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TECHNOLOGY OF ADDITIVE MANUFACTURING: A COMPREHENSIVE REVIEW

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ABSTRACT

The process of additive manufacturing (AM), commonly known as 3D printing, is a method of constructing a component by progressively adding material in layers using digital 3D design information. As part of 'Industry 4.0,' many industrial technologies are rapidly increasing to thrive in the twenty-first century. This study goes over seven different types of additive manufacturing in great detail. These technologies make it possible to make complex, high-value parts quickly and in small quantities without using as much energy or material or making as many tools as subtractive manufacturing does. Besides, AM also possesses some particular challenges, like post-processing, material unavailability, software issues, etc. The application of AM is expanding rapidly from micro to macro-scale sectors. 3D printing technology will change industrial operations in the following years. Eventually, the elected technology will be closely related to the proposed function.

KEYWORDS

Additive Manufacturing, Photopolymerization, 3D printing, Applications, Challenges.

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1. INTRODUCTION

In the late 1980s, additive manufacturing (AM) technology emerged in the United States. This innovative process, which involves material layering, is considered a significant advancement in manufacturing over the past three decades. The introduction of 3D Systems Corporation's SLA-1 in the mid-1980s marked the beginning of various emerging techniques to create product prototypes directly from computer-aided design (CAD) data. These techniques were initially called rapid prototyping (Chen et al., 2017; Cheah et al., 2005). Producing entity components with additive manufacturing involves the gradual accretion of material. It is a collective word for all manufacturing techniques that may build three-dimensional physical entity models directly and mathematically coherently. Additive manufacturing fuses aspects of mechanical engineering, CAD, layered fabrication, numeric control, materials science, and laser technology. It may convert design concepts into specific functioning prototypes or even the direct production of parts. The two phases of AM technology are virtual and physical. Preparing 3D CAD models using CAD software programs like Pro-E, Catia, etc. comes first before manufacturing physical models. Manufacturing the physical model is the second stage of an appropriate AM process, employing CAD data to create physical models (Rosa et al., 2004). This innovation can be utilized to form distinctive models, which can be used for visual assessment, thought assessment and introduction, and practical testing at different stages of the item improvement preparation. In the case of visible review, models can be utilized to assess an item plan before it is made outwardly. It may assist in spotting potential faults within the procedure that may lead to difficulties during manufacturing or utilization. Besides this, innovation models can be applied to examine and display new product ideas to partners. It will help stimulate criticism of the plan and ensure that it satisfies the specifications of the target showcase. In the case of helpful testing, models can be utilized to test an item plan to guarantee that it operates as anticipated. It could help distinguish any probable faults with the program since it was made. In addition to these three applications, innovation can be utilized for other errands within item improvement preparation. It can create unused item concepts by mimicking distinctive plan-conceivable outcomes.

This innovation can be utilized to analyze the execution of an item plan under diverse conditions and to arrange the fabrication preparation for an unused item (Negi et al., 2013). The long-term effects of additive manufacturing are yet to be determined. It is a technology still in its infancy and makes up a relatively small portion of production. The future is far from assured, although that little portion is expanding swiftly. Almost 25 years have passed since the first rapid prototyping stereolithography equipment hit the market. In that brief period, additive manufacturing has not only spread widely throughout science, academia, and industry, but it has also changed from a technique for producing visual models quickly to a brand-new manufacturing approach. Revenues from goods and services indicate that additive manufacturing has developed into a multibillion-dollar sector during the past 20 years.

Additive manufacturing could drastically alter the production and distribution of numerous goods. Essential advancements in manufacturing technology have significantly influenced our society and culture. Examining the uses and technologies discussed here leads one to believe that additive manufacturing has the potential to be a disruptive technology. We must look at the historical background of traditional production to fully comprehend how revolutionary additive manufacturing can be characterized as a technological procedure (Horn et al., 2012). The chronological order of the 3D printing process is illustrated in Fig. 1.

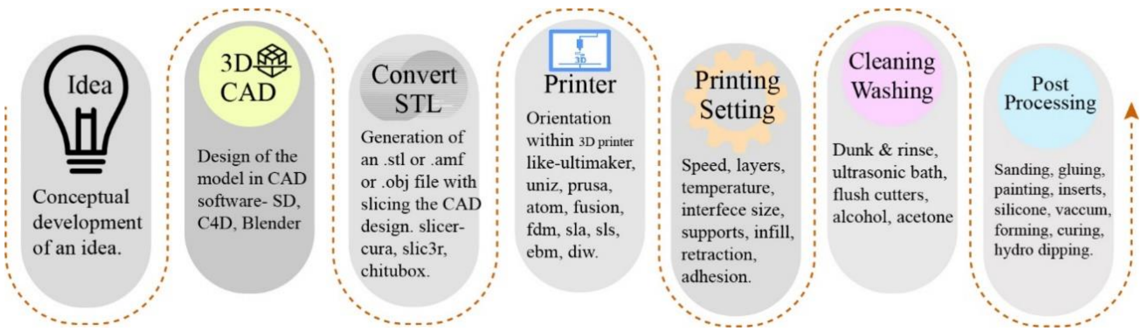

Fig. 1. Stages of additive manufacturing process.

2. ADDITIVE MANUFACTURING PROCESSES AND TECHNOLOGIES

Unlike subtractive methods, additive manufacturing, or 3D printing, involves creating objects by layering materials based on digital models. This technology has been developed for over two decades and is seen as a revolutionary and creative tool. Additive manufacturing, also known as 3D printing, is a swiftly advancing technology with substantial potential in design. It has ushered in a new era of creativity and innovation by enabling the fabrication of intricate shapes and structures that were previously impractical using conventional techniques (Guo et al., 2013). This technology is being hailed as a burgeoning industrial revolution capable of disrupting established manufacturing methods.

Additionally, additive manufacturing is environmentally more sustainable, minimizing waste and emissions (Huang et al., 2013; Zhai et al., 2014; Schelly et al., 2015;). Its adaptability permits the on-demand creation of personalized items, potentially transforming manufacturing processes. Beyond technical merits, additive manufacturing nurtures creativity, influence, and exploratory pursuits. It empowers designers to experiment with novel concepts and cater to individual user requirements, propelling the development of inventive products and services that enhance our daily lives. Unlike traditional methods, additive manufacturing builds parts layer by layer directly from CAD designs, allowing for intricate and complex shapes. It reduces the gap between the design and the final product and can work with various materials (Herderick et al., 2015; Yang et al., 2015;). Additive manufacturing enables the processing of a diverse range of materials, encompassing metals (Frazier et al., 2014), blends (Guessasma et al., 2015; Tang et al., 2015), pottery (Gaytan et al., 2015), macromolecules (Guessasma et al., 2015), amalgamated (Quan et al., 2015), structures with hollow spaces (Lee et al., 2012), and materials composed of multiple phases (Takezawa et al., 2015). ASTM International classifies additive manufacturing into seven categories based on techniques like photopolymerization, powder fusion, and more. These categories are material extrusion, VAT photopolymerization, material jetting, powder bed fusion, binder jetting, direct energy deposition, and sheet lamination. Fig. 2 categorizes different additive manufacturing processes based on the raw material.

