**Additive manufacturing technologies: industrial and medical applications**

Saquib Rouf1, Abrar Malik1, Navdeep Singh2, Ankush Raina1, Nida Naveed3, Md Irfanul Haque Siddiqui4, Mir Irfan Ul Haq1\*

1School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra, Jammu and Kashmir, India

2UIET, University of Jammu

3University of Sunderland, United Kingdom

4Department of Mechanical Engineering, King Saud University, Riyadh 11421, Saudi Arabia;

\*Corresponding author: haqmechanical@gmail.com

**Abstract**

3D printing is increasingly becoming an important technology in the manufacturing sector and has the potential to revolutionize manufacturing. 3D printing allows customization, which produces sophisticated structures while lowering waste and at the same time allowing more flexibility in the design. This paper includes a brief overview of the main types of additive manufacturing (AM) technologies. It reviews the work carried out in various types of 3D printing technologies particularly focusing on mechanical characterization. Based on the literature studied, comparisons have been drawn on the various merits and challenges offered by various 3D printed materials. Dedicated sections on various materials aspects and application areas have been included particularly from a medical science point of view. This paper ends with a dedicated section on applications of Additive Manufacturing (AM) in orthopaedic, dental, prosthetics, food and textile sectors. It tries to establish relationships between AM, industry 4.0 and sustainability. This paper shall act as a stimulant to trigger further advancements in the above fields.

*Keywords: Additive Manufacturing; Medical; applications; Orthopaedic; Dental; 3D Printing; Industry; Mechanical Properties*

1. **Introduction**

The manufacturing landscape is continuously changing. The rise in competition for sustainable designs and the possibility of using materials like alloys and metals are already exhausted. This makes it very hard to attain the highest traits of materials and their performance measures under the most current techniques. Consumers’ expectations for more customized products and services, combined with the introduction of modern production techniques are also the reason for such shifts in manufacturing scale and distribution [1]. Due to this increased competition for sustainable designs and the continuous attempts to achieve the highest traits of the material, 3D printing has emerged as a breakout technology possessing a huge potential for social and environmental transformation. It is the best usable technology with minimal production volumes, regular design changes, and the high complexity of designs necessary. Over the years, this technology has evolved and its machines have become more and more useful along with their lower and affordable prices. 3D printing due to its novel approach has now found its use in various sectors such as engineering, construction, medical, military, aerospace, fashion, architecture, computer industry, etc. This technology is slowly replacing the traditional way of manufacturing as it offers greater flexibility as compared to conventional manufacturing techniques. Most current technologies need materials with a unique combination of the properties found in conventional materials [2]. Therefore, the development of such composites has replaced traditional materials. 3D printing technology is also described as additive manufacturing. This is a quickly rising technology within the manufacturing sector. There has been a drastic decrease in 3D printer costs, resulting in increased demand in the market [3]. 3D printing fabricates components through the use of 3D computerized data having information on the object geometries. 3D printing is the best usable technology with minimal production volumes, regular design changes, and the high complexity of designs necessary [4]. AM procedures tend to fabricate various computer data and STL files of the geometry existing in the object [5][6]. 3D printing technology is way better suitable unlike the traditional manufacturing procedures. Traditionally, there were lesser volumes of production, constant changes in designs, and also increased complexities of design were needed. The key differences between the additive manufacturing technologies and traditional manufacturing listed in table 1, which highlights some important features of AM such as waste reduction, time efficiency and the feature for product optimization and recreation. However, there are some limitations in printing space. AM is restricted to its printing bed, but this issue is also being addressed by researchers and nowadays we see additive manufactured houses [Ref].

**Table 1: Key Difference between AM and Traditional Manufacturing**

|  |  |  |
| --- | --- | --- |
| **Description** | **Additive manufacturing**  | **Traditional manufacturing** |
| Prototype production | Does not need any special tooling in making parts [3][7] | Needs special tools to make parts |
| Waste prevention | Incredibly resource-efficient | Consumes a lot of resources |
| Large-scale production | Produces parts at speed | Less efficient and reliable |
| Presence of specific materials | Ability to make objects out of metallic polymers [3][7] | No ability to make objects out of external materials |
| The scale of produced parts | Restricts to a total area of the printing bed | Manufactures certain larger parts |
| Customization | Incredible use of small one-off production runs | Need for several tooling |
| Cost | Costs keep falling | Not easy to get started |
| Waste and energy | Saves on material waste and energy | No ability to add a material unit part |
| Inventory | Does not need much hands-on inventory [3][7] | Need for a lot of hands-on inventory |
| Legacy parts | Easy to recreate and optimize parts | Inability to recreate or to optimize legacy parts [3][7] |

This paper is an attempt towards highlighting the role AM can play in implementing Industry 4.0 in various sectors and also at the same time achieving sustainability. This paper is structured in a manner to focus on various technologies and applications of AM particularly the medical field.

1. **Literature survey of 3D Printing Technologies.**

3D printing technology has improved over the past years. This sector is quite young, and many technological growth and discoveries are still under development. The technology may not manage to revolutionize the manufacturing sector yet in a sizable manner. 3D printers utilize additive manufacturing procedures and other technologies in building layers that become the final objects. There are many varieties of 3D printing technologies that occur under various functions [8]. They are cataloged into seven different groups, as represented in the figure 1:



**Figure 1: Types of 3D Printing**

The table 2 represents some of the recent advancements brought in the fields of electronics, aerospace, medicine and construction using 3D printing technologies.

**Table 2: Recent advancements in electronics, space and medical by 3D printing**

|  |  |
| --- | --- |
| **Methodology** | **Work involved and results** |
| Hybrid 3D manufacturing system (Stereolithography and direct-write technology)  | 3D embedded electronic structures 3D555 timer circuit – a 3D embedded electronic circuit was fabricated.[9] |
| Fused deposition modeling and ultrasonic wire mesh embedded approach. | A patch antenna having a gain of 5.5 Db at the resonance peak was developed using this technology [10]. |
| Inkjet Printing | Flexible electronics such as cellulose nanofibril-based coatings which control ink penetration to woven cotton fabrics were developed for e-textile manufacturing [11]. |
| 3D Bioprinting | A bio-ink that combines the outstanding shearthinning properties of nano fibrillated cellulose (NFC) with thethe fast cross-linking ability of alginate was formulated by a research group from Chalmers university technology which has the potential to be used for 3D bioprinting of living tissues and [12] |
| 3D Bioprinting | A bionic ear was generated using a cell-seeded hydrogel matrix similar to the shape of the human ear along with the intertwined conducting polymer. Enhanced auditory sensing for radio frequency reception was exhibited by the printed ear [13]. |
| Selective Laser Manufacturing | NASA engineers used Nickel-Chromium Alloy powder to construct a complex metal rocket injector component for the J-2X engine on the next-generation Space Launch System (SLS). The part was built into a single piece without joints and was structurally stronger and more reliable and thus was a significant improvement in saving time and cost [14]. |
| Selective Laser Sintering | A prototype model of a 25-kN of aircraft engine was fabricated by Hindustan Aeronautics Limited and was on display in the Aero-India expo 2015. The material used for the components was nylon plastic material. The cost and development time of this prototype were significantly reduced as compared to conventional manufacturing [14]. |
| Fused Deposition Modelling like technique | A 6-axis robotic arm mounting an extrusion printhead was used to deposit the material layer by layer to produce ultra-high-performance concrete. This technique allowed in producing 3D large-scale complex geometries without the use of temporary support which was not possible before and thereby enabled the multi-functionality of both the structural elements [15]. |

* 1. **Binder Jetting**

This process pertains to rapid prototyping. It also involves creating different parts that are additive to the binding agent in use [16]. Liquid binding agents are utilized for joining powder particles. The binding agent is deposited on top of the metal powder material starting from one layer on the next as per the 3D model [17]. Some of the common materials utilized are metals, sand, ceramics, and even polymers that are granular in form [18]. Other common applications include larger sand casting cores and even mold, cheap 3D printed metallic parts, and full-color fabricated prototypes. Unlike other Additive manufacturing technologies, which use heat or light as the fusing agent of raw materials, Binder jetting glues the material particles layer by layer to form the object of a specific geometry, Hence the heat is not required to bind the material together. It was invented in 1993 at MIT and after two years, Z Corporation acquired the license from MIT for its processing [19][20]. The binder jet printing technology is accessible for materials like ceramics, metals, and polymers [21][22][23][24]. Despite the availability of various materials, it is still useful for just prototyping, as the performance of the printed parts does not meet the required performance standards. This is due to the low packing factor of powder material; hence, the volume of pores is high and low density in the printed parts [25]. These parts generally require post-processing techniques like sintering and infiltration [26]. Among the two, Sintering is the most prominent technique for post-processing. However, this technique is responsible for dimensional inaccuracy, development of creep, and porosity [27][28]. The infiltration involves immersing of printed part into the solution of multi-phase fluid where the infiltrants enter the part through the capillary action. Mostly, among the materials used for binder jetting, ceramics are subjected to infiltration to decrease the percentage of porosity in the printed part [29]. The main problem with this method is that the porosity is not reduced up to the mark due to insufficient deposition of the infiltrant into holes of the binder-jetted printed part size smaller than the average particle size of the solid loadings [30]. The figure 2 shows the various processes/ phases during the binder jetting.



**Figure 2: Processes of Binder Jetting**

The process starts with the preparation of raw material, fabrication, and post-processing. At the first, the roller spreads the layer of powder to the building platform from the powder stock then the print head defines the layers with the help of a binder as defined in the 3D design/model file. As the first layer is finished, the height of the layer is lowered and the process starts again for the second layer as of the first layer. The same process is repeated till the full geometry is acquired and this obtained part is known as the green part which is then separated from the powder for post-processing. Curing, de-binding, sintering, and optional densification are some post-processing steps. The green part is heated up to the temperature of 2000C, which toughens the green part by polymerization. The green part is then converted into the brown part in which the binder is burnt down and left for sintering. Here the density is increased and so are the mechanical properties, This is called the finished product [31]. Table 3 represents recent work in binder jet printing ranging from orthopedics to space technologies. Most of the studies listed in table 3 put emphasis on the printing parameters and their impact on mechanical and structural properties.

**Table 3: Recent work done in binder jet printing**

|  |  |  |  |
| --- | --- | --- | --- |
| **Author** | **Material Type** | **Application Area** | **Remarks** |
| [32] | Calcium sulfate hemihydrate | Artificial Bones | In this study, mechanical Anisotropy and fracture were investigated. Various printing parameters like printing directions, nozzle structure have shown their influence on these properties. Ink/Volume ratio showed its impact on the density as the precipitated content of dehydrating was affected. |
| [33] | porcelain ceramic | Dental | Various printing parameters like binder amount, drying power level, drying time, powder spread speed and sintering schedule temperature, holding time, the heating rate on the properties of printed parts for dental applications. It was seen that all the parameters affect the geometrical properties of dental ceramics. |
| [34] | Hydroperm, Lunar Highland Simulant, Zeolite 13X | Space  | The paper establishes the dependence of aerosol emission in binder jetting printing on the powder properties as well as on the powder spreading process. |
| [35] | Synthetic Light weight ceramic ((Al–32%), silicon (Si–42.5%) with trace amounts of Fe2O3, CaO2, TiO2.) | Electromagnetic and Bio-medical implants | The material stands light weight with high mechanical stresses and corrosion resistance. The material reports a low coefficient of thermal expansion. |

* 1. **Extrusion Based Methods**

This technology is widely utilized since it is cost-effective. Several materials, multi-colored plastics, and living cells are then printed following a material extrusion-based technology [36]. Additionally, this process could be built completely based on the product's functional aspects [37][38]. Fused deposition modeling or fused filament fabrication are methods for material extrusion manufacturing. The fused deposition modeling contains filament-type thermoplastic as the input material, which is fed into the heated nozzle where it is melted and squeezed out from it in the form layers. The layer thickness and pattern of the printing design are fed to the printing software. After one layer is completed, the bed automatically lowers down, and the second layer is printed. This process continues till the final product is completed. The important feature of extrusion based FDM is to manufacture the products with functionally graded properties [39]. Recent developments in the field have developed this process in such a way that it is now directly being used to manufacture the products rather than the prototypes. Figure 3 shows the various parameters that affect the properties of products manufactured by this technique.



**Figure 3: Process Parameters of FDM**

Recently, a lot of work has been done in the field of fused deposition modeling techniques. Effect of various printing parameters like specimen orientation [40] [41][42], raster angle [43][44], nozzle temperature [43], layer thickness [45] have been studied and their impact on various mechanical, tribological and structural properties have been studied as shown in table 4. Secondary parameters, like environmental parameters, have also shown their effect on the mechanical properties of materials printed with fused filament fabrication [46] [47][48].

**Table 4: Effect of Process Parameters on the Printability of Various Materials**

|  |  |  |  |
| --- | --- | --- | --- |
| **Author** | **Material type** | **Process Parameters** | **Observation** |
| [49] | ABS and PLA | Layer ThicknessRaster Angle | With the increase in layer thickness, frictional force and 450 show better wear resistance. Also, PLA shows less wear resistance than ABS. |
| [50] | PA12 (Polyamide12) | Layer ThicknessExtruder TemperatureFilling StructureOccupancy rate | Layer Thickness has the maximum effect on the tensile and impact strength. The optimized Mechanical properties are obtained at: 0.25 mm layer thickness, 50% occupancy, Rectilinear Filling structure, and 250°C extruder temperature. |
| [51] | ABS | Layer thickness, Deposition temperature, Deposition speed (speed of material application), Chamber temperature. | Layer thickness is the most important parameter among all mentioned for ultimate tensile strength. For moist filaments, thin layers should be used. |
| [52] | Stainless steel 316L | The comparative study is performed between the 316L steel manufactured by SLM and that of FDM | The specimens developed by the SLS technique showed very little porosity in comparison to the specimens of FDM. The yield strength and ultimate tensile strength of SLS samples are more than that of FDM samples. |
| [53] | poly(acrylonitrile-butadiene-styrene)/multi-walled carbonnanotubes | Raster angleLayer ThicknessIn fill % of CNTs | Results showed that with the increase in nano-filler percentage, the tensile strength and elastic moduli increase. With the increase in layer thickness, the tensile strength decreases. The raster angle did not have a significant impact on the properties. |

 From the literature cited in table 4, it is very clear that in terms of porosity, extrusion based FDM is quite effective but in the case of mechanical properties, SLS is more dominant. Here also, the printing parameters play an important role for deciding the mechanical and tribological properties of products. Thus, it is very important to understand the impact on properties with respect to each printing parameter taken into the consideration independently.

