and software. The current trend in this method is the manufacturing of embedded electronic system at the time of 3D printing itself. The other trends are Three Dimensional Scanning, Bio Printing etc. This is one of the most promising methods for printing human tissues, bones etc. This is also being developed for human organs. NASA is currently monitoring a 3D printing situated in the international space station, where astronauts can print their necessary tools thereby reducing the payload during the launch time. The 3D model for these tools is developed at the mission control in ground and it is then analysed and sent to the International Space Station.

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