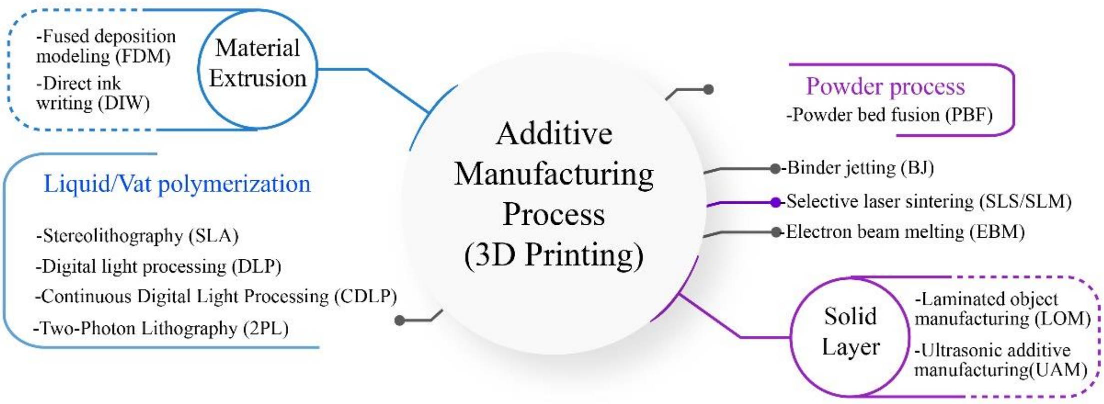

Fig. 2. Different type of additive manufacturing processes.

2.1. Material extrusion process

Material extrusion is an additive manufacturing process that involves gradually depositing material in layers using a nozzle or aperture. The material can be a liquid, semi-liquid, polymer, paste, solution, or dispersion. The build platform or the nozzle moves upward or downward after each layer is deposited. Material extrusion includes techniques such as 3D dispensing, 3D micro extrusion, 3D microfiber extrusion, 3D fiber deposition, fluid dosing and deposition, and 3D plotting. Fused deposition modeling (FDM), commonly called fused filament fabrication (FFF), is a frequently employed material extrusion technique. In short, material extrusion is an additive manufacturing procedure that constructs three-dimensional objects by gradually depositing material, one layer at a time. FDM is a common material extrusion technique. (Hossain et al., 2023; Ligon et al., 2017)

Step 1: The initial stage entails generating a computer-generated 3D model in a virtual environment and transforming it into an AM file format. Supported options for 3D printers encompass the 3D manufacturing format (3MF), additive manufacturing file format (AMF), and standard tessellation language (3MF). The STL format is the most prevalent among these choices. (Kumar et al., 1997)

Step 2: This procedure establishes parameters like printing orientation, layer height, and print temperature before initiating printing. During this step, process planning links additive manufacturing machines and virtual models by converting the models into instructions that guide and control the hardware. The process planning for various additive manufacturing methods comprises four main phases: determining printing orientation, generating support structures, slicing, and generating printing paths. Each step significantly affects material usage, printing duration, and final quality. The printing orientation determines the location and manner in which the component will be sliced and constructed. Apart from influencing the number of layers and printing time, a suitable printing orientation also impacts the necessity of support material. By selecting an appropriate printing orientation, overhangs can be identified, enabling the proper placement of supports to ensure successful fabrication. The process of slicing entails separating 3D models into distinct layers. Ultimately, the G-code-based print path is derived from the information obtained during the slicing method for the 3D printing process.

Step 3: The AM machine constructs the object by adding layers one at a time and may undergo post-processing. Extensive research has explored sustainable additive manufacturing (AM) methods to reduce energy, material, and production time across these three procedures. Multiple articles have addressed the environmental consequences of AM, focusing on energy consumption, worker health, waste, lifecycle effects, and broader policy concerns instead of just the technology. Enhancements in the AM process stages substantially reduce material, time, and energy consumption. Many studies have been published in this realm. Furthermore, upcoming research avenues for achieving sustainable AM are also outlined. (Griffiths, 2016; Rejeski et al., 2018).

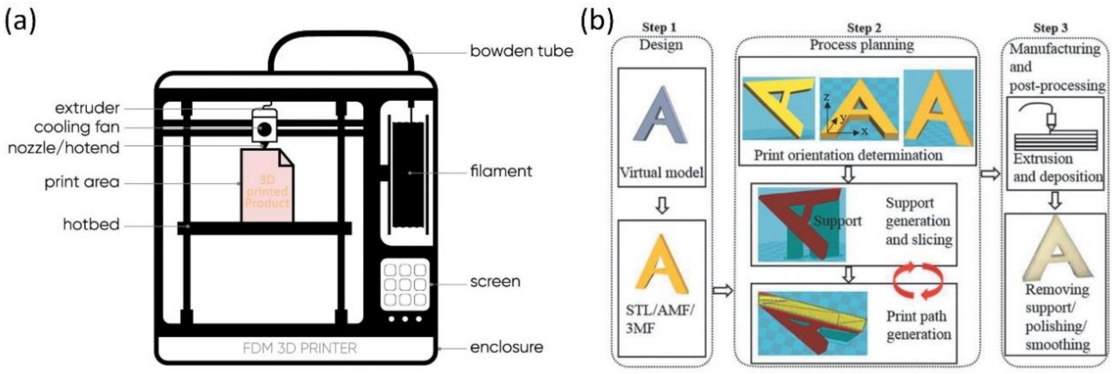

Fig. 3.(a) Graphical model of FDM 3D Printer, (Hossain et al., 2023) **and (b) A visual representation illustrating three fundamental steps in the AM process of material extrusion** (Jiang et al., 2020).

2.2. Vat Photo-polymerization process

A photopolymer, a resin that may be light-cured, is kept in a vat and exposed to either visible light or ultraviolet light treatment. The curing light starts the polymerization reaction, which manifests as chains of polymers or cross-links to form solid resin. The photopolymer mixture consists of monomers, oligomers, and photoinitiators. Photoinitiators are substances that react with light to generate free radicals.These radicals start a process that turns monomers and oligomers into a polymer. This creates a structure that can not be changed back to a monomer or oligomer.. This unique property enables the layer-by-layer creation of 3D objects from sliced STL files.