* 1. **Powder Bed Fusion**

This method generates products with precision. The technique utilizes electron beams and laser in melting and fusing the material powder [21]. This assists in the manufacturing of a wide array of geometrically sophisticated products. Materials brought into use here are metals, ceramics, composites, polymers, and hybrids [54] [55]. Powder Bed Fusion surely presents many viable technologies such as SLS, SHS, SLM, and EBM. SLS (Selective Laser Sintering) is a 3D printing procedure that utilized lasers for sintering [56]. The coalesce powdered materials are sintered one layer after the other in coming up with solid structures. Loose powder assists in enveloping the end products that are taken out using brushes and pressurized air. In essence, SLS is a 3D printing technique that functions at extremely high speeds with increased accuracy as it changes with the finishing of surfaces. SHS (Selective Heat Sintering) is yet another 3D printing method that do not utilize high power laser [57]. However, it uses thermal print heads for melting the material that produces 3D objects. SHS 3D printers utilize thermoplastic materials. These heated platforms offer layers of thermoplastic powder that are applicable using rollers. Such thermal print heads would normally sinter the top layers of powder by tracing various objects under cross-sectional regions over the powder. This goes on until the initial layer is to be completed. The process repeats until a 3D object is formed. SLM (Selective Laser Melting) is a sintering process that is done directly on metal through technical principles that yield metallic parts exclusively [58]. SLM undertakes complete melting of powder that is attained for single component metallic parts such as aluminum. Sintering of powder is normally restricted for alloys alone. To lower the occurrences and distortions of high residual stress, various techniques would be induced as extra support is brought in. EBM (Electron Beam Melting) is another 3D printing technique enhancing energy source to the heated material [59]. It is a highly useful technology for high value industries such as aerospace and defense. This is because it utilizes minimal energy as it yields lesser residual stress because it works faster than the SLS. The contribution of powder bed fusion (PBF) techniques in various domains is given in table 5. The most common PBF methods that are being used widely in the medical and aerospace sector are SLS and SLM. Nowadays, researchers have been using SLS for the pharmaceutical industry. In the case of orthopedic and dental applications, they have their dominance over the other manufacturing technologies. Literature in table 5 clearly shows that PBF techniques are mostly used for metallic materials. The mechanical properties like creep and flexural strength have been enhanced using PBF for high temperature applications.

**Table 5: Contribution of Powder Bed fusion Techniques in various domains**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Authors | PBF Method | Material | Domain | Remarks |
| [60] | SLS | lopinavir  | Pharmaceutical  | This study has developed an amorphous LPV using an SLS printer. The study is the first of its kind with SLS.  |
| [61] | SLS | Copovidone and Paracetamol | Pharmaceutical | This work deals with the development of solid oral dosage forms using SLS. Various important features including porosity for drug-releasing capacity have been enhanced. |
| [62] | SLS | Polyamide, Alkali lignin | Mechanical/bio material | In this study, lignin replaced PA12 for cost-effectiveness and while maintaining the cost-effectiveness. SLS proved an effective method for thermal stability and wettability. |
| [63] | SLS | silica-based ceramic cores | Aerospace | The flexural strength of the material was increased with the increase in infiltration time. SLS improved high-temperature flexural strength and creep deformation. |
| [64] | SLM | Ti6AI4V  | Orthopedic implant | SLS is used to develop a heterogeneous porous structure for orthopedic implants. Hydrothermal treatment and FEA simulations assist the process. The mechanical properties were enhanced due to the core-shell structure. |
| [65] | SLM | 316L stainless steel | Stent Application (Surgery) | The paper shows the manufacturing of Stent with the SLS process. Surface roughness, constituting phases were analyzed and significant changes were recorded in the final product. The technique proves to have the potential for the generation of patient-specific medical devices. |
| [66] | SLM | AlSi10Mg alloy | Aerospace Application | The Manufacturing of the Flapping wing mechanism with SLM brought 99% dimensional accuracy. There are cost cuts, which were prevailing in the previous conventional manufacturing processes.  |
| [67] | EBM | Ti6Al4V | Medical Implants | This is the state of art review focused on the developing implants of Ti6Al4V using Electron beam melting. This review gives the advantages of using EBM for biomedical applications. |

* 1. **Direct energy deposition**

Directed energy deposition (DED) technology develops different parts by melting various materials and depositing them in the workplace one layer after the next. DED differs from material extrusion in that the DED nozzle may not be fixed to a certain axis before moving it in various directions. DED is utilized in repairing and adding extra material to the existing components. DED technology is a sophisticated process that produces sound quality products given its great control of the grain structure [37]. DED pertains to various technologies that distinguish each other as per the material that has been fused [68]. It enables the printing of material by simply melting the powder. This method has been employed on ceramics, polymers but it has been widely used on metal powder, hence it is also known as metal deposition technology. LENS (Laser Engineering Net Shaping) deposition is an example of a DED technology that utilized lasers controlled by the computer in building objects [69]. The procedure followed here is layer after another starting from powdered materials such as metal, alloys, and ceramics. Through exploitation of thermal energy utilized for melting, LENS technology assists in accomplishing DED. EBAM (Electron Beam Additive Manufacturing) is yet another 3D printing technology that utilizes electron beam guns [70]. This deposits metallic materials with wired feedstock one layer after the other. This goes on up until the net shape is attained. EBAM is usable in the production of large-scale metallic structures. The main issue with the DED is with the residual stresses caused by the non-uniform thermal contraction and expansion, which result in the formation of cracks due to distortion. Researchers developed a stereo-based path planning and laser scanning system to overcome the above mentioned problem [67]. The other issue arises with the surface finishing of DED manufactured parts. The parts printed with DED show low geometrical tolerance and surface finish [71] [72]. These defects can be solved by post processing given in figure 4.



**Figure 4: Post processing techniques for DED**

* 1. **Sheet Lamination**

This 3D printing process allows various sheets of materials to become bonded together [73]. Initially, the material is bonded in place over an existing layer using adhesives. The required shape is then cut out through the use of a digitally guided laser. In essence, high-resolution colored objects are constructed through this process. Other technologies adopt the process of laminated object manufacturing (LOM). LOM may form 3D objects using localized energy sources, given that the laser is used for binding stacks of metal sheets. This process has many metal sheet rolls being utilized as a feedstock into the build areas where heat is pressed using heat rollers onto other layers before they are cut using a laser in predetermined shapes. LOM can even produce sophisticated geometrical parts at minimal costs and reduced operational timing [74]. Ultrasonic additive manufacturing (UAM) and ultrasonic consolidation (UC) are the most commonly utilized manufacturing techniques for sheet lamination procedures [75][76][77][78]. The various advantages and disadvantages of Sheet lamination are given in table 6. The material compatibility and applications are shown in figure 6.

**Table 6: Advantages and disadvantages of Sheet Lamination**

|  |  |
| --- | --- |
| **ADVANTAGES** | **DISADVANTAGES** |
| Manufacturing time is reduced | The surface finish is poor |
| Low-Cost manufacturing | Low dimensional accuracy |
| Tooling time is reduced | Difficulty in manufacturing complex shapes |
| Applicable for a vast variety of material | Poor bonds between the layers |



**Figure 5: Material Compatibility and applications of LOM**

* 1. **Vat Polymerization**

This technique of 3D printing utilizes photo-polymerization of materials to form solid parts. Materials such as photopolymers and liquid are amassed in a vat. The materials are then successively put in layers by irradiating them with light sources resulting in 2D layered patterns [17]. SLA (stereolithography) and DLP (digital light processing) utilize photopolymerization using the 3D printing technique [79]. Some of the key parameters here include the exposure time, wavelength and the power supplied. Among the all-additive manufacturing processes, vat polymerization is referred to as the scalable method, since it can be used for micro-manufacturing [80]. SLA photo-polymerization occurs either by a top-down printing approach or a bottom-up approach. In a top-down approach, the laser is positioned above the platform where the material is cured. With each layer being processed, the bed lowers down for the second layer and this process continues till the whole part is manufactured. For the bottom-up approach, the laser is placed at the bottom and the layer formation starts from the bottom, then the bed rises to complete the process. The DLP works on vat photo-polymerization process with a light mask projector [4]. This method is adopted from the dynamic mask projection, which uses layer-wise curing of materials (liquid photosensitive resin) when exposed to UV light [81].

1. **Material Considerations**

The AM processes are divided based on the state of materials being used in them. There are three types of AM processes based on this classification; solid, liquid, and powder. In addition, the mechanical properties of the materials should be acceptable and should also meet the service standards. The variety of materials suitable for 3D printing is limited but work is going on to increase the domain of materials that can be used in different 3D printing techniques. The most common type of materials being used in 3D printing includes plastics, metals, ceramics, and composites. Plastics have two types; thermoplastics and thermosets. Thermoplastic materials are used in two processes; material extrusion and powder bed fusion. Among these types, amorphous thermoplastics are used for material extrusion processes because of their melt properties. They form a highly viscous melt which is ideal for extrusion. The typical nozzle size used for extrusion of these materials is 0.2-0.5mm [82]. The two most common examples of such plastics are Polylactide (PLA) and Acrylonitrile butadiene styrene (ABS). Some other examples of amorphous materials being used in material extrusion are Polycarbonate (PC), PC/ABS blend, and Polyetherimide (PEI). In the case of powder bed fusion, semi-crystalline thermoplastics are used. These materials are melted and fused using an IR laser or IR or UV heat source. The most common material being used for powder bed fusion is Polyamide 12 (nylon). Its melting point is around 35oC above the recrystallization temperature and recrystallization takes place uniformly only after the print has completed and also minimizes the residual stresses. Highly dense and low porous objects can be fabricated using these materials by adjusting various process parameters. Other examples of semi-crystalline materials being used in powder bed fusion are Polypropylene and Polyetheretherketone (PEEK). In the case of thermosets, the most common examples are Acrylics, Acrylates, and Epoxies. Photopolymers undergo a process called “curing” in which the oligomers become cross-linked upon exposure to light and form network polymers which are thermosets in nature. These photopolymers are made up of monomers, oligomers, and some additives like antifoaming agents and antioxidants which enhance the properties of these photopolymers [81]. Toughening agents are also being used actively in resins to improve their mechanical properties. These toughening agents can either be reactive or non-reactive. In some forms, the elastomeric cores have a reactive shell [83]. Some examples of such core materials include are polysiloxane, polybutadiene, and rubber while the examples of reactive shells include compounds with epoxy, hydroxyl, vinyl ester, vinyl ether, and acrylate groups. Thermosetting materials are also being used in the material jetting process. Material jetting becomes useful in cases of deposition of multiple materials. This is done by using different nozzles for different materials. If this process is used for the deposition of different materials in the same layer, the final product will have properties different from the properties of materials constituting it. The mechanical properties of products manufactured using material jetting have been shown to have the property of anisotropy and at the same time have significant variance in tensile and compressive properties [84]. Researchers have specified that the properties of the part change over time and have also revealed the consequence of aging [85]. From the perspective of metals, powder bed fusion and direct energy deposition are the two most commonly used powder-based AM techniques to manufacture metal products. However, in direct energy deposition, there is a provision of using a metal wire in place of powder as well. In addition to these two techniques, binder jetting is also used to manufacture metal prints. The most commonly available commercial metals/alloys for use in 3D printing include pure titanium, Ti6Al4V [86], 316L stainless steel [87], 17-4PH stainless steel [88] and 18Ni300 maraging steel [89], AlSi10Mg [90] [91], CoCrMo [92], and nickel-based super-alloys Inconel 718 and Inconel 625 [93][94]. This list of materials is continuously increasing as new materials for use in 3D printing are being developed. Selective laser melting is used for printing objects while using silver and gold and platinum as raw materials [95]. There are several reasons for the limited number of metals available for 3D printing. In aluminum and aluminum alloys, the affinity with the air is a problem. It forms an aluminum oxide layer at the surface and causes problems in particle sintering. 18Ni300 maraging steel and Inconel 718 also cause problems in the melt pool as they form stable oxides which rise to the top [96]. Alloys having low absorption and high thermal conductivity like copper, aluminum, silver, and gold create problems in establishing the melt pool. Furthermore, in metal 3D printing, the amount of residual stresses is also a matter of concern. The residual stresses include high tensile stresses at outer surfaces accompanied by zones of compressive stresses in the center. In addition, stress gradients also form in the product and depend on product height, product geometry and build direction. Ceramics are also being increasingly used in AM. However owing to their high melting point and low toughness, they pose problems in their direct use in AM [97]. Direct energy deposition and powder bed fusion techniques have been employed to print using alumina and its alloys [97] [98]. Many methods were adopted to directly use ceramics in AM but they resulted in thermally induced cracking. In the case of indirect use of ceramics in AM, a binder is needed to bind the object together. Barring direct energy deposition, all the other AM technologies are used in the indirect fabrication of ceramic products [99]. When ceramics were introduced in AM, one of the first methods adopted was mixing ceramic (essentially alumina or silicon nitride) with a stereolithography resin. The binder used in indirect AM of ceramic materials is typically transient. It is either removed or converted in post-processing which results in the final product being purely ceramic or a ceramic composite. Freeze-form extrusion fabrication (FEF) is a technique that produces 3D objects by using ceramics while keeping an environmentally friendly approach. It builds the object layer upon layer which is controlled by a computer in the form of aqueous colloidal pastes that have slight quantities of organic binder [99]. Since FEF makes objects by deposition of these pastes in a controlled freezing pattern, there are however certain problems associated with this. One biggest problem associated with FEF is big crystals of ice are formed during freezing which results in low densities of the final product as well as formation of pores in the product which affects its overall properties. One way to deal with this problem is adopting Ceramic-on-demand technique which is carried out at room temperature and employs radiation for drying the product. It is also very useful in producing complex shapes using ceramic materials [100] [101]. The use of composites in 3D printing is on the rise and new composites with improved properties are being developed continuously. While developing a composite, the most important properties to consider are the feedstock material, properties and their homogeneity. There should be appropriate bonding between the composites and they should have good mechanical properties. The most commonly used composites are polymer composites, metal composites and ceramic matrix composites. Fiber reinforced composites, generally carbon fiber reinforced composites/fiberglass are also used as composites in AM. Their mechanical properties are a function of the orientation of the fibers. These fibers are further classified into whiskers, short or continuous fibers. The metal composites being used in 3D printing encompass laminates, particulate composites, fibrous composites and functionally graded materials. The fabrication of metals by AM is mostly done by Selective laser melting (SLM) and Laser metal deposition (LMD). Metal composites can also be developed from powder form by using Liquid phase sintering (LPS) and has already been tried on metal-matrix composites. In case of functionally graded materials, controlling grain growth and the coefficient of thermal expansion are key factors which need attention and additives are being used to control these parameters. Functionally graded materials are finding an increasing use in aerospace applications in which different properties are needed in a single component like as in propulsion nozzles where different thermal and mechanical properties are required [102]. Composites of ceramics are also being used in AM especially in biomaterials and it is a rapidly developing research field [103] [104]. Ceramic polymers require very less amount of post processing and the products manufactured by using them can be used immediately after their production [105]. Binder jetting is most commonly used to manufacture ceramic matrix products because of its high accuracy and intricate geometry. A novel AM technique called Selective laser gelation (SLG) has also been developed which has enabled manufacturers to use ceramic sol-gel along with SLS. This technique opened new opportunities with regards to including slurries in AM while providing good flexibility. A typical example of this method is silica sol with embedded stainless steel [106]. Furthermore, the FEF technique with respect to ceramic composites has been advanced to incorporate functionally graded materials including tungsten and zirconium carbide [107]. The processing of dense components can be effectively done using ceramic suspensions and improvements have been done in this regard by incorporating opaque suspensions in stereolithography [108]. Some important AM materials and their application is given in table 7.