There are four essential photopolymerization 3D printing methods, each using distinct curing approaches:

- Stereolithography (SLA): It utilizes a laser for incremental resin curing.
- Digital Light Processing (DLP): It simultaneously relies on a projector to cure entire resin layers.
- Light-emitting diodes (LEDs) can also cure resin, albeit slower than SLA and DLP.
- Continuous digital light processing (CDLP): It employs a moving oxygen laser for layer-wise resin curing.

The choice of technique hinges on factors such as the desired resolution, speed, and cost of the 3D printing process. (Crivello et al., 2013; Pagac et al., 2021; Tumbleston et al., 2015; Huang et al., 2020).

2.2.1. Stereolithography (SLA)

A transparent tank containing light-curable resin (hereafter referred to as resin) is filled with resin in a 3D printer using SLA technology. The laser beam cures the areas with the cut STL template while the platform is submerged in the resin, and the laser beam tracks the building area. Depending on whether the machine uses a top-down or bottom-up approach, the platform is either lowered or raised in the Z direction following the formation of a layer by a fixed amount corresponding to a layer's height. Up until the completion of a 3D model, the curing procedure is repeated layer by layer. A layer may be anywhere between 12 and 150 µm in height. One of SLA's most important advantages is its sizable spatial resolution. In reality, the most commonly used layer height is 100 µm. Standard SLA printers can print at a rate of 10 to 20 millimeters per hour. Fig. 4 depicts the workings of a 3D printer using SLA technology. The diameter of the laser beam at the curing point, or the spot size, affects the precision of SLA production. For instance, the spot size for a Form Labs Form 2 SLA is 140 µm (Pagac et al., 2021).

2.2.2. Digital light processing (DLP)

During a sequential layering process, light carefully connects a photosensitive resin to make a three-dimensional object that can stand independently, called DLP. Like SLA, DLP exposes every stratum of resin to light. However, unlike SLA, DLP exposes the entire layer at once. As a result, the DLP process is faster than the SLA and less vulnerable to oxygen inhibition. The resolution of DLP printers is typically in the range of 10-50 micrometers, which is determined by the number of pixels/mirrors on the DMD and the optics used to project the patterns onto the build platform. In summary, DLP is a fast and accurate 3D printing technology well-suited for creating high-quality objects with fine details (Tesavibul et al., 2012; Ligon et al., 2017).

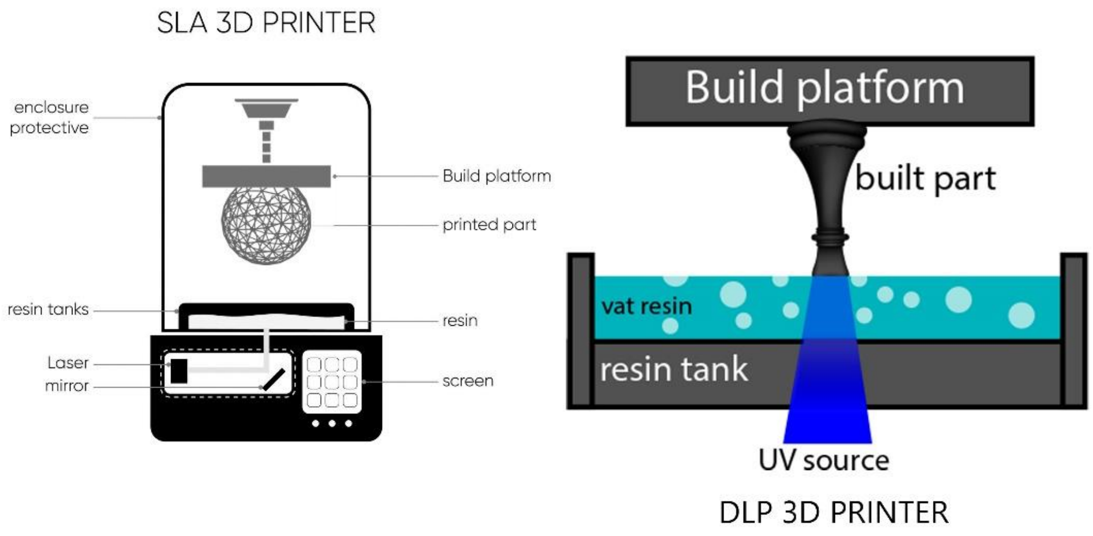

Fig. 4. The image introduces the graphical model and concept of (a) stereolithography (SLA) (Hossain et al., 2023), and (b) digital light processing (DLP). (Hossain et al., 2023)

2.2.3. Continuous digital light processing/ continuous liquid interface production (CDLP/CLIP)

CDLP/CLIP technology is a newer and improved version of DLP technology. It uses digital projection using LEDs instead of traditional glass windows, and it differs from SLA and DLP technology by using an oxygen-permeable window. CDLP/CLIP machines also have an ongoing motion of the construction platform, which allows for uninterrupted generation of prototypes through printing at velocities of a few hundred millimeters per hour. There are some critical differences between CDLP/CLIP technology and DLP technology, such as that CDLP/CLIP uses a digital display using LEDs, while DLP uses a laser; CDLP/CLIP has an oxygen-permeable window; on the other hand, DLP does not. Besides, CDLP/CLIP has a continuous movement of the build platform, while DLP does not. These differences make CDLP/CLIP technology a faster and more efficient way to 3D print prototypes. Moreover, it offers greater flexibility than DLP technology, enabling printing more materials (Pagac et al., 2021; Tumbleston et al., 2015; Huang et al., 2020).

2.2.4. Two-Photon Lithography (TPL)

Two-photon lithography (TPL) is a 3D printing technique that uses a laser beam to solidify polymer resin in a vat. This method permits the production of intricate 3D microstructures with a finer resolution than the diffraction limit, a feat not achievable with conventional 3D printing. Unlike the step-by-step layering approach of traditional methods, TPL enables polymer curing anywhere within the resin vat. As a result, it can fabricate intricate 3D shapes with complex features and overhangs that are challenging for conventional techniques. In this technology, the smallest polymer unit is an ellipsoidal 3D point, or voxel, determining the print resolution. The scope of TPL extends to generating diverse objects like microscale devices, medical implants, and prototypes. While slower than traditional methods, TPL yields extremely high-resolution structures. Despite its initial high cost, the expense decreases as the technology gains wider adoption (Zheng et al., 2019).

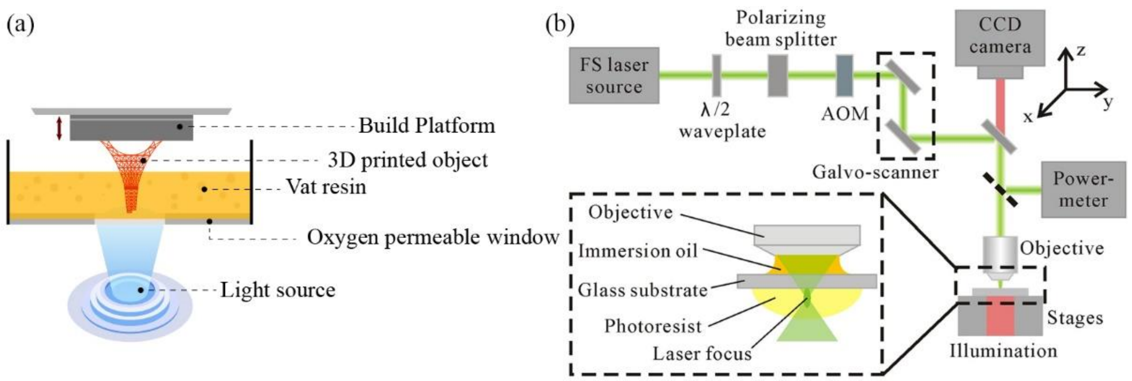

Fig. 5. Schematic diagram of (a) continuous digital light processing (CDLP) process, and (b) Two-Photon Lithography fabrication system (Zheng et al., 2019).

2.3. Direct ink writing process (DIW)

AM has received widespread attention for its ability to advance technology as a sustainable, flexible, and customizable manufacturing option. DIW has emerged as the most versatile 3D printing technology for the broadest range of materials among various additive manufacturing technologies. DIW can print almost any material as long as the precursor ink can be designed to exhibit appropriate rheological behavior. This technology is a unique approach to simultaneously introducing design freedom, versatility, and stability into its printed structures.DIW prints complex 3D structures from different materials, such as metals, polymers, ceramics, glass, cement, graphene, and combinations. DIW is an extrusion-based 3D printing method where ink is dispensed layer by layer from a small nozzle onto a surface. UV-based in-situ photocuring-assisted direct ink writing (DIW) technology keeps the benefits of photopolymerization for controlling space and time. The proper photocuring behavior can make it easier for DIW to build complex structures and let polymeric materials be printed without support. However, the curing efficiency and yield could be better when printing ceramics because ultraviolet or visible light can not get through high-solids-content ceramic slurries very well. Many ceramic particles suspended in the photosensitive slurry introduce additional light scattering and refraction. Light energy slowly decreases in the photosensitive medium after several absorption, distribution, and refraction steps. This stops the photopolymerization process. Although ultraviolet light can go through many things, near-infrared light (NIR) can go through more things because it does not absorb or scatter as much. This method uses near-infrared light to upconvert particles and help with photopolymerization. It has been used successfully for 3D printing biomedical materials, reactive/controlled photopolymerization, and deep photocuring (Zhao et al., 2023).

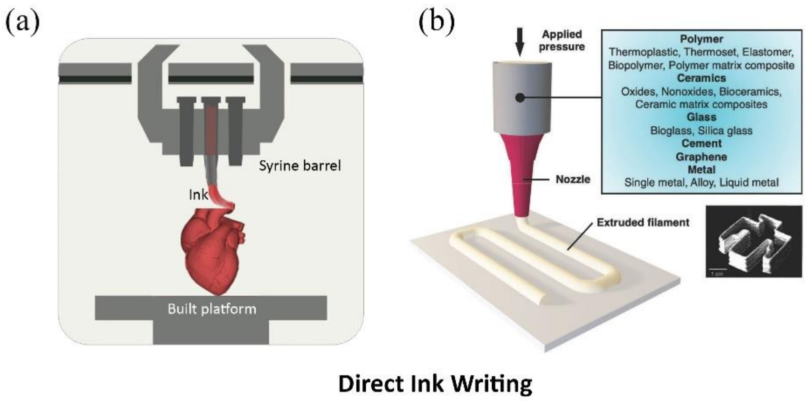

Fig. 6. (a) An illustration of the most popular 3D printing methods: Direct Ink Writing (DIW), (Hossain et al., 2023) and (b) DIW process flow diagram illustration the method has drawn much interest since it can handle the widest variety of materials for creating intricate, multifaceted 3D constructions. The inset shows one of Cesarano's initial experimental constructs created at Sandia National Laboratory. (Saadi et al., 2022)

2.4. Powder Bed process

Laser powder bed fusion (L-PBF) and electron beam melting (EBM) are two ways to add to existing parts that use powder bed fusion (PBF) to make complex metal-like parts with unique chemical makeups and mechanical properties. PBF involves layering powder and selectively melting sections with lasers or electron beams, repeated layer by layer to form the final part. L-PBF and EBM are promising for metallic components, yet they diverge significantly. L-PBF employs lasers, while EBM utilizes electron beams to melt the powder, leading to variations in the resulting part properties. L-PBF yields smoother surfaces and superior mechanical qualities compared to EBM.

Conversely, EBM operates at higher speeds. The selection between the techniques depends on the part requirements. For L-PBF for excellent parts with smooth finishes and mechanical strength, choose EBM for faster production when speed is paramount (Guo et al., 2015; Murr et al., 2012; Gu et al., 2012; Gaytan et al., 2009; Korner et al., 2016). Three significant process steps can be used to describe the PBF process: the first step is reducing of the construction surface by the standard layer thickness, which is the pre-established layer measurement. Then, a new powder layer is created by moving a recoating device over the powder bed and the object's surface, resulting in a consistent powder layer with the correct thickness. Then, turn on the power source, like a ray or electron beam, and use the laser parameters given in the PBF build file to scan the powder layer's edges and corners. A crucial step in PBF involves spreading a portion of metal powder using the recoated arm to establish a fresh powder layer. The area where solid metal particles melt and mix to make a melt pool is created when the laser beam and the new powder layer interact. The previously solidified material from earlier layers melds with the melt pool as it solidifies again. PBF-based devices utilize thermal energy to fuse specific areas within the powder bed selectively. Following the principle of adding one layer at a time, the PBF process is an innovative manufacturing technique capable of creating actual components from the required 3D solid CAD model data. Various lasers are commonly used as the primary heat source in the PBF process (Duda et al., 2018; Zhang et al., 2018; Subhedar et al., 2018; Stavropoulos and Foteinopoulos, 2018).

2.4.1. Selective laser sintering (SLS) process

Here is an example of the SLS approach in Fig. 7. A roller mechanism can disseminate powder around the constructed platform when the powder supply piston rises. Based on 3D CAD data, the powders are scanned selectively utilizing a targeted laser beam, causing the particles to fuse and create the initial sintered layer. The procedure entails sintering a first layer of powder with a laser beam, followed by selective scanning and the fusion of a second layer onto the first layer. If necessary, a portion is collected from the RP machine cleaning for further procedures. The process can continue until every physical part has been built (Dev et al., 2021; Kok et al., 2018; Bahnini et al., 2018). The CO_2 laser beam is occasionally employed. A mixed powder is used in the SLS process for metal. The mixture is formed by blending a powder that melts at a low temperature with another with a high melting point. Only powders with low melting points can partially melt during the SLS process, forming a connection with powders with higher melting points that cannot melt (Gu et al., 2012).