**Table 7: Some important AM Materials and there applications**

|  |  |  |
| --- | --- | --- |
| **AM Material** | **AM Process** | **Application** |
| TilAl4V [109] | EBMSLM | Aerospace |
| Inconel 718 [110] | EBMSLM | Aerospace |
| Polyphenyl-sulfone [111] | FDM | Space Applications |
| ULTEM™ 9085 [111] | FDM | Space Applications |
| Aluminium-filled polyamide 12 powder [111] | SLS | Space Applications |
| Ti6Al4V [98] | DEED | Medical Implants |
| Ciba–Geigy 5170 [112] | VP | Prostheses |
| AlSi10Mg [113] | PBF-LB | Ballistics |
| Maraging steel [114] | SLM | Ballistics |

1. **Bio Manufacturing**

The field of additive manufacturing is expanding day by day. Due to its layer-by-layer formation, it has tremendous potential for bio manufacturing. Fields like dentistry or implant generation where the anisotropy is needed as per the requirement pose as best clients for additive manufacturing. One of the important medical applications for AM is the implant section. The implants are customized as per the needs are requirements of the patients, hence AM can help in printing those implants as needed [115]. For dentistry, splints, models, and drill guides are developed with the help of AM. Also, AM has been used for the development of artificial tissues and organs [116]. Moreover, the AM technique is widely used nowadays for 3D models of organs, which are useful for understanding the complex human anatomy. It is estimated that the market of AM for bio manufacturing is going to reach 26 billion U.S dollars by 2022 [117]. These sections deal with the comprehensive review of additive manufacturing techniques for various aspects of medical needs. Some important medical sections that are emerging in the AM domains are discussed below:

* 1. **AM for orthopedics and prosthetics**

 The bone has a porous and anisotropic structure,which means that the density of bone changes along with the length/breadth or height. The porosity of the bone helps in bone ingrowth, pore size helps in cell proliferation [117]. In addition, different pore shapes can be responsible for the change in permeability, which can lead to different bone ingrowth [118]. Also, the ingrowth of the bone is directly responsible for developing effective mechanical properties. Researchers have shown that the compressive strength and young’s modulus can be altered by simply controlling the porosity and pore shape and size of scaffolds [119] [120]. Hence, from the above-mentioned literature, it is clear that scaffolds need to have precise pore shape, size, and the type of pore distribution for optimal mechanical property and behavior as that of the actual bone. This problem can be better addressed by considering additive manufacturing. Researchers used SLS for porous scaffold generation using hydroxyapatite (HA) and poly(ε-caprolactone) PCL composite [121]. The SEM analysis shows that the microspheres of the scaffolds by SLS were well established and connected. The SLS is also used for bio ceramic scaffolds. Researchers have successfully used SLS for β-tricalcium phosphate (β-TCP) and bio-glass [122] [123]. Apart from the above-mentioned materials, SLS has posed to be an excellent method for the manufacturing of scaffolds with low dimension materials as additives (carbon Nanotubes, graphene, and boron nitride Nanoparticles) [124]. For metallic scaffolds, SLM can be used due to the high energy density laser for the metal melting process [125]. Researchers have used SLM for scaffolds manufacturing with 316 L stainless steel. The results show that scaffolds were highly porous (87% by volume) and mechanical properties were similar to that of trabecular bone [126]. The other common method of AM for scaffold generation is the FDM, mainly used for polymers with low melting temperatures. Researchers have shown the use of FDM for scaffolds using PCL at different printing orientations. The porosity of 56% and more was achieved with pore size ranging from 380 to 590µm [127]. FDM has been used to design and fabricate the scaffolds of polymer and ceramic composites with mechanical properties similar to that of the actual bone [128] [129]. The products of FDM require post-processing to attain better mechanical properties as the shrinkage characteristic comes into play. EBM can also be the better player for scaffold manufacturing, but the only disadvantage is that it can work with conducting materials. Besides that, EBM takes a lot of time which certainly decreases the efficiency of the production system. Orthosis is one of the basic thing that orthopedics recommend for supporting the skeletal and neuromuscular system externally. The development of orthosis by additive manufacturing is not too old as it started just a decade ago and their manufacturing is still manual. By employing AM for this job, Orthosis manufacturing has become more cost-effective and comfortable for the user [130] [131]. Material for orthosis is in the form of foams, composites, and thermoplastics [132]. Apart from this, it has been also used for the development of the diabetic foot, plantar fasciitis [133] [134].

* 1. **Dental Applications of AM**

 AM for dental practices is not a new talk of the town. It has been there for almost 20 years. For metallic dental crowns, Researchers have used FDM, SLS, SLA, and LOM techniques for dental applications specifically for dental pieces, crowns, bridges, etc. [135] [136]. SLA and FDM are generally used for non-metallic oral implants, models for dental study, orthodontics, crowns and bridges, and surgical equipment, specifically surgical guides for dental surgery[137]. The researchers are using additive manufacturing for maxillofacial implants where the metallic powder using selective laser melting method (SLM) [138] [139] replaces the entire jaw of the patient. Additive manufacturing technologies have been used for creating complete or partial dentures. DLMS, a direct laser metal sintering process has been used for creating metallic dentures [140] [141]. FDM, the fused deposition modeling technique has the potential for creating polymer dentures with hollow, semi-hallow, or solid structures [142]. Now the research is being conducted for developing the dentures using AM, which have the anti-microbial property [143]. Researchers have used processes such as FDM and SLA for the generation of bioresorbable polymer dental implants , which even exhibit odontogenic properties [144] [145]. Some Recent advances in the field given in table 8 clearly show that powder bed fusion technologies are taking lead in dental applications. Moreover, the roughness associated with the printed parts can be problematic. Therefore, some processing needs to be done for reducing the roughness in dental implants.

**Table 8: Recent advances in AM for dental applications**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Author** | **Material** | **AM Process** | **Dental Domain** | **Remarks** |
| [146] | PVA filament | FDM | Provisional Dental Crown | LAVA –TDS was used to scan the molar abutment. Surface accuracy was compared with a conventional model made by a conventional stone cast model. The author concludes by saying that 3D printed PVA models can be used for crown fabrication with good accuracy.  |
| [147] | Alumina-Ceramic | FDM | Dental Crown | The author of the infiltration of glass into the alumina. The specimens were pre-sintered at 11500C. Mechanical properties are similar to that of pure alumina. The method proves to be energy efficient, the cost has also been reduced. |
| [148] | Co-Cr alloy | SLMConventional Milling | Dental Prostheses | The Shear bond strength in the specimens manufactured by two processes had no significant impact. However, the roughness of the specimen is enhanced with the SLM process. |
| [149] | Co–Cr–W alloy | SLM | Dental inlays and bridges | The roughness was modified after 3D printing of specimens using different blasting media and altering the roughness as per the medical need. The sand blast process increased the hardness. |
| [150] | 3Y-TZP dental ceramics | SLM+Cold isostatic pressing | A dental crown, prostheses, dental restoration. | The sample sintered at 15000C has maximum flexural strength and maximum densification. This method laid the foundation of SLS/CIP technology for 3Y-TZP dental ceramics |

1. **Aerospace Applications of AM**

3D printing technology has been on the rise ever since its introduction in the manufacturing world. As its potential and applicability are being identified, it is finding increasing use in almost every industrial facet. The aerospace industry is no exception to this trend. It is one of the rapidly growing sectors with revenues expected to cross $100 billion in the next two decades [14]. The advantages provided by additive manufacturing such as superior flexibility, complex geometries, and faster production are ideal for aerospace applications. In addition, the capability of 3D printing to produce highly intricate and lightweight parts with almost no material waste has brought the attention of many industries towards it. The requirements of the aerospace industry such as thin-walled, durable, strong, and lightweight components are fulfilled by 3D printing. Furthermore, the aerospace industry has been able to advance the process by combining design to end-use parts as well as repairs [151]. Among the various AM processes, ones best suited for use in the aerospace industry are Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Wire and Arc Additive Manufacturing (WAAM) [152]. The reason behind the increasing use of these technologies in the aerospace industry is the production of very dense parts with considerably less post-processing as compared to traditional manufacturing processes [153]. EBM employs a high energy density electron beam to produce dense and void-less components made out of metals [111]. Friction Stir Additive Manufacturing (FSAM) is also used in the aerospace industry. Researchers showed that not only the mechanical properties were enhanced but the properties that were obtained by using FSAM were different from those achieved by traditional processes [154]. Stiffeners, stringers, wing spars, and longerons are being manufactured using FSAM in the aerospace industry [155]. Laser Metal Deposition (LMD) is best suited for repairs in aerospace parts. It makes use of a metal powder to repair the parts. The metal powder is deposited on the damaged portion and is then cured employing a laser. The strength obtained by this method is the same as that of the original part [14]. Developing new materials, especially metals and metal alloys is the hot field of research in 3D printing. Examples of AM manufactured aerospace parts are shown in figure 7.The domain of the aerospace industry with regards to materials being used is categorized into metallic and non-metallic components [156]. Nickel and Titanium-based alloys are given more attention in the aerospace industry [157]. As far as Nickel-based alloys are concerned, they offer high tensile strength, damage tolerance, and good corrosion and oxidation resistance [158]. In Titanium alloys, Ti-6Al-4V gives different hardness and ductility in different processes like SLS and EBM. The reason behind this is the different coolingrate of Ti-6Al-4V in these processes which results in the different microstructures. Researchers have also shown that the mechanical properties of Ti-6Al-4V manufactured using AM can be altered and adjusted by heat treatment[159][109]. Many aviation industries have started the production of various aircraft components using 3D printing. In March 2015, at least 200 special parts to be used in 10 different aircraft were manufactured by Boeing. Till then, at least 20,000 parts (nonmetallic) had been installed in various airplanes [160]. Till 2019, tens of thousands of components made by AM were installed on 16 different commercial as well as military aircraft by Boeing [161]. In 2017, a minimum of four AM parts made of Ti-alloys were used by Boeing in the manufacture of 787 Dreamliner aircraft. Plans to fabricate 1000 components by using AM were also being made which would end up saving a total amount of $2-3 million per airplane [162]. Boeing has also come forward in the manufacture of thermoplastic parts using laser sintering to be used in its aircrafts such as 737, 747, 777, and 787 [163]. Some components do have an intricate structure but they are fabricated by removing the production limit in less time and enhanced features using 3D printing [164]. Another leading company in the use of AM in the aerospace industry is Airbus. Airbus A320neo and A350 XWB test aircraft have also been installed with components such as metal brackets and bleed pipes made through AM [165]. Both Boeing and Airbus wanted to eliminate the mechanical and thermodynamic resistance and as a result, they shifted towards 3D printing. Boeing is also in the race of making plastic interior parts using 3D printing. The materials being used for this purpose are Ultem and nylon [111].