2.4.2. Selective Laser Melting (SLM) process

The SLM process functions similarly to the SLS procedure. Instead of sintering, alloy powder particles are melted (Azam et al., 2018). Unlike standard production techniques, the finer microstructure can be seen at high cooling rates by decreasing the manufacturing cycle duration when crafting intricate components. SLM components provide superior mechanical qualities. SLM manufactures parts for the automotive, medical, and aerospace industries. Selective laser melting can be used to produce lattice structures. It is possible to locate and assess flaws (Selo et al., 2020; Lu et al., 2020).

2.4.3. Direct metal Laser Sintering (DMLS) process

DMLS is a rapid prototyping or additive manufacturing process that uses a laser to fuse metal powder to create usable parts. The process is similar to selective laser sintering (SLS). Still, DMLS uses raw, untreated metal powders that are already alloyed, as opposed to employing coated polymers or metal powders. This makes DMLS parts denser and more vital than SLS parts. However, DMLS parts may require post-treatment to ensure gas or pressure tightness. In short, DMLS is a metal 3D printing process that uses a laser to fuse metal powder. DMLS is a versatile technique capable of producing diverse metal components (Bahnini et al., 2018; Gu et al., 2012). Fig. 7 shows a schematic diagram of the direct metal laser sintering process.

2.4.4. Selective heat Sintering (SHS) process

A head that has undergone heating causes plastic powder particles to fuse. By the sliced STL model, the hot head contacts the powder and moves. Manufacturing structural components and conceptual prototypes are done using this technique. The blue Printer is a desktop 3D printer that uses SHS technology. It has a built-in chamber measuring 200 mm x 160 mm x 140 mm, prints at a speed of 0.078-0.118 inch per hour, and uses a 0.0039-inch layer thickness (Dev et al., 2021).

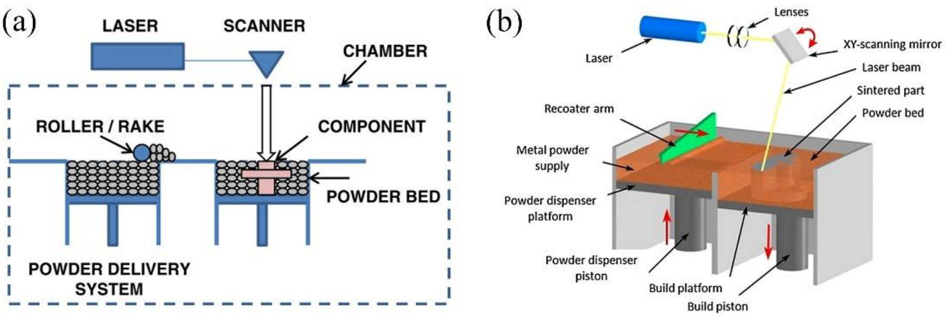

Fig. 7. (a) Illustration scheme of the Powder bed fusion (PBF), (Zadi-Maad et al., 2018) **and (b) a schematic diagram of direct metal laser sintering (DMLS) process.** (Duda et al., 2018)

2.5. Polyjet (Material Jetting) process

Material jetting is an additive manufacturing technique that uses droplets of photopolymer materials to create three-dimensional objects. The MJ process is similar to inkjet printing, but it uses ultraviolet (UV) light to cure the liquid material on the build platform. It allows for high-resolution printing with smooth surfaces. MJ printers are available from Stratasys (PolyJet) and 3D Systems (MultiJet). The two technologies are essentially the same; however, their names differ due to originating from various companies. The MJ process starts with storing a liquid photopolymer in an air-excluding tank. The photopolymer is then heated and deposited as droplets onto the build platform. The droplets are cured with UV light, which causes them to solidify (Gulcan et al., 2021; Tino et al., 2020; Pilipovic et al., 2020).

Once a material layer has been cured, the construction surface is lowered, and a fresh stratum of liquid materials is placed. This procedure is reiterated until the entire object has been created. According to the reference, the light source's wavelength in millijoules (MJ) can be limitless. It differentiates it from the light sources used in SLA (355 nm) and DLP (405 nm) techniques. However, light sources with wavelengths ranging from 190 to 400 nm are typically utilized, as references state. MJ printers can create various objects, including prototypes, models, and jewelry. They are also being used in medical applications to create patient-specific implants (Quan et al., 2020).

One of the advantages of MJ printing is that it can create parts with very smooth surfaces. The photopolymer droplets are tiny and cured with UV light, resulting in a uniform surface finish. Another advantage of MJ printing is that it is a fast process. Parts can be created in hours, making prototyping and rapid manufacturing ideal. MJ printers can also print multiple materials on the same object. It is called multi-material printing, allowing for the creation of objects with different properties. For example, a thing could be made with a strong material for the structural components and a flexible material for the moving parts. MJ is a versatile and powerful additive manufacturing technology used in various industries. It is a good choice for high-resolution printing applications, fast turnaround times, and multi-material printing (Dilag et al., 2019; Sireesha et al., 2018; Elkaseer et al., 2022).

2.6. Binder jetting process

In additive manufacturing, binder jetting is a technique where a liquid binding agent is harnessed to meld powder particles together into a cohesive whole. It can create complex parts from various materials, including metals, ceramics, and polymers (Li et al., 2020). Binder jetting is a non-fusion-based process that does not use heat to melt the powder particles. It results in parts with no residual stresses. The binder-jetting process consists of the following steps: firstly, the 3D CAD file is converted into 2D files with the appropriate layer thickness. Then, a fine powder coat is evenly distributed on the printing surface. After that, the print head selectively deposits the binder onto the powder, according to the 2D files. In the fourth step, down goes the platform, and an additional layer of powder is spread over the preceding one. Then, steps 3 and 4 are repeated until the part is complete. In the next step, the part is cured to increase its strength. Then, the part is de-powdered, which removes the excess powder. Lastly, the part is sintered, which increases its density and strength. Binder jetting is a relatively affordable AM process and can be used with various metals. It is a good choice for creating complex parts with no residual stresses. Binder jetting is a relatively slow process, but it is becoming faster with the development of new technologies. Binder jetting can be used to create parts with excellent details. It is a good choice for creating prototypes and small-batch production. The binder jetting technique allows for the creating of parts that exhibit various properties, including strength, stiffness, and conductivity (wang, 2017; Chen 2016; Frykholm, 2016; Utela, 2008; Meteyer, 2014; Gokeldoss, 2017; Do, 2017; Nandwana, 2017; Mostafaei, 2018; Mirzababaei, 2019).

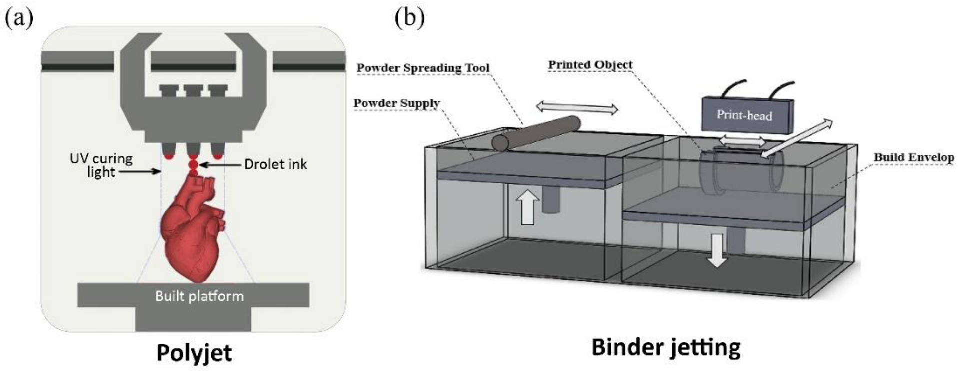

Fig. 8. An illustration of the most fashionable 3D printing methods: (a) Material Jetting (MJ/Polyjet), (Hossain et al., 2023) and (b) a depiction of the binder jetting system (Ziaee et al., 2019)

While a binder is "jetted" over a bed of powder in binder jetting, material jetting involves the deposition of photosensitive resin droplets that are then solidified by ultraviolet radiation.

2.7. Electron beam melting (EBM) process

Electron pillar softening (EBM) could be a powder combination strategy that employs electron pillars as a source of warm vitality to soften metal powders. The electron pillar is produced by a warmed tungsten fiber and is centered by an attractive field. The centered bar is, at that point, checked over the layer of powder, softening the powder particles in a little region. This preparation is rehashed layer by layer until the portion is total. EBM could be a high-temperature preparation that takes place in a vacuum chamber. It makes a difference in anticipating the oxidation of the metal powders and ensures that the parts have excellent surface wrap-up and mechanical properties. EBM could be a moderate handle but can deliver parts with complex geometries and tall accuracy. EBM could be a good choice for applications requiring high-quality parts with complex geometries. It is additionally an excellent choice for applications where erosion resistance is essential. Hastelloy X could be a nickel-based combination safe for erosion in various situations. It can be processed utilizing both SLM and EBM. In common, EBM may be a powder fusion strategy that employs electron bars as a source of warm vitality. It could be a high-temperature preparation that takes place in a vacuum chamber.

Moreover, EBM may be a moderate preparation, but it can be utilized for crafting parts with elaborate geometries and exceptional precision. EBM could be an excellent choice for applications requiring high-quality parts with complex geometries. EBM is additionally a perfect choice for applications where erosion resistance is vital (Romedenne et al., 2020; Galati et al., 2021).

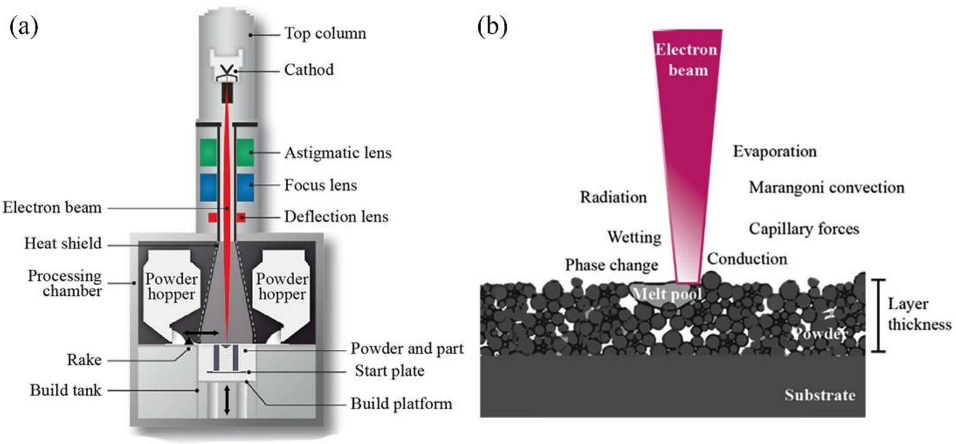

Fig. 9. (a) A schematic diagram of electron beam melting (EBM) machine's architecture, and (b) physical mechanisms of electron beam melting during the melting phase. (Galati et al., 2021)

2.8. Direct energy deposition

Directed Energy Deposition (DED) is an additive manufacturing (AM) method. It supplies powder or wire feedstock to a surface while producing an energy source like a laser, electron beam, plasma, or electric arc. It causes a melted area, enabling the gradual buildup of material in layers (Svetlizky et al., 2021). Various types of Directed Energy Deposition (DED) systems exist, such as melt-based, kinetic energy-based, and powder-feed/wire-feed DED, each utilizing different feedstocks (Greer et al., 2019; Heralic et al., 2012). Generally, Directed Energy Deposition (DED) employs a concentrated high-energy heat source like a laser, electron beam, plasma, or electric arc on the substrate. It creates a small molten pool and simultaneously melts feedstock material (powder or wire) introduced into this pool. The molten material hardens as the heat source progresses, forming a metal track. The spacing between these tracks determines their overlap. The deposition head and feedstock system slightly increase after finishing one layer, following the computer-aided design (CAD) model to create a 3D near-net-shape object through layer-by-layer deposition (Rodrigues et al., 2019; Wysocki et al., 2017).

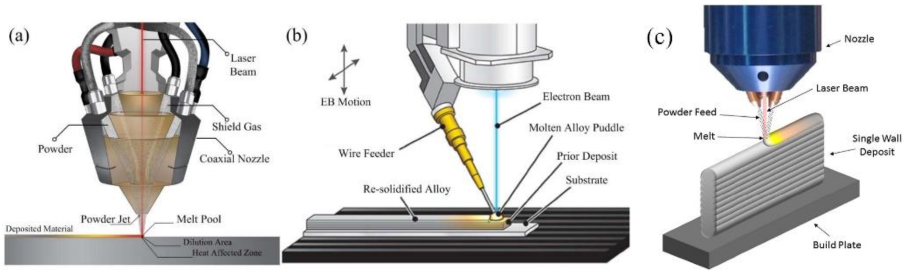

Fig. 10. A visual representation illustrating the steps involved in the direct energy deposition (DED) (a) Powder DED (laser source); (b) Wire DED, (Selema et al., 2022) **and (c) RPM laser metal deposition system schematic.** (Reichardt et al., 2016)

2.9. Sheet lamination process (SL)

The feedstock for the SL process consists of metallic sheets. These sheets, meticulously cut, are brought together in a stack to form a three-dimensional object by harnessing a concentrated energy source, commonly an ultrasonic or laser system (Obikawa et al., 1999). Within additive manufacturing using the SL technique, a solitary two-dimensional layer of feedstock material is positioned onto a construction platform (alternatively referred to as a cutting bed). Further layers are incrementally incorporated until the construction cycle is finished. Feedstock materials include two-dimensional paper or polymer sheets, ceramic tape, tapes, films, or ribbons composed of metal (Stefaniak et al., 2021). Methods for layering sheets involve both laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) processes, as illustrated in Fig. 11 (Srinivas et al., 2017).