**Figure 7: Aerospace AM manufactured Parts(a) GE Leap Nozzle, (b) GE Turboprop, (c)Airbus A350 XWB jet wing bracket, (d) Titanium door hinge**[166]**.**

AM is being actively used by many institutions around the world for manufacturing components to be used in the aerospace industry. One such institution namely Harvest Technologies makes the use of plastic laser sintering from Electro-optical systems (EOS) to manufacture components to be used in Bell helicopters [167]. EADS innovation works and EOS, one of the front runners in laser sintering of metals performed experiments and concluded that both the energy and emissions were significantly reduced by replacing a cast steel hinge bracket on Airbus A320 with a Titanium part which was made by using additive manufacturing. It further revealed that by doing this, raw material consumption was reduced by 75% and also saved a total of 10kgs in each chipset [168]. National Aeronautics and Space Administration (NASA) is also promoting research in the field of fabrication of aerospace components by using various AM techniques. They are exploring the various possibilities and opportunities to manufacture these components on earth, abroad the International Space Station (ISS), in open space as well as on the moon or mars itself [169]. As far as NASA’s exploration of Mars continues, 3D printing and its potential are being recognized in this field as well. NASA is actively exploring new technologies that will assist in its mission of exploring Mars. In this regard, the engineers of NASA have successfully been able to print the first full-scale engine part for a rocket made of copper [170]. In addition, when metal injectors of rocket engines were fabricated using 3D printing, savings up to 80% in the cost of a $300,000 component were obtained. The manufacture of fuel turbopumps using 3D printing is also being tested [171]. Laser sintering was also employed to produce liquid oxygen and gaseous hydrogen injector by using nickel-chromium. By using this injector, a record thrust of 20,000 pounds was obtained under the testing of NASA [169]. Tethers Unlimited, Inc., US along with the support of NASA have been working on the development of multifunctional aircraft structures in open orbit [169]. Another big company adopting 3D printing in its setup is SpaceX. SuperDraco is a 3D-printed engine manufactured by SpaceX. It is used in the launch of the Dragon spacecraft [111]. In addition to this, SpaceX also manufactures impellers and other components of Merlin engines by using the laser sintering technique. These components are used in the driving of the Falcon 9 launch vehicle [172]. Boeing and GE Aviation have been working together to rebuild and redevelop GE90-94B jet engines by incorporating at least 400 3D printed parts in them. Furthermore, the LEAP jet engine manufactured by GE has 19 fuel nozzles all of which are fabricated using 3D printing have already been flight tested[173][174]. Their main aim is to run Boeing 737MAX and Airbus A320neo aircraft [174]. As far as LEAP and GE9X engines of GE are concerned, the target was to produce more than 100,000 3D printed parts for them by the end of 2020 [175]. Their next aim is to replace Titanium leading-edge blade covers manufactured using forging by remanufacturing them using 3D printing [176]. In the case of Super Hornet jets, more than 100 components are used in their air-cooling ducts [177]. The main area in the aerospace industry where 3D printing can be adopted swiftly is unmanned air vehicles and experimental aircraft because the scrutiny required for them is the least [111]. These areas are rapidly developing and 3D printing is finding an increasing use in both of these setups and is continuing to revolutionize an industry as sophisticated as the aerospace industry.

1. **Revolutionized Food Industry with Additive Manufacturing**

The concept of AM in food technology originated from the researchers of Cornell University as they developed a printer known as “Fab@home” [178]. Soon various other printers were developed, some of them are: Imagine 3D printer by Essential Dynamics and Choc creator by choc edge [179]. In conventional manufacturing, a lot of time is wasted in between the processes and hectic laboring is required. These problems are to be tackled by AM as all the processes run in the sequential manner without any delay. The concept of 3D food printing is quite different from robotic manufacturing as the process involves the layer-by-layer development of difficult shapes of different sizes and then binding them altogether with some chemical reaction or phase transition[180][8]. In addition, the 3D food printing involves selecting shapes, flavors, ingredients etc as per the requirement of the user [179]. Currently the 3D based food printers are developed on the need basis such as 3D food printers for the manufacturing of 3D chocolates using the laser technology [181]. Input materials supplied to 3D Food printer are classified into the three categories: Liquid, powder and cell culture [182]. Liquid based raw materials are processed by extrusion and inkjet based methods, the powder based input powder binding and for meat bio-printing is used [183]. Extrusion based FDM was used to develop chocolate bars and candies by a prototype digital chocolatier [184]. In addition, cakes were printed using Fab@home 3D printer. Apart from chocolates, extrusion based methods have been used to print carbohydrate; protein and mashed meat puree [185]. The inkjet printing is the powder based material input printing method that mainly uses liquid material for bonding of solid particles [186]. This method employs piezo-electric mechanism or thermal methods for the printer head. This approach is mainly used for printing of pastries and cakes [187]. De Grood Innovations printer is used to print pizza bases using pneumatic membrane nozzle jets. Powder binding deposition is another type of method for 3D food printing which consists of selective laser sintering (SLS), selective hot air sintering and melting (SHASAM), and liquid binding (LB or PBP: powder bed printing) technologies. SLS is used in making sugar and fat based products[188]. The LB or PBP works on the accumulation of powder layers by direct fusion [189]. Chef Jet printer, which works on the principles of LB was used to print sugar products and fondants [189]. From table 9, it is observed that recent advances in the domain of the food industry is mostly associated with extrusion-based manufacturing.

 Bio printing technique is used to develop the tissues without using the bio-base. This method deposits the biomaterial layer by layer, which event involves the deposition of culture of living cells. Researchers have used this method to develop edible porcine tissue [190]. The procedure for 3D bioprinting is shown in figure 8.



**Figure 8 : 3D Bio Manufacturing** [191]

However, this technology is in its early stage and hence the problem occurs at bulk production. The optimization is not achieved properly yet. Due to its user-friendly features, it will emerge as the leader of the food industry.

**Table 9: Recent work in 3D Food Printing**

|  |  |  |  |
| --- | --- | --- | --- |
| **Author** | **Printing Technology** | **Food Printed** | **Remarks** |
|  [192] | Extrusion Based Printing | soybean protein and steak-like foods | This research aims to develop 3D printed steak like food. TSP and DSP ink is used as the substitute for meat like material. The effect of printing parameters like printing pattern, infill percentage on the hardness, gumminess and chewiness is evaluated. Triangular pattern and infill percentage of 60% shows the optimum results. |
|  [193] | Extrusion Based Printing | Protein based doughs are prepared  | Pea protein concentrate (PPC), Porcine plasma protein (PPP), Soy protein isolate (SPI) are used to prepare protein based doughs. The effect of glycerol ratio and the composition of PPP, PPC and SPI on printing and rheology is studied. The percentage of glycerol has an adequate effect on followability. Further, biopolymers can alter the viscosity and viscoelastic moduli. |
| [194] | Extrusion Based Printing | Food pastes (Fiber and protein rich material) | The 3D extrusion based printer was used to check the printability of milk powder, faba protein, oat and cellulose Nano-fiber was examined. The studies suggest that printing shape stability is achieved with semi-skimmed milk powder-based paste.  |
| [195] | Extrusion Based Printing | Edible Gel Material | The study focuses on the development of edible gel material using 3D printing technology. Mechanical and Rheological characterization of Agar and Konjac based gels are obtained. The effect of weight ratios on the 3D printing performance is studied. The Konjac content enhances the visco-elastic properties of the gel which can be beneficial for extrusion-based 3D printing.  |
| [196] | Extrusion Based Printing | Vegetable and fruit gel system | The reason for this study is to develop protein-based fruit and vegetable composite ink with good printability. The proteins are obtained from five different animals and vegetables, which are taken in a matrix form. Results depict that peanut protein based ink exhibits best printing characteristics. Also, the sensory score of peanut based protein ink secured maximum among the all.  |

1. **Fashion Industry Empowered by Additive Manufacturing**

The highly automated nature of 3D printing has helped in its growth in the fashion industry. Fabrication of complex products with high levels of automation helps in their accurate and precise manufacturing. Production of highly customized products leads to higher customer satisfaction which plays a key role in today’s market [197]. One of the biggest names which uses 3D printing in their manufacturing setup is Nike where 3D printing is used to manufacture lightweight plates which are used in Vapour Laser Talon and Vapour High Agility football cleats [198][199]. Using 3D printing, Nike was able to reduce the time taken in prototyping and manufacturing from two to three years to six months [200]. Many mass market fashion brands are open to providing their customers with customized products using 3D printing [201]. San Francisco-based Continuum manufactures bathing suits on order through their retailer’s website [202]. They have joined hands with Shapeways, a 3D printing company for production of these customized products [203]. In addition, they also use 3D printing to make jewellery and women’s shoes [198]. Most of the modern designers look up to 3D printing as a technique to improve the quality of products as well as their design by allowing the customers to personalize their own products in a unique way [204]. With the advancement in 3D printing technology, the designers are now able to manufacture breathable fabric like materials which result in lightweight and flexible products [205]. Materialise, a Belgian company has developed a new material TPU-92A-1 which is used to manufacture customized products. It is a lightweight material which is characterized by high elasticity and is particularly used in fashion industry [206]. Polyjet Flex material by Solid Concepts Inc. has also developed some materials which offer varying density and stiffness within the same material. These advanced materials can help the designers and fashion experts in designing new outfits. They can efficiently make new garments and take care of the places where the garment needs more rigidity and where it needs more flexibility. This provides more movement and fit to the garment [200]. 3D printing has emerged as a technique which has reduced the complexities and problems like more lead time and extensive wastage associated with the clothing industry [207]. Lead time is vital in the fashion industry [208]. Customer’s changing needs poses a challenge in delivering the fashion products to them in an efficient and time saving method while avoiding over-production. Lead time in such cases becomes more important than cost itself. In traditional practices, raw material is ordered from one place, assembled at other place and finally manufactured at some another place. This is very time consuming. 3D printing cuts the line here as well as it can manufacture the products immediately via on-site manufacturing [209]. It has also provided more freedom to designers in terms of the variety and complexity of the geometries that can be incorporated in the products of dresses and shoes[210][211].

3D printing uses the 3D modelling software before actual printing is started. Using this 3D scanning technique, real time data can be obtained for several products like jewellery, shoes and garments. These scanning techniques come in handy in reverse engineering as well where modifications, alterations and adulterations of products can be made quickly using the scan data. This eliminates the need for developing the base model from the start [212]. The other advantage that 3D printing provides the fashion designers with is the interdisciplinary knowledge and skills, which would greatly help in teamwork and collaboration. 3D printing fashion designers and experts like Van Herpen are looking to collaborate with the people of other fields to create more wearable garments which would otherwise have posed serious challenges for a traditional fashion design team [208].

 **8.** **3D printing in relation with Industry 4.0 and Sustainability**

3D printing, commonly known as additive manufacturing, has been a buzz word in the manufacturing sector in the past decade. The current era of the fourth industrial revolution or Industry 4.0 has also encouraged techniques like 3D printing to be adopted in industrial setups. “The term Industry 4.0 stands for the fourth industrial revolution which is defined as a new level of organization and control over the entire value chain of the life cycle of products, it is geared towards increasingly individualized customer requirements” [213]. Industry 4.0 majorly focusses on meeting customer demands through proper research methodology, product development, manufacturing, order management and recycling [214] and has led to many significant developments in various industrial setups [215].

Industry 4.0 has nine fundamental pillars viz. simulation, augmented reality, system integration, cloud computing, big data, advanced robotics, 3D printing, cyber security and IOT [216]. 3D printing, apart from being one of the main pillars of Industry 4.0, has a good link with its other pillars as well. As of now, 3D printing has already found its use in the fields of robotics, AR, cloud manufacturing and IOT. The introduction of 3D printing in modern industries has significantly changed the entire manufacturing and production chains and has transformed them into more sophisticated and automated lines of production with higher accuracy and intelligent data exchange [217]. It has also eliminated the use of many expensive tools, fittings, jigs and fixtures which further make this technology cost and time efficient.

One important aspect of Industry 4.0 is advanced robotics and this field has been revolutionized by 3D printing. 3D printing is widely being used in the manufacture of mobile robots and soft robots [218]. Soft robots have seen an increasing demand in the market and 3D printing due to its time efficiency and labor-friendly nature has emerged as front runners for their manufacture [219]. Augmented reality is another integral part of Industry 4.0 which has benefitted from 3D printing technology. The integration of 3D printing in AR has great potential in the medical field and has proven to be of great help to medical practitioners and physicians as well [220]. In the printing of various medical implants and equipment, a lot of time is invested. Sometimes, due to errors, the final print obtained does not match the required criteria and as a result, time, effort and money is wasted. AR has greatly assisted in such cases by letting the engineers and medical practitioners actually visualize the print before even printing it. This has eradicated all the ambiguity surrounding the printing of various parts where time is the main consideration.

Another important pillar of Industry 4.0 is cloud manufacturing. It involves a series of connected manufacturing services to meet all the needs of customers. Real time communication is key in such systems. 3D printing has helped cloud manufacturing in establishing a completely new production mode capable of replacing the traditional mass production mode by assisting it set up all its services as underlying process equipment [221]. This has assisted customers in making their own customized products in the cloud and enjoy the benefit of having personalized products. IOT is an integral component in almost all new smart equipment. In this system, real time data is collected using sensors and then transmitted to the system which analyses the data and suggests changes according to the needs [222]. This technology has proven to be helpful in solving various problems in the medical industry [223]. Researchers [224] worked on improving the global manufacturing using 3D printing by designing an IOT system in which the customers give their order online. On the basis of location and distance, these orders are distributed in parts to nearby 3D printing outlets. Once printing is complete, these parts are assembled at a main facility and delivered to the customer.

Due to rapidly increasing population and its never ending demands, the exploitation of natural resources is currently on an all-time high. The rate of exploitation of resources is taking place at an alarming rate and if this goes unchecked, soon we will face a time where these resources will become extinct, and we will be in need of other alternatives. This is where sustainability comes into the picture. Sustainability means careful and measured use of these resources to ensure that these last for a long time and the future generations are not deprived of it. The “Brundtland report-1987” of the UN has defined sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations General Assembly, 11 December 1987. 96th Plenary Meeting. Report of the World Commission on Environment and Development, A/ RES/42/187; [225]).

Sustainability is majorly concerned with the following three aspects: environment, economic and social aspects. 3D printing has been able to provide various advantages in all these aspects and thus has emerged as a potential solution to various sustainability problems[226]. From a social sustainability viewpoint, researchers have presented 3D printing as a solution to social sustainability problems of supply chain management by introducing distributed production and open design [227]. Ocean plastic accumulation is one of the biggest challenges we are facing today. Large amount of plastic is continuously being dumped into oceans which leads to formation of islands of plastic waste. Researchers gave a possible solution to this problem by suggesting shoreline collection of plastic waste and then remanufactured the same into filaments which will then be used as raw material in 3D printing [228].

From an economic sustainability point of view, 3D printing aims at improving resource efficiency by reducing the waste significantly. The concept of Circular economy (CE) has always been around 3D printing. Researchers [16] in their work emphasized on the importance of 3D printing in creating a suitable and favorable environment for economic sustainability and in the application of CE [229]. They also studied the promoters, enhancers and challenges in the path of 3D printing towards attaining CE. In concrete construction technology, researchers revealed that 3D printing has numerous advantages as compared to traditional techniques from economic point of view as it has proven to save a lot of money associated with labor and framework, mostly in geometrical irregular structures [230]. In order to cover most of the needs to the modern world, many materials are being continuously tested and developed for 3D printing and metals is the most recent addition to that list. The advantages of 3D printing of metals from an economic perspective include shorter processes, shorter assembly chains, less lead time, lesser spare parts and fast manufacturing. However the disadvantages include high cost of production, high manufacturing time and limited part dimensions [231].

In regard to environmental sustainability, 3D printing offers certain unique advantages compared to conventional manufacturing processes. Both carbon dioxide emissions and energy consumption have decreased using 3D printing, however they depend largely on the type of material being used [232]. Reducing the resource consumption, waste management and pollution control are the main aspects of environmental sustainability offered by 3D printing [233]. Since there is almost no use of lubricants and cutting fluids in 3D printing, their associated pollution also gets eliminated and this is considered a big step towards achieving green production [234]. 3D printing also encourages the use of recycled plastic as raw material. Recycled polymer and plastic filaments have been named as second life of polymeric waste [235]. This is one of the major environmental benefits of 3D printing because of the non-biodegradability of many plastics [236]. The waste of metals and various alloys is also recyclable and also contributes in establishing CE [237].

**9. Conclusions and Recommendations**

 The various additive manufacturing technologies due to their ability to handle complex designs and other technical advantages have emerged as a technology for manufacturing advanced products with optimized geometries. The benefits such as waste reduction, energy saving make AM more relevant in an era when industries and nations are focusing on sustainability. Although a lot of work has been done to optimize the various process parameters and their effect on mechanical behavior, various challenges limit the use of AM technologies at a large scale. The applications of AM in developing various medical applications need to be explored at a large scale. More material options need to be explored to make AM technologies more versatile and widen their application arena. AM being an important pillar of Industry 4.0 is an important enabler for sustainability and hence broadening the application arena of AM and exploiting its potential can help in achieving sustainability as well as in implementing industry 4.0.

 The paper has dealt with extrusion-based technologies in more detail in comparison to the other technologies. Based on the discussion and literature presented in this paper, future studies could be undertaken to study the various technologies of AM in detail and compare their sustainability potential, cost and role in implementing Industry 4.0. Future studies could be organized in a manner to stress on a particular application and exploit the potential of AM particularly in medical science.

**Conflict of Interest:** The authors declare that there is no conflict of interest.

**References**

[1] D. I. Wimpenny, P. M. Pandey, L. J. Kumar, and others, *Advances in 3D printing \& additive manufacturing technologies*. Springer, 2017.

[2] W. D. Callister Jr and D. G. Rethwisch, *Fundamentals of materials science and engineering: an integrated approach*. John Wiley \& Sons, 2020.

[3] M. Attaran, “The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing,” *Bus. Horiz.*, vol. 60, no. 5, pp. 677–688, 2017.

[4] O. Abdulhameed, A. Al-Ahmari, W. Ameen, and S. H. Mian, “Additive manufacturing: Challenges, trends, and applications,” *Adv. Mech. Eng.*, vol. 11, no. 2, p. 1687814018822880, 2019.

[5] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, and M. I. U. Haq, “n3D Printing--A Review of Processes, Materials and Applications in Industry 4.0,” *Sustain. Oper. Comput.*, 2021.

[6] M. I. U. Haq, A. Raina, M. J. Ghazali, M. Javaid, and A. Haleem, “Potential of 3D Printing Technologies in Developing Applications of Polymeric Nanocomposites,” in *Tribology of Polymer and Polymer Composites for Industry 4.0*, Springer, 2021, pp. 193–210.

[7] B. Berman, “3-D printing: The new industrial revolution,” *Bus. Horiz.*, vol. 55, no. 2, pp. 155–162, 2012.

[8] A. C. F. on Additive Manufacturing Technologies and A. C. F. on Additive Manufacturing Technologies. Subcommittee F42. 91 on Terminology, *Standard terminology for additive manufacturing technologies*. Astm International, 2012.

[9] A. J. Lopes, E. MacDonald, and R. B. Wicker, “Integrating stereolithography and direct print technologies for 3D structural electronics fabrication,” *Rapid Prototyp. J.*, 2012.

[10] M. Liang, C. Shemelya, E. MacDonald, R. Wicker, and H. Xin, “3-D printed microwave patch antenna via fused deposition method and ultrasonic wire mesh embedding technique,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 14, pp. 1346–1349, 2015.

[11] A. Kamyshny and S. Magdassi, “Conductive nanomaterials for 2D and 3D printed flexible electronics,” *Chem. Soc. Rev.*, vol. 48, no. 6, pp. 1712–1740, 2019.

[12] K. Markstedt, A. Mantas, I. Tournier, H. Mart\’\inez Ávila, D. Hagg, and P. Gatenholm, “3D bioprinting human chondrocytes with nanocellulose--alginate bioink for cartilage tissue engineering applications,” *Biomacromolecules*, vol. 16, no. 5, pp. 1489–1496, 2015.

[13] M. S. Mannoor *et al.*, “3D printed bionic ears,” *Nano Lett.*, vol. 13, no. 6, pp. 2634–2639, 2013.

[14] L. J. Kumar and C. G. K. Nair, “Current trends of additive manufacturing in the aerospace industry,” in *Advances in 3D printing \& additive manufacturing technologies*, Springer, 2017, pp. 39–54.

[15] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, “Large-scale 3D printing of ultra-high performance concrete--a new processing route for architects and builders,” *Mater. \& Des.*, vol. 100, pp. 102–109, 2016.

[16] C. Silbernagel, “Additive Manufacturing 101-4: What is material jetting?,” *Canada Makers*, 2018.

[17] Z.-X. Low, Y. T. Chua, B. M. Ray, D. Mattia, I. S. Metcalfe, and D. A. Patterson, “Perspective on 3D printing of separation membranes and comparison to related unconventional fabrication techniques,” *J. Memb. Sci.*, vol. 523, pp. 596–613, 2017.

[18] J. W. Stansbury and M. J. Idacavage, “3D printing with polymers: Challenges among expanding options and opportunities,” *Dent. Mater.*, vol. 32, no. 1, pp. 54–64, 2016.

[19] E. Sachs, M. Cima, P. Williams, D. Brancazio, and J. Cornie, “Three dimensional printing: rapid tooling and prototypes directly from a CAD model,” 1992.

[20] N.-T. Nguyen, “et al.,‘MEMS-Micropumps: A Review,’ Transaction of ASME, Vol. 124,” *Jung*, 2002.

[21] C. L. Ventola, “Medical applications for 3D printing: current and projected uses,” *Pharm. Ther.*, vol. 39, no. 10, p. 704, 2014.

[22] K. V Wong and A. Hernandez, “A review of additive manufacturing,” *Int. Sch. Res. Not.*, vol. 2012, 2012.

[23] B. Utela, D. Storti, R. Anderson, and M. Ganter, “A review of process development steps for new material systems in three dimensional printing (3DP),” *J. Manuf. Process.*, vol. 10, no. 2, pp. 96–104, 2008.

[24] Y. Bai and C. B. Williams, “An exploration of binder jetting of copper,” *Rapid Prototyp. J.*, 2015.

[25] J. Suwanprateeb, S. Kerdsook, T. Boonsiri, and P. Pratumpong, “Evaluation of heat treatment regimes and their influences on the properties of powder-printed high-density polyethylene bone implant,” *Polym. Int.*, vol. 60, no. 5, pp. 758–764, 2011.

[26] Y. Tang, Y. Zhou, T. Hoff, M. Garon, and Y. F. Zhao, “Elastic modulus of 316 stainless steel lattice structure fabricated via binder jetting process,” *Mater. Sci. Technol.*, vol. 32, no. 7, pp. 648–656, 2016.

[27] N. B. Crane, J. Wilkes, E. Sachs, and S. M. Allen, “Improving accuracy of powder-based SFF processes by metal deposition from a nanoparticle dispersion,” *Rapid Prototyp. J.*, 2006.

[28] R. Melcher, S. Martins, N. Travitzky, and P. Greil, “Fabrication of Al2O3-based composites by indirect 3D-printing,” *Mater. Lett.*, vol. 60, no. 4, pp. 572–575, 2006.

[29] A. Farzadi, M. Solati-Hashjin, M. Asadi-Eydivand, and N. A. Abu Osman, “Effect of layer thickness and printing orientation on mechanical properties and dimensional accuracy of 3D printed porous samples for bone tissue engineering,” *PLoS One*, vol. 9, no. 9, p. e108252, 2014.

[30] S. Maleksaeedi, H. Eng, F. E. Wiria, T. M. H. Ha, and Z. He, “Property enhancement of 3D-printed alumina ceramics using vacuum infiltration,” *J. Mater. Process. Technol.*, vol. 214, no. 7, pp. 1301–1306, 2014.

[31] W. Du, X. Ren, C. Ma, and Z. Pei, “Binder jetting additive manufacturing of ceramics: A literature review,” in *ASME International Mechanical Engineering Congress and Exposition*, 2017, vol. 58493, p. V014T07A006.

[32] R. Hamano, Y. Nakagawa, V. Irawan, and T. Ikoma, “Mechanical anisotropy and fracture mode of binder jetting 3D printed calcium sulfate moldings,” *Appl. Mater. Today*, vol. 25, p. 101160, 2021.

[33] H. Miyanaji, S. Zhang, A. Lassell, A. Zandinejad, and L. Yang, “Process development of porcelain ceramic material with binder jetting process for dental applications,” *Jom*, vol. 68, no. 3, pp. 831–841, 2016.

[34] A. C. Hayes, J. Osio-Norgaard, S. Miller, M. E. Vance, and G. L. Whiting, “Influence of powder type on aerosol emissions in powder-binder jetting with emphasis on lunar regolith for in situ space applications,” *ACS ES\&T Eng.*, vol. 1, no. 2, pp. 183–191, 2020.

[35] B. Mummareddy, E. Burden, J. G. Carrillo, K. Myers, E. MacDonald, and P. Cortes, “Mechanical performance of lightweight ceramic structures via binder jetting of microspheres,” *SN Appl. Sci.*, vol. 3, no. 4, pp. 1–10, 2021.

[36] A. Müller and S. Karevska, “How will 3D printing make your company the strongest link in the value chain,” *EY’s Glob. 3D Print. Rep.*, 2016.

[37] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O’Donoghue, and C. Charitidis, “Additive manufacturing: scientific and technological challenges, market uptake and opportunities,” *Mater. today*, vol. 21, no. 1, pp. 22–37, 2018.

[38] Y. L. Yap *et al.*, “3D printed bio-models for medical applications,” *Rapid Prototyp. J.*, 2017.

[39] G. D. Goh, S. Agarwala, G. L. Goh, V. Dikshit, S. L. Sing, and W. Y. Yeong, “Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential,” *Aerosp. Sci. Technol.*, vol. 63, pp. 140–151, 2017.

[40] A. K. Sood, R. K. Ohdar, and S. S. Mahapatra, “Parametric appraisal of mechanical property of fused deposition modelling processed parts,” *Mater. \& Des.*, vol. 31, no. 1, pp. 287–295, 2010.

[41] G. C. Onwubolu and F. Rayegani, “Characterization and optimization of mechanical properties of ABS parts manufactured by the fused deposition modelling process,” *Int. J. Manuf. Eng.*, vol. 2014, 2014.

[42] F. Górski, W. Kuczko, and R. Wichniarek, “Influence of process parameters on dimensional accuracy of parts manufactured using fused deposition modelling technology,” *Adv. Sci. Technol. Res. J.*, vol. 7, no. 19, pp. 27–35, 2013.

[43] M. Montero, S. Roundy, D. Odell, S.-H. Ahn, and P. K. Wright, “Material characterization of fused deposition modeling (FDM) ABS by designed experiments,” *Soc. Manuf. Eng.*, vol. 10, no. 13552540210441166, pp. 1–21, 2001.

[44] A. W. Fatimatuzahraa, B. Farahaina, and W. A. Y. Yusoff, “The effect of employing different raster orientations on the mechanical properties and microstructure of Fused Deposition Modeling parts,” in *2011 IEEE Symposium on Business, Engineering and Industrial Applications (ISBEIA)*, 2011, pp. 22–27.

[45] M. Alhubail, “Statistical-based optimization of process parameters of fused deposition modelling for improved quality,” University of Portsmouth, 2012.

[46] F. Lederle, F. Meyer, G.-P. Brunotte, C. Kaldun, and E. G. Hübner, “Improved mechanical properties of 3D-printed parts by fused deposition modeling processed under the exclusion of oxygen,” *Prog. Addit. Manuf.*, vol. 1, no. 1, pp. 3–7, 2016.

[47] E. Kim, Y.-J. Shin, and S.-H. Ahn, “The effects of moisture and temperature on the mechanical properties of additive manufacturing components: fused deposition modeling,” *Rapid Prototyp. J.*, 2016.

[48] S. N. A. Mohd Halidi and J. Abdullah, “Moisture and humidity effects on the ABS used in fused deposition modeling machine,” in *Advanced materials research*, 2012, vol. 576, pp. 641–644.

[49] M. S. Amirruddin, K. I. Ismail, and T. C. Yap, “Effect of layer thickness and raster angle on the tribological behavior of 3D printed materials,” *Mater. Today Proc.*, 2021.

[50] M. Kam, A. \.Ipekçi, and Ö. \cSengül, “Investigation of the effect of FDM process parameters on mechanical properties of 3D printed PA12 samples using Taguchi method,” *J. Thermoplast. Compos. Mater.*, p. 08927057211006459, 2021.

[51] R. Wichniarek, A. Hamrol, W. Kuczko, F. Górski, and M. Rogalewicz, “ABS filament moisture compensation possibilities in the FDM process,” *CIRP J. Manuf. Sci. Technol.*, vol. 35, pp. 550–559, 2021.