2.10. Laminated object manufacturing (LOM)

LOM, one of the rapid prototyping methods, is used to construct three-dimensional solid objects. This technique involves adding layers of differently shaped and sized components, building the object progressively. The process typically includes stacking, bonding, and cutting material sheet layers to form the desired shape. A roller places adhesive-coated material sheets onto a platform bonded using heat and pressure. A laser removes excess material from each layer, and the platform descends to the next layer. This sequence is repeated, and the layers are adhered together with pressure. For crafting moisture-sensitive wood-like components without post-processing, adhesive-coated paper sheets were initially bonded to create LOM (Sonmez et al., 1998; Mekonnen et al., 2016; Ligon et al., 2017; Chiu et al., 2003).

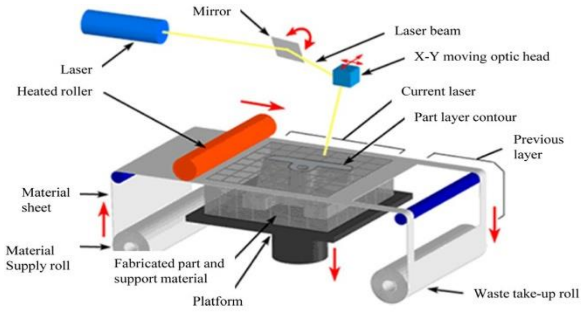

Fig. 11. A schematic diagram of laminated object manufacturing (LOM) process. (Ahn et al., 2012)

2.11. Ultrasonic additive manufacturing (UAM)

Ultrasonic additive manufacturing (UAM) is a metal 3D printing method that uses ultrasonic welding to join metal foils into a 3D structure. This procedure commences by applying a metal foil onto a foundational platform. A sonotrode, a tool that vibrates at ultrasonic frequencies, applies pressure and vibration to the metal foil. It causes the foil to heat up and fuse to the underlying layer. The procedure is replicated to construct the item gradually, one layer at a time. UAM is a unique AM technique because it does not require metal melting. Instead, the metal foils are joined by diffusion at ambient temperature. It results in parts with excellent mechanical properties and surface finish. UAM machines can be either low-power or high-power. Low-power machines are typically used for prototyping and small-scale production. High-power machines are used for large-scale production and applications where high strength and surface finish are required.

UAM is a versatile AM technique that can create various metal parts. It is particularly well-suited for applications requiring complex geometries or high strength. Here are some of the critical benefits of UAM:

* No melting is required, resulting in parts with excellent mechanical properties and surface finish.

* A flexible method that can produce a diverse range of metal components.

* Suitable for applications where complex geometries or high strength are required.

There are also some of the limitations of UAM:

* Relatively slow process compared to other AM techniques.

* Requires specialized equipment.

* Not suitable for all materials.

UAM is a promising AM technique with several advantages over traditional manufacturing methods. This method exhibits adaptability and can craft a broad spectrum of metal components with excellent mechanical properties and surface finish. However, it is essential to note that UAM is a relatively slow process and requires specialized equipment (Hehr et al., 2019; Zhang et al., 2018).

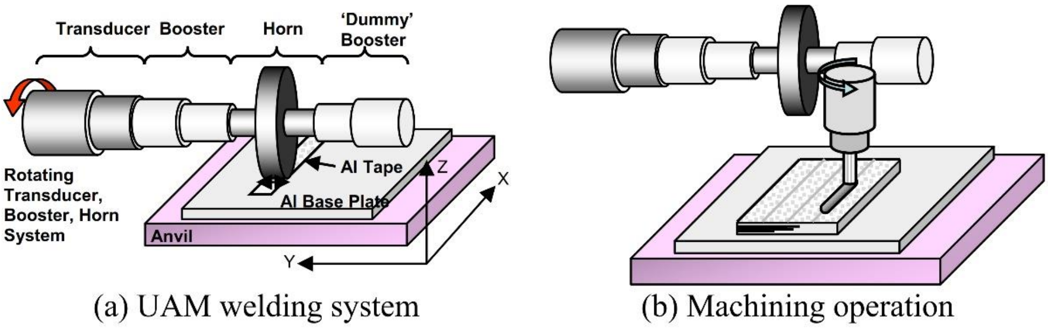

Fig. 12. A schematic diagram of ultrasonic additive manufacturing (UAM) process: (a) a rolling ultrasonic welding system is depicted in (a), consisting of a booster, a welding horn, an ultrasonic transducer, and a second "dummy" booster. The thin metal tape and a base plate are joined together by an ultrasonic solid-state weld, which are transmitted to the disk-shaped welding horn (also known as the "sonotrode") rolling in the x-direction, (b) to create a solid metal part by welding a series of tapes, first side by side, then one on top of the other (but staggered so that seams do not overlap), as illustrated. (Graff et al., 2010)

3. APPLICATION OF ADDITIVE MANUFACTURING TECHNOLOGY

3.1. Aerospace application

Additive Manufacturing (AM) technology has the potential to become a significant partner for the aviation industry, serving purposes such as prototyping, testing, and manufacturing final products. Essential AM methods for crafting aircraft components encompass Laser Metal Deposition, Laser Curing, Direct Metal Laser Sintering, Laser Melting, and Selective Laser Melting (Uriondo et al., 2015).

Aviation components frequently feature intricate shapes and are constructed from advanced materials such as titanium blends, nickel superalloys, rare steels, or high-temperature ceramics, which pose challenges in terms of production due to their difficulty, expense, and time requirements. Moreover, aviation manufacturing batches are typically small, producing at most a few thousand parts. Consequently, additive manufacturing technology is well-suited for use in aircraft applications (Guo et al., 2013).

By using additive manufacturing, also called 3D printing, it ispossible to reduce the material needed for producing aircraft parts, leading to fuel efficiency. 3D printing has also been extensively used to create spare parts for various airplane components, including engines that are prone to frequent damage and need replacement during maintenance. It makes using 3D printing technology to purchase such spare parts highly beneficial (Wang et al., 2018).