[52] H. Gong, D. Snelling, K. Kardel, and A. Carrano, “Comparison of stainless steel 316L parts made by FDM-and SLM-based additive manufacturing processes,” *Jom*, vol. 71, no. 3, pp. 880–885, 2019.

[53] M. Razavi-Nouri, A. M. Rezadoust, Z. Soheilpour, K. Garoosi, and S. R. Ghaffarian, “Morphology and mechanical properties of poly (acrylonitrile-butadiene-styrene)/multi-walled carbon nanotubes nanocomposite specimens prepared by fused deposition modeling,” *Polym. Compos.*, vol. 42, no. 1, pp. 342–352, 2021.

[54] S. K. Tiwari, S. Pande, S. Agrawal, and S. M. Bobade, “Selection of selective laser sintering materials for different applications,” *Rapid Prototyp. J.*, 2015.

[55] M. P. Sealy, G. Madireddy, R. E. Williams, P. Rao, and M. Toursangsaraki, “Hybrid processes in additive manufacturing,” *J. Manuf. Sci. Eng.*, vol. 140, no. 6, 2018.

[56] F. Fina, A. Goyanes, S. Gaisford, and A. W. Basit, “Selective laser sintering (SLS) 3D printing of medicines,” *Int. J. Pharm.*, vol. 529, no. 1–2, pp. 285–293, 2017.

[57] X. Tian, G. Peng, M. Yan, S. He, and R. Yao, “Process prediction of selective laser sintering based on heat transfer analysis for polyamide composite powders,” *Int. J. Heat Mass Transf.*, vol. 120, pp. 379–386, 2018.

[58] B. Zhang, Y. Li, and Q. Bai, “Defect formation mechanisms in selective laser melting: a review,” *Chinese J. Mech. Eng.*, vol. 30, no. 3, pp. 515–527, 2017.

[59] M. Galati and L. Iuliano, “A literature review of powder-based electron beam melting focusing on numerical simulations,” *Addit. Manuf.*, vol. 19, pp. 1–20, 2018.

[60] R. Hamed, E. M. Mohamed, Z. Rahman, and M. A. Khan, “3D-printing of lopinavir printlets by selective laser sintering and quantification of crystalline fraction by XRPD-chemometric models,” *Int. J. Pharm.*, vol. 592, p. 120059, 2021.

[61] Y. A. Gueche *et al.*, “Selective Laser Sintering of Solid Oral Dosage Forms with Copovidone and Paracetamol Using a CO2 Laser,” *Pharmaceutics*, vol. 13, no. 2, p. 160, 2021.

[62] R. Ajdary *et al.*, “Selective laser sintering of lignin-based composites, ACS Sustain,” *Chem. Eng*, vol. 9, 2021.

[63] W. Zheng *et al.*, “Fabrication of high-performance silica-based ceramic cores through selective laser sintering combined with vacuum infiltration,” *Addit. Manuf.*, p. 102396, 2021.

[64] X. Pei *et al.*, “Fabrication of customized Ti6AI4V heterogeneous scaffolds with selective laser melting: Optimization of the architecture for orthopedic implant applications,” *Acta Biomater.*, vol. 126, pp. 485–495, 2021.

[65] E. Langi *et al.*, “Microstructural and mechanical characterization of thin-walled tube manufactured with selective laser melting for stent application,” *J. Mater. Eng. Perform.*, vol. 30, no. 1, pp. 696–710, 2021.

[66] S. Ganesan, B. Esakki, L.-J. Yang, D. Rajamani, M. Silambarsan, and K. Raghunath, “Fabrication of flapping-wing micromechanism assembly using selective laser melting and aerodynamic performance measures,” *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, p. 14644207211035422, 2021.

[67] Z. Wang, R. Liu, T. Sparks, H. Liu, and F. Liou, “Stereo vision based hybrid manufacturing process for precision metal parts,” *Precis. Eng.*, vol. 42, pp. 1–5, 2015.

[68] U. M. Dilberoglu, B. Gharehpapagh, U. Yaman, and M. Dolen, “The role of additive manufacturing in the era of industry 4.0,” *Procedia Manuf.*, vol. 11, pp. 545–554, 2017.

[69] Y. Hu, F. Ning, W. Cong, Y. Li, X. Wang, and H. Wang, “Ultrasonic vibration-assisted laser engineering net shaping of ZrO2-Al2O3 bulk parts: Effects on crack suppression, microstructure, and mechanical properties,” *Ceram. Int.*, vol. 44, no. 3, pp. 2752–2760, 2018.

[70] J. Raplee *et al.*, “Thermographic microstructure monitoring in electron beam additive manufacturing,” *Sci. Rep.*, vol. 7, no. 1, pp. 1–16, 2017.

[71] O. Oyelola, P. Crawforth, R. M’Saoubi, and A. T. Clare, “On the machinability of directed energy deposited Ti6Al4V,” *Addit. Manuf.*, vol. 19, pp. 39–50, 2018.

[72] O. Oyelola, P. Crawforth, R. M’Saoubi, and A. T. Clare, “Machining of additively manufactured parts: implications for surface integrity,” *Procedia Cirp*, vol. 45, pp. 119–122, 2016.

[73] I. Astm, “ASTM52900-15 standard terminology for additive manufacturing—general principles—terminology,” *ASTM Int. West Conshohocken, PA*, vol. 3, no. 4, p. 5, 2015.

[74] S. Vijayavenkataraman, J. Y. H. Fuh, and W. F. Lu, “3D printing and 3D bioprinting in pediatrics,” *Bioengineering*, vol. 4, no. 3, p. 63, 2017.

[75] D. R. White, “Ultrasonic consolidation of aluminum tooling,” *Adv. Mater. \& Process.*, vol. 161, no. 1, pp. 64–66, 2003.

[76] A. Hehr and M. Norfolk, “A comprehensive review of ultrasonic additive manufacturing,” *Rapid Prototyp. J.*, 2019.

[77] A. Hehr, J. Wenning, M. Norfolk, J. Sheridan, J. A. Newman, and M. Domack, “Selective reinforcement of aerospace structures using ultrasonic additive manufacturing,” *J. Mater. Eng. Perform.*, vol. 28, no. 2, pp. 633–640, 2019.

[78] V. K. Nadimpalli, G. M. Karthik, G. D. Janakiram, and P. B. Nagy, “Monitoring and repair of defects in ultrasonic additive manufacturing,” *Int. J. Adv. Manuf. Technol.*, vol. 108, pp. 1793–1810, 2020.

[79] C. Schmidleithner and D. M. Kalaskar, “Stereolithography,” IntechOpen, 2018.

[80] M. Vaezi, H. Seitz, and S. Yang, “A review on 3D micro-additive manufacturing technologies,” *Int. J. Adv. Manuf. Technol.*, vol. 67, no. 5–8, pp. 1721–1754, 2013.

[81] I. Gibson, D. W. Rosen, B. Stucker, and M. Khorasani, *Additive manufacturing technologies*, vol. 17. Springer, 2021.

[82] D. Bourell *et al.*, “Materials for additive manufacturing,” *CIRP Ann.*, vol. 66, no. 2, pp. 659–681, 2017.

[83] L. Messe and C. Chapelat, “Curable composition.” Google Patents, 2013.

[84] J. Mueller and K. Shea, “The effect of build orientation on the mechanical properties in inkjet 3D printing,” in *International Solid Freeform Fabrication Symposium*, 2015, pp. 983–992.

[85] L. Bass, N. A. Meisel, and C. B. Williams, “Exploring variability of orientation and aging effects in material properties of multi-material jetting parts,” *Rapid Prototyp. J.*, 2016.

[86] P. Edwards and M. Ramulu, “Fatigue performance evaluation of selective laser melted Ti--6Al--4V,” *Mater. Sci. Eng. A*, vol. 598, pp. 327–337, 2014.

[87] T. Niendorf, S. Leuders, A. Riemer, H. A. Richard, T. Tröster, and D. Schwarze, “Highly anisotropic steel processed by selective laser melting,” *Metall. Mater. Trans. B*, vol. 44, no. 4, pp. 794–796, 2013.

[88] A. Yadollahi, N. Shamsaei, S. M. Thompson, A. Elwany, L. Bian, and M. Mahmoudi, “Fatigue behavior of selective laser melted 17-4 PH stainless steel,” 2015.

[89] G. Casalino, S. L. Campanelli, N. Contuzzi, and A. D. Ludovico, “Experimental investigation and statistical optimisation of the selective laser melting process of a maraging steel,” *Opt. \& Laser Technol.*, vol. 65, pp. 151–158, 2015.

[90] X. Xin, N. Xiang, J. Chen, D. Xu, and B. Wei, “Corrosion characteristics of a selective laser melted Co--Cr dental alloy under physiological conditions,” *J. Mater. Sci.*, vol. 47, no. 12, pp. 4813–4820, 2012.

[91] K. Kempen, L. Thijs, J. Van Humbeeck, and J.-P. Kruth, “Processing AlSi10Mg by selective laser melting: parameter optimisation and material characterisation,” *Mater. Sci. Technol.*, vol. 31, no. 8, pp. 917–923, 2015.

[92] I. Maskery *et al.*, “Quantification and characterisation of porosity in selectively laser melted Al--Si10--Mg using X-ray computed tomography,” *Mater. Charact.*, vol. 111, pp. 193–204, 2016.

[93] S. Li, Q. Wei, Y. Shi, Z. Zhu, and D. Zhang, “Microstructure characteristics of Inconel 625 superalloy manufactured by selective laser melting,” *J. Mater. Sci. \& Technol.*, vol. 31, no. 9, pp. 946–952, 2015.

[94] R. R. Dehoff *et al.*, “Site specific control of crystallographic grain orientation through electron beam additive manufacturing,” *Mater. Sci. Technol.*, vol. 31, no. 8, pp. 931–938, 2015.

[95] D. Zito *et al.*, “Optimization of SLM technology main parameters in the production of gold and platinum jewelry,” in *Santa Fe Symposium on Jewelry Manufacturing Technology*, 2014, pp. 439–470.

[96] Y. N. Zhang, X. Cao, P. Wanjara, and M. Medraj, “Oxide films in laser additive manufactured Inconel 718,” *Acta Mater.*, vol. 61, no. 17, pp. 6562–6576, 2013.

[97] F. Y. Niu, D. J. Wu, S. Yan, G. Y. Ma, and B. Zhang, “Process optimization for suppressing cracks in laser engineered net shaping of Al 2 O 3 ceramics,” *Jom*, vol. 69, no. 3, pp. 557–562, 2017.

[98] J. Wilkes, Y.-C. Hagedorn, W. Meiners, and K. Wissenbach, “Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting,” *Rapid Prototyp. J.*, 2013.

[99] M. C. Leu and D. A. Garcia, “Development of freeze-form extrusion fabrication with use of sacrificial material,” *J. Manuf. Sci. Eng.*, vol. 136, no. 6, 2014.

[100] D. McMillen, W. Li, M.-C. Leu, G. Hilmas, and J. L. Watts, “Designed extrudate for additive manufacturing of zirconium diboride by ceramic on-demand extrusion,” 2016.

[101] A. Ghazanfari, W. Li, M.-C. Leu, and G. Hilmas, “Novel extrusion-based additive manufacturing process for ceramic parts,” 2016.

[102] D. C. Hofmann *et al.*, “Compositionally graded metals: A new frontier of additive manufacturing,” *J. Mater. Res.*, vol. 29, no. 17, pp. 1899–1910, 2014.

[103] E. E. de Obaldia, C. Jeong, L. K. Grunenfelder, D. Kisailus, and P. Zavattieri, “Analysis of the mechanical response of biomimetic materials with highly oriented microstructures through 3D printing, mechanical testing and modeling,” *J. Mech. Behav. Biomed. Mater.*, vol. 48, pp. 70–85, 2015.

[104] A. Thomas, K. C. R. Kolan, M. C. Leu, and G. E. Hilmas, “Freeform Extrusion Fabrication of Titanium Fiber Reinforced Bioactive Glass Scaffolds,” in *Proceedings of SFF Symposium*, 2015, pp. 1688–1699.

[105] Y. Du, H. Liu, J. Shuang, J. Wang, J. Ma, and S. Zhang, “Microsphere-based selective laser sintering for building macroporous bone scaffolds with controlled microstructure and excellent biocompatibility,” *Colloids Surfaces B Biointerfaces*, vol. 135, pp. 81–89, 2015.

[106] F.-H. Liu, Y.-K. Shen, and Y.-S. Liao, “Selective laser gelation of ceramic--matrix composites,” *Compos. Part B Eng.*, vol. 42, no. 1, pp. 57–61, 2011.

[107] A. Li *et al.*, “Freeze-form extrusion fabrication of functionally graded material composites using zirconium carbide and tungsten,” in *Solid Free. Fabr. Symp., Austin, TX, USA*, 2012, pp. 467–479.

[108] A. Zocca, P. Colombo, C. M. Gomes, and J. Günster, “Additive manufacturing of ceramics: issues, potentialities, and opportunities,” *J. Am. Ceram. Soc.*, vol. 98, no. 7, pp. 1983–2001, 2015.

[109] L. Facchini, E. Magalini, P. Robotti, A. Molinari, S. Höges, and K. Wissenbach, “Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders,” *Rapid Prototyp. J.*, 2010.

[110] B. Baufeld, “Mechanical properties of Inconel 718 parts manufactured by shaped metal deposition (SMD),” *J. Mater. Eng. Perform.*, vol. 21, no. 7, pp. 1416–1421, 2012.

[111] S. C. Joshi and A. A. Sheikh, “3D printing in aerospace and its long-term sustainability,” *Virtual Phys. Prototyp.*, vol. 10, no. 4, pp. 175–185, 2015, doi: 10.1080/17452759.2015.1111519.

[112] S. Lathers and J. La Belle, “Advanced manufactured fused filament fabrication 3D printed osseointegrated prosthesis for a transhumeral amputation using Taulman 680 FDA,” *3D Print. Addit. Manuf.*, vol. 3, no. 3, pp. 166–174, 2016.

[113] M. Kristoffersen, M. Costas, T. Koenis, V. Brøtan, C. O. Paulsen, and T. Børvik, “On the ballistic perforation resistance of additive manufactured AlSi10Mg aluminium plates,” *Int. J. Impact Eng.*, vol. 137, p. 103476, 2020.

[114] M. Costas *et al.*, “Ballistic impact resistance of additive manufactured high-strength maraging steel: An experimental study,” *Int. J. Prot. Struct.*, p. 20414196211035490, 2021.

[115] A. B. V Pettersson, M. Salmi, P. Vallittu, W. Serlo, J. Tuomi, and A. A. Mäkitie, “Main clinical use of additive manufacturing (three-dimensional printing) in Finland restricted to the head and neck area in 2016--2017,” *Scand. J. Surg.*, vol. 109, no. 2, pp. 166–173, 2020.

[116] A. A. Zadpoor and J. Malda, “Additive manufacturing of biomaterials, tissues, and organs.” Springer, 2017.

[117] A. A. Zadpoor, “Bone tissue regeneration: the role of scaffold geometry,” *Biomater. Sci.*, vol. 3, no. 2, pp. 231–245, 2015.

[118] A. Arjunan, M. Demetriou, A. Baroutaji, and C. Wang, “Mechanical performance of highly permeable laser melted Ti6Al4V bone scaffolds,” *J. Mech. Behav. Biomed. Mater.*, vol. 102, p. 103517, 2020.

[119] C. Torres-Sanchez, F. R. A. Al Mushref, M. Norrito, K. Yendall, Y. Liu, and P. P. Conway, “The effect of pore size and porosity on mechanical properties and biological response of porous titanium scaffolds,” *Mater. Sci. Eng. C*, vol. 77, pp. 219–228, 2017.

[120] B. Zhao, A. K. Gain, W. Ding, L. Zhang, X. Li, and Y. Fu, “A review on metallic porous materials: pore formation, mechanical properties, and their applications,” *Int. J. Adv. Manuf. Technol.*, vol. 95, no. 5, pp. 2641–2659, 2018.

[121] Y. Du *et al.*, “Selective laser sintering scaffold with hierarchical architecture and gradient composition for osteochondral repair in rabbits,” *Biomaterials*, vol. 137, pp. 37–48, 2017.

[122] C. Shuai, P. Li, J. Liu, and S. Peng, “Optimization of TCP/HAP ratio for better properties of calcium phosphate scaffold via selective laser sintering,” *Mater. Charact.*, vol. 77, pp. 23–31, 2013.

[123] J. Liu, H. Hu, P. Li, C. Shuai, and S. Peng, “Fabrication and characterization of porous 45S5 glass scaffolds via direct selective laser sintering,” *Mater. Manuf. Process.*, vol. 28, no. 6, pp. 610–615, 2013.

[124] A. Järvenpää, L. P. Karjalainen, and K. Mäntyjärvi, “Passive laser assisted bending of ultra-high strength steels,” in *Advanced Materials Research*, 2012, vol. 418, pp. 1542–1547.

[125] D. Gu *et al.*, “Densification behavior, microstructure evolution, and wear performance of selective laser melting processed commercially pure titanium,” *Acta Mater.*, vol. 60, no. 9, pp. 3849–3860, 2012.

[126] J. Čapek *et al.*, “Highly porous, low elastic modulus 316L stainless steel scaffold prepared by selective laser melting,” *Mater. Sci. Eng. C*, vol. 69, pp. 631–639, 2016.

[127] D. W. Hutmacher, “Scaffolds in tissue engineering bone and cartilage,” *Biomaterials*, vol. 21, no. 24, pp. 2529–2543, 2000.

[128] J.-H. Shim *et al.*, “Comparative efficacies of a 3D-printed PCL/PLGA/$β$-TCP membrane and a titanium membrane for guided bone regeneration in beagle dogs,” *Polymers (Basel).*, vol. 7, no. 10, pp. 2061–2077, 2015.

[129] A. Youssef, S. J. Hollister, and P. D. Dalton, “Additive manufacturing of polymer melts for implantable medical devices and scaffolds,” *Biofabrication*, vol. 9, no. 1, p. 12002, 2017.

[130] J. Barrios-Muriel, F. Romero-Sánchez, F. J. Alonso-Sánchez, and D. Rodriguez Salgado, “Advances in orthotic and prosthetic manufacturing: A technology review,” *Materials (Basel).*, vol. 13, no. 2, p. 295, 2020.

[131] N. Herbert, D. Simpson, W. D. Spence, and W. Ion, “A preliminary investigation into the development of 3-D printing of prosthetic sockets.,” *J. Rehabil. Res. \& Dev.*, vol. 42, no. 2, 2005.

[132] L. Ejnisman, B. Gobbato, A. F. de França Camargo, and E. Zancul, “Three-Dimensional Printing in Orthopedics: from the Basics to Surgical Applications,” *Curr. Rev. Musculoskelet. Med.*, pp. 1–8, 2021.

[133] Z. Ma *et al.*, “Design and 3D printing of adjustable modulus porous structures for customized diabetic foot insoles,” *Int. J. Light. Mater. Manuf.*, vol. 2, no. 1, pp. 57–63, 2019.

[134] R. Xu, Z. Wang, T. Ma, Z. Ren, and H. Jin, “Effect of 3D printing individualized ankle-foot orthosis on plantar biomechanics and pain in patients with plantar fasciitis: A randomized controlled trial,” *Med. Sci. Monit. Int. Med. J. Exp. Clin. Res.*, vol. 25, p. 1392, 2019.

[135] G. Oberoi, S. Nitsch, M. Edelmayer, K. Janjić, A. S. Müller, and H. Agis, “3D Printing—encompassing the facets of dentistry,” *Front. Bioeng. Biotechnol.*, vol. 6, p. 172, 2018.

[136] C. Zaharia *et al.*, “Digital dentistry-3D printing applications,” *J. Interdiscip. Med.*, vol. 2, no. 1, pp. 50–53, 2017.

[137] T. Dikova, D. A. Dzhendov, D. Ivanov, and K. Bliznakova, “Dimensional accuracy and surface roughness of polymeric dental bridges produced by different 3D printing processes,” *Arch Mater Sci Eng*, vol. 94, no. 2, 2018.

[138] J. Liu, H. H. Hwang, P. Wang, G. Whang, and S. Chen, “Direct 3D-printing of cell-laden constructs in microfluidic architectures,” *Lab Chip*, vol. 16, no. 8, pp. 1430–1438, 2016.

[139] J. D. Prince, “3D printing: an industrial revolution,” *J. Electron. Resour. Med. Libr.*, vol. 11, no. 1, pp. 39–45, 2014.

[140] J.-P. Carrel, A. Wiskott, M. Moussa, P. Rieder, S. Scherrer, and S. Durual, “A 3D printed TCP/HA structure as a new osteoconductive scaffold for vertical bone augmentation,” *Clin. Oral Implants Res.*, vol. 27, no. 1, pp. 55–62, 2016.

[141] S.-L. Chang, C.-H. Lo, C.-P. Jiang, and D.-J. Juan, “The fit consideration of the denture manufactured by 3D printing and sintering,” *Int. J. Pharma Med. Biol. Sci.*, vol. 4, no. 3, pp. 184–187, 2015.

[142] K. A. O. Arafa, “Comparing the effects of titanium alloy and chrome cobalt in removable partial denture connectors on tooth mobility, bone loss and tissue reaction,” *Saudi J. Dent. Res.*, vol. 7, no. 2, pp. 112–117, 2016.

[143] M. Molitch-Hou, “Dentures get 3D printed boost with DENTCA’s FDA approval.” 2015.

[144] U. Scheithauer, E. Schwarzer, H.-J. Richter, and T. Moritz, “Thermoplastic 3D printing—an additive manufacturing method for producing dense ceramics,” *Int. J. Appl. Ceram. Technol.*, vol. 12, no. 1, pp. 26–31, 2015.

[145] P. S. P. Poh *et al.*, “Polylactides in additive biomanufacturing,” *Adv. Drug Deliv. Rev.*, vol. 107, pp. 228–246, 2016.

[146] S. Muta *et al.*, “Chairside fabrication of provisional crowns on FDM 3D-printed PVA model,” *J. Prosthodont. Res.*, vol. 64, no. 4, pp. 401–407, 2020.

[147] A. Arnesano, S. K. Padmanabhan, A. Notarangelo, F. Montagna, and A. Licciulli, “Fused deposition modeling shaping of glass infiltrated alumina for dental restoration,” *Ceram. Int.*, vol. 46, no. 2, pp. 2206–2212, 2020.

[148] M. Revilla-León, N. A.-H. Husain, M. M. Methani, and M. Özcan, “Chemical composition, surface roughness, and ceramic bond strength of additively manufactured cobalt-chromium dental alloys,” *J. Prosthet. Dent.*, vol. 125, no. 5, pp. 825–831, 2021.

[149] E.-R. Baciu *et al.*, “Surface Analysis of 3D (SLM) Co--Cr--W Dental Metallic Materials,” *Appl. Sci.*, vol. 11, no. 1, p. 255, 2021.

[150] E.-J. Bae, I.-D. Jeong, W.-C. Kim, and J.-H. Kim, “A comparative study of additive and subtractive manufacturing for dental restorations,” *J. Prosthet. Dent.*, vol. 118, no. 2, pp. 187–193, 2017.

[151] M. Kalender, S. E. K\il\iç, S. Ersoy, Y. Bozkurt, and S. Salman, “Additive manufacturing and 3D printer technology in aerospace industry,” in *2019 9th International Conference on Recent Advances in Space Technologies (RAST)*, 2019, pp. 689–694.

[152] B. Lyons, “Additive manufacturing in aerospace: Examples and research outlook,” *Bridg.*, vol. 44, no. 3, 2014.

[153] A. Uriondo, M. Esperon-Miguez, and S. Perinpanayagam, “The present and future of additive manufacturing in the aerospace sector: A review of important aspects,” *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.*, vol. 229, no. 11, pp. 2132–2147, 2015.

[154] S. Palanivel, H. Sidhar, and R. S. Mishra, “Friction stir additive manufacturing: route to high structural performance,” *Jom*, vol. 67, no. 3, pp. 616–621, 2015.

[155] S. Palanivel, P. Nelaturu, B. Glass, and R. S. Mishra, “Friction stir additive manufacturing for high structural performance through microstructural control in an Mg based WE43 alloy,” *Mater. \& Des.*, vol. 65, pp. 934–952, 2015.

[156] J. C. Najmon, S. Raeisi, and A. Tovar, “Review of additive manufacturing technologies and applications in the aerospace industry,” *Addit. Manuf. Aerosp. Ind.*, pp. 7–31, 2019.

[157] F. C. Campbell Jr, *Manufacturing technology for aerospace structural materials*. Elsevier, 2011.

[158] T. J. Nijdam and R. van Gestel, “Service experience with single crystal superalloys for high pressure turbine shrouds,” 2011.

[159] L. Facchini, E. Magalini, P. Robotti, and A. Molinari, “Microstructure and mechanical properties of Ti-6Al-4V produced by electron beam melting of pre-alloyed powders,” *Rapid Prototyp. J.*, 2009.

[160] R. Liu, Z. Wang, T. Sparks, F. Liou, and J. Newkirk, “13 - Aerospace applications of laser additive manufacturing,” in *Laser Additive Manufacturing*, M. Brandt, Ed. Woodhead Publishing, 2017, pp. 351–371.

[161] H. Lee, C. H. J. Lim, M. J. Low, N. Tham, V. M. Murukeshan, and Y.-J. Kim, “Lasers in additive manufacturing: A review,” *Int. J. Precis. Eng. Manuf. Technol.*, vol. 4, no. 3, pp. 307–322, 2017.

[162] L. Mearian, “Boeing Turns to 3D-Printed Parts to Save Millions on its 787 Dreamliner. April 11, 2017.” .

[163] C. Weller, R. Kleer, and F. T. Piller, “Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited,” *Int. J. Prod. Econ.*, vol. 164, pp. 43–56, 2015.

[164] \.I\cs\il YAZAR, H. C. GÖKÇE, and M. Ö. ÖTEYAKA, “HAVACILIK ALANINDA ER{\.I}Y{\.I}K YI{\u{G}}MA MODELLEME UYGULAMASI: BOEING 737-800 MODEL UÇA{\u{G}}IN 3 BOYUTLU ÖLÇEKL{\.I} MODELLENMES{\.I},” *Int. J. 3D Print. Technol. Digit. Ind.*, vol. 2, no. 3, pp. 37–44.

[165] M. Caujolle, “First Titanium 3D-Printed Part Installed Into Serial Production Aircraft,” *Newsroom 2017*, 2017.

[166] A. Vafadar, F. Guzzomi, A. Rassau, and K. Hayward, “Advances in metal additive manufacturing: a review of common processes, industrial applications, and current challenges,” *Appl. Sci.*, vol. 11, no. 3, p. 1213, 2021.

[167] J. Nehro, “TECHNICAL SPOTLIGHT USING 3D PRINTING TO BUILD FLIGHT-CERTIFIED HARDWARE,” *Adv. Mater. \& Process.*, vol. 173, no. 5, pp. 16–19, 2015.

[168] G. Warwick, “Just getting started,” *Aviat. Week \& Sp. Technol.*, vol. 175, no. 39, p. 22, 2013.

[169] E. Goldstein, “Just hit print.” AMER INST AERONAUTICS ASTRONAUTICS 1801 ALEXANDER BELL DRIVE, STE 500~…, 2014.

[170] L. Nickels, “Crowdfunding metallurgy,” *Met. Powder Rep.*, vol. 71, no. 5, pp. 324–327, 2016.

[171] A. Witze, “NASA to send 3D printer into space,” *Nat. News*, vol. 513, no. 7517, p. 156, 2014.

[172] J. F. Morring, “Space-component manufacturers turn to 3-D printing,” *Aviat. Week \& Sp. Technol.*, vol. 177, no. 16, p. 1, 2015.

[173] Y. Tadjdeh, “3D printing promises to revolutionize defense, aerospace industries,” *Natl. Def.*, vol. 98, no. 724, pp. 20–23, 2014.