In the past, added substance fabricating (AM) innovation was generally utilized to generate model parts and tooling, after which these model parts were put through fit and work tests. The application of the wrapped-up items, especially the metal parts, has been the center of the current ponder of AM innovation (Kumar et al., 2016). Nickel-based alloys are favored within the aviation division due to their tensile qualities, oxidation/corrosion resistance, and harm resilience. Although AM innovation has been utilized within the creation of parts, ordinarily in small sums (Uriondo et al., 2015).

3.2. Automotive industry

The automotive industry has benefited from using additive manufacturing (AM) technologies. AM has enabled more innovative designs, cleaner, lighter, safer products, shorter lead times, and more affordable costs. 3D printing technology rapidly creates more lightweight and complex structures, revolutionizing the automotive industry. For example, Local Motors released the first 3D-printed electric car in 2014. Local Motors also released a 3D-printed shuttle called OLLI, which expands the technology's range of applications beyond just cars. OLLI is a 3D-printed, electric, driverless, and highly intelligent shuttle that is also recyclable. Additionally, Ford, a pioneer in 3D printing technology, uses it to create prototypes and engine components. AM technology can accelerate the product development cycle and reduce manufacturing and product costs, making it a valuable tool in designing and developing automotive parts.

There are some specific examples of how AM is being used in the automotive industry:

* 3D printing is being used to create prototypes of new car designs. It allows designers to test different ideas quickly and cheaply without investing in expensive tooling.

* 3D printing is being used to create custom parts for cars. It can be used to personalize cars or create replacement parts for older models no longer in production.

* 3D printing is being used to create tooling for manufacturing car parts. It can reduce manufacturing costs and improve the features' quality.

* 3D printing is used to create lightweight and complex car structures. It can help to improve the fuel efficiency and performance of cars.

AM technology is still in its early stages of development, but it has the potential to revolutionize the automotive industry. As the technology continues to mature, we can expect to see even more innovative applications of AM in cars (Bahnini et al., 2018; Mok et al., 2016).

3.3. Medical application

3D printing has significantly advanced in the medical field in the past 20 years. AM manufacturing methods are now used to create medical devices, implants, prostheses, bionics, training models for surgeons, and other medical equipment. Combining medical imaging and 3D printing allows for the customization of prostheses and implants and the visualization of complex disorders.

AM technology is widely used in orthopedics and dentistry, offering innovative, precise, and personalized solutions for diagnosing and treating diseases. Recent advances in AM technology, as well as in biomaterials, biological sciences, and biomedicine, have expanded the range of applications for AM in the biomedical industry. These applications include natural chips (made by printing or designing cells and proteins), tissue scaffolds, artificial organs, medical devices, and micro-vascular systems.

Another promising 3D printing application is cell tissue engineering to create living tissue structures, such as bones and organs. This technology can potentially revolutionize the medical field by providing personalized treatments for patients with various diseases.

Some examples of how 3D printing is being used in the medical field today are given below.

3D printed implants: 3D printing can create custom-made implants that perfectly match the patient's anatomy. It is essential for patients with complex or rare conditions where off-the-shelf implants may not be suitable.

3D printed prostheses: 3D printing can be used to create custom-made prostheses that are both functional and aesthetically pleasing. It can help improve the quality of life for patients who have lost limbs or other body parts.

3D-printed medical devices: 3D printing can be used to create a variety of medical devices, such as surgical guides, splints, and braces. It can help to improve the accuracy and efficiency of medical procedures.

3D printed tissue scaffolds: 3D printing can be used to create tissue scaffolds that can be used to grow new tissue. It has the potential to be used to treat a variety of diseases, including burns, heart disease, and cancer.

3D printing is a rapidly evolving technology with the potential to revolutionize the medical field. As the technology continues to develop, we can expect to see even more innovative and life-changing applications for 3D printing in the years to come (Chang et al., 2010; Kang et al., 2016).

3.4. Architecture, building, and construction industry

In structural design, 3D printing innovation contains many potential applications. Ten structures were effectively conveyed in Shanghai, China, in Admirable 2014 after 24 hours were spent creating them utilizing an airbrushing procedure and a sizable 3D printer (Chen et al., 2017).

3D printing technology enables companies to rapidly and cost-effectively create the external appearance of buildings, preventing delays and aiding in identifying potential problem areas. This innovation also facilitates improved communication between construction engineers and clients by providing a more precise and effective way to bring the client's vision to life, moving beyond traditional methods like using paper and pencil, which are outdated (Hager et al., 2016).

The combination of 3D printing innovation and Building Data Displaying (BIM) can lead to way better applications of 3D printing within the construction industry. BIM may be a computerized representation of a building incorporating its physical and valuable characteristics. It permits sharing information and ability about the structure, which can be utilized to form more informed choices about how to plan and construct it. 3D printing can, at that point, be used to create the building concurring with the BIM demonstration, coming about in a more precise and productive development handle. The Canal House in Amsterdam is a case of a 3D-printed building that utilized BIM. The BIM show guaranteed that the building was fundamentally sound and met all vital security prerequisites. It moreover permitted the builders to optimize the plan of the building for 3D printing, coming about in a more effective and cost-effective development handle. The combination of 3D printing and BIM can potentially revolutionize the development industry. By making planning and constructing complex structures less demanding, this innovation can offer assistance to form development more proficient, feasible, and reasonable (Sakin et al., 2017).

4. OUTLOOK AND MAJOR CHALLENGES OF 3D PRINTING TECHNOLOGIES

Additive manufacturing industries are multiplying to ace the modern technological revolution due to its automation capabilities. However, some issues regarding 3D printing manufacturing are under research and development.

Researchers in the 2017 study said their most significant additive manufacturing obstacles were related to prices (of pre- and additional processing, process equipment, and materials). In 2019, researchers said 3D printing material concerns were the most difficult. Today, however, the obstacles appear to vary: the expense of pre-and after-processing, a restricted diversity of materials, and technological constraints are the most significant 3D printing challenges in 2021.

Significant challenges regarding additive manufacturing technologies are included;

Challenge 1: (Slow production speeds)

Industrial 3D printers have yet to match the rapidity and effectiveness of traditional automated mass-production equipment since they struggle to make parts in minutes or seconds instead of days or hours.

Challenge 2: (Materials development and inconsistencies in material properties)

Another difficulty for the 3D printing business is the scarcity of acceptable materials compared to typical production methods. In 3D printing technology, metal, ceramic, polymer, and composites are used, but all materials are not viable for particular applications. Even final product material properties are unsuitable enough against conventional manufacturing. Therefore, using moderate materials based on application is expensive.

Challenge 3: (Size restrictions)

The additive process currently needs help producing large and uniquely shaped objects, posing a significant challenge in industries like aviation and automotive. These technologies are theoretically best for creating complex and functional parts, but generating them in different sizes and shapes