[174] F. Richards, “Aerospace today: composites, 3d printing, \& a shot of espresso,” *Adv. Mater. \& Process.*, vol. 173, no. 5, pp. 4–5, 2015.

[175] H. Smith, “3D Printing News and Trends: GE Aviation to Grow Better Fuel Nozzles Using 3D Printing.” 2017.

[176] T. Wohlers, “Additive manufacturing and 3D printing state of the industry,” *Wohlers Assoc. Fort Collins, CO*, vol. 6, pp. 269–375, 2013.

[177] S. H. Khajavi, J. Partanen, and J. Holmström, “Additive manufacturing in the spare parts supply chain,” *Comput. Ind.*, vol. 65, no. 1, pp. 50–63, 2014.

[178] D. Periard, N. Schaal, M. Schaal, E. Malone, and H. Lipson, “Printing food,” 2007.

[179] J. Sun, Z. Peng, W. Zhou, J. Y. H. Fuh, G. S. Hong, and A. Chiu, “A review on 3D printing for customized food fabrication,” *Procedia Manuf.*, vol. 1, pp. 308–319, 2015.

[180] C. Severini, A. Derossi, and D. Azzollini, “Variables affecting the printability of foods: Preliminary tests on cereal-based products,” *Innov. food Sci. \& Emerg. Technol.*, vol. 38, pp. 281–291, 2016.

[181] L. Hao, S. Mellor, O. Seaman, J. Henderson, N. Sewell, and M. Sloan, “Material characterisation and process development for chocolate additive layer manufacturing,” *Virtual Phys. Prototyp.*, vol. 5, no. 2, pp. 57–64, 2010.

[182] F. C. Godoi, S. Prakash, and B. R. Bhandari, “3d printing technologies applied for food design: Status and prospects,” *J. Food Eng.*, vol. 179, pp. 44–54, 2016.

[183] J. I. Lipton, M. Cutler, F. Nigl, D. Cohen, and H. Lipson, “Additive manufacturing for the food industry,” *Trends food Sci. \& Technol.*, vol. 43, no. 1, pp. 114–123, 2015.

[184] C. Causer, “They’ve got a golden ticket,” *IEEE Potentials*, vol. 28, no. 4, pp. 42–44, 2009.

[185] D. der Linden, “3D Food printing Creating shapes and textures,” *Netherlands TNO Innov. Life*, 2015.

[186] B. C. Gross, J. L. Erkal, S. Y. Lockwood, C. Chen, and D. M. Spence, “Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences.” ACS Publications, 2014.

[187] M. Molitch-Hou, “The 3D fruit printer and the raspberry that tasted like a strawberry,” *Retrieved Sept.*, 2016.

[188] J. V. Diaz, K. J. C. Van Bommel, M. W.-J. Noort, J. Henket, and P. Briër, “Method for the production of edible objects using sls and food products.” Google Patents, 2018.

[189] T. F. Wegrzyn, M. Golding, and R. H. Archer, “Food Layered Manufacture: A new process for constructing solid foods,” *Trends Food Sci. \& Technol.*, vol. 27, no. 2, pp. 66–72, 2012.

[190] F. Marga *et al.*, “Toward engineering functional organ modules by additive manufacturing,” *Biofabrication*, vol. 4, no. 2, p. 22001, 2012.

[191] J. Liu, É. Hocquette, M.-P. Ellies-Oury, S. Chriki, and J.-F. Hocquette, “Chinese Consumers’ Attitudes and Potential Acceptance toward Artificial Meat,” *Foods*, vol. 10, no. 2, p. 353, 2021.

[192] Y. Chen, M. Zhang, and B. Bhandari, “3D Printing of Steak-like Foods Based on Textured Soybean Protein,” *Foods*, vol. 10, no. 9, p. 2011, 2021.

[193] E. Álvarez-Castillo, S. Oliveira, C. Bengoechea, I. Sousa, A. Raymundo, and A. Guerrero, “A rheological approach to 3D printing of plasma protein based doughs,” *J. Food Eng.*, vol. 288, p. 110255, 2021.

[194] M. Lille, A. Nurmela, E. Nordlund, S. Metsä-Kortelainen, and N. Sozer, “Applicability of protein and fiber-rich food materials in extrusion-based 3D printing,” *J. Food Eng.*, vol. 220, pp. 20–27, 2018.

[195] J. M. H. Rahman, M. D. N. I. Shiblee, K. Ahmed, A. Khosla, M. Kawakami, and H. Furukawa, “Rheological and mechanical properties of edible gel materials for 3D food printing technology,” *Heliyon*, vol. 6, no. 12, p. e05859, 2020.

[196] Y. Chen, M. Zhang, and P. Phuhongsung, “3D printing of protein-based composite fruit and vegetable gel system,” *LWT*, vol. 141, p. 110978, 2021.

[197] A. Standard, “F2792-12a" Terminology for Additive Manufacturing Technologies". ASTM International. West Conshohocken, PA, DOI: 10.1520/F2792-12A.” 2012.

[198] M. Fitzgerald, “With 3-D printing, the shoe really fits,” *MIT Sloan Manag. Rev.*, vol. 15, 2013.

[199] M. Meier, K. H. Tan, M. K. Lim, and L. Chung, “Unlocking innovation in the sport industry through additive manufacturing,” *Bus. Process Manag. J.*, 2018.

[200] A. Vanderploeg, S.-E. Lee, and M. Mamp, “The application of 3D printing technology in the fashion industry,” *Int. J. Fash. Des. Technol. Educ.*, vol. 10, no. 2, pp. 170–179, 2017.

[201] R. Nayak and R. Padhye, “Introduction: the apparel industry,” in *Garment manufacturing technology*, Elsevier, 2015, pp. 1–17.

[202] J. A. Rosenau and D. L. Wilson, *Apparel merchandising: The line starts here*. A\&C Black, 2014.

[203] T. Cui, V. Chattaraman, and L. Sun, “Examining consumers’ perceptions of a 3D printing integrated apparel: a functional, expressive and aesthetic (FEA) perspective,” *J. Fash. Mark. Manag. An Int. J.*, 2021.

[204] A. Peterson, “Utilization of Recycled Filament for 3D Printing for Consumer Goods,” 2020.

[205] A. Janssens and M. Lavanga, “An expensive, confusing, and ineffective suit of armor: Investigating risks of design piracy and perceptions of the design rights available to emerging fashion designers in the digital age,” *Fash. Theory*, vol. 24, no. 2, pp. 229–260, 2020.

[206] Y. Li, Y. Cheng, Q. Hu, S. Zhou, L. Ma, and M. K. Lim, “The influence of additive manufacturing on the configuration of make-to-order spare parts supply chain under heterogeneous demand,” *Int. J. Prod. Res.*, vol. 57, no. 11, pp. 3622–3641, 2019.

[207] S. Chakraborty and M. C. Biswas, “3D printing technology of polymer-fiber composites in textile and fashion industry: A potential roadmap of concept to consumer,” *Compos. Struct.*, vol. 248, p. 112562, 2020.

[208] L. Sun and L. Zhao, “Envisioning the era of 3D printing: a conceptual model for the fashion industry,” *Fash. Text.*, vol. 4, no. 1, pp. 1–16, 2017.

[209] A. O. Laplume, B. Petersen, and J. M. Pearce, “Global value chains from a 3D printing perspective,” *J. Int. Bus. Stud.*, vol. 47, no. 5, pp. 595–609, 2016.

[210] K. V Thepale and V. S. Gawli, “3D printing technology and its influences on the fashion industry,” *Int. Res. J. Eng. Technol.*, vol. 6, no. 4, pp. 4405–4407, 2019.

[211] D. B. Sitotaw, D. Ahrendt, Y. Kyosev, and A. K. Kabish, “Additive Manufacturing and Textiles—State-of-the-Art,” *Appl. Sci.*, vol. 10, no. 15, p. 5033, 2020.

[212] L. Sun and J. L. Parsons, “3D printing for apparel design: Exploring apparel design process using 3D modeling software,” in *International Textile and Apparel Association Annual Conference Proceedings*, 2014, vol. 71, no. 1.

[213] M. Rüßmann *et al.*, “Industry 4.0: The future of productivity and growth in manufacturing industries,” *Bost. Consult. Gr.*, vol. 9, no. 1, pp. 54–89, 2015.

[214] R. Neugebauer, S. Hippmann, M. Leis, and M. Landherr, “Industrie 4.0-From the perspective of applied research.” Elsevier, 2016.

[215] A. K. Inkulu, M. V. A. R. Bahubalendruni, A. Dara, and K. SankaranarayanaSamy, “Challenges and opportunities in human robot collaboration context of Industry 4.0-a state of the art review,” *Ind. Robot Int. J. Robot. Res. Appl.*, 2021.

[216] A. Malik, M. I. U. Haq, A. Raina, and K. Gupta, “3D printing towards implementing Industry 4.0: sustainability aspects, barriers and challenges,” *Ind. Robot Int. J. Robot. Res. Appl.*, 2022.

[217] S. Besklubova, M. J. Skibniewski, and X. Zhang, “Factors Affecting 3D Printing Technology Adaptation in Construction,” *J. Constr. Eng. Manag.*, vol. 147, no. 5, p. 4021026, 2021.

[218] L. G. Marques, R. A. Williams, and W. Zhou, “A mobile 3D printer for cooperative 3D printing,” in *Proceeding of the 28th international solid freeform fabrication symposium*, 2017, pp. 1645–1660.

[219] Y. L. Yap, S. L. Sing, and W. Y. Yeong, “A review of 3D printing processes and materials for soft robotics,” *Rapid Prototyp. J.*, 2020.

[220] R. Moreta-Martinez, D. Garc\’\ia-Mato, M. Garc\’\ia-Sevilla, R. Pérez-Mañanes, J. A. Calvo-Haro, and J. Pascau, “Combining augmented reality and 3D printing to display patient models on a smartphone,” *JoVE (Journal Vis. Exp.*, no. 155, p. e60618, 2020.

[221] L. Guo and Q. Jingxiong, “Combination of cloud manufacturing and 3D printing: research progress and prospect,” *Int. J. Adv. Manuf. Technol.*, vol. 96, no. 5–8, pp. 1929–1942, 2018.

[222] L. Tan and N. Wang, “Future internet: The internet of things,” in *2010 3rd international conference on advanced computer theory and engineering (ICACTE)*, 2010, vol. 5, pp. V5--376.

[223] S. Fatima, A. Haleem, S. Bahl, M. Javaid, S. K. Mahla, and S. Singh, “Exploring the significant applications of Internet of Things (IoT) with 3D printing using advanced materials in medical field,” *Mater. Today Proc.*, 2021.

[224] T. Chen and Y.-C. Wang, “An advanced IoT system for assisting ubiquitous manufacturing with 3D printing,” *Int. J. Adv. Manuf. Technol.*, vol. 103, no. 5, pp. 1721–1733, 2019.

[225] H. A. Nasser *et al.*, “Pros and cons of using green biotechnology to solve food insecurity and achieve sustainable development goals,” *Euro-Mediterranean J. Environ. Integr.*, vol. 6, no. 1, pp. 1–19, 2021.

[226] S. Rouf, A. Raina, M. Irfan Ul Haq, N. Naveed, S. Jeganmohan, and A. Farzana Kichloo, “3D Printed Parts and Mechanical Properties: Influencing Parameters, Sustainability Aspects, Global Market Scenario, Challenges and Applications,” *Adv. Ind. Eng. Polym. Res.*, 2022, doi: https://doi.org/10.1016/j.aiepr.2022.02.001.

[227] A. Beltagui, N. Kunz, and S. Gold, “The role of 3D printing and open design on adoption of socially sustainable supply chain innovation,” *Int. J. Prod. Econ.*, vol. 221, p. 107462, 2020.

[228] K. Vones, D. Allan, I. Lambert, and S. Vettese, “3D-printing ‘Ocean plastic’--Fostering childrens’ engagement with sustainability,” *Mater. Today Commun.*, vol. 16, pp. 56–59, 2018.

[229] M. Despeisse *et al.*, “Unlocking value for a circular economy through 3D printing: A research agenda,” *Technol. Forecast. Soc. Change*, vol. 115, pp. 75–84, 2017.

[230] Y. Han, Z. Yang, T. Ding, and J. Xiao, “Environmental and economic assessment on 3D printed buildings with recycled concrete,” *J. Clean. Prod.*, vol. 278, p. 123884, 2021.

[231] C. G. Machado, M. Despeisse, M. Winroth, and E. H. D. R. da Silva, “Additive manufacturing from the sustainability perspective: Proposal for a self-assessment tool,” *Procedia CIRP*, vol. 81, pp. 482–487, 2019.

[232] J. Nyika, F. M. Mwema, R. M. Mahamood, E. T. Akinlabi, and T. C. Jen, “Advances in 3D printing materials processing-environmental impacts and alleviation measures,” *Adv. Mater. Process. Technol.*, pp. 1–11, 2021.

[233] A. Majeed *et al.*, “A big data-driven framework for sustainable and smart additive manufacturing,” *Robot. Comput. Integr. Manuf.*, vol. 67, p. 102026, 2021.

[234] T. Peng, K. Kellens, R. Tang, C. Chen, and G. Chen, “Sustainability of additive manufacturing: An overview on its energy demand and environmental impact,” *Addit. Manuf.*, vol. 21, pp. 694–704, 2018.

[235] S. Zou, J. Xiao, T. Ding, Z. Duan, and Q. Zhang, “Printability and advantages of 3D printing mortar with 100% recycled sand,” *Constr. Build. Mater.*, vol. 273, p. 121699, 2021, doi: https://doi.org/10.1016/j.conbuildmat.2020.121699.

[236] K. Mikula *et al.*, “3D printing filament as a second life of waste plastics—A review,” *Environ. Sci. Pollut. Res.*, vol. 28, no. 10, pp. 12321–12333, 2021.

[237] L. Cordova, M. Campos, and T. Tinga, “Revealing the effects of powder reuse for selective laser melting by powder characterization,” *Jom*, vol. 71, no. 3, pp. 1062–1072, 2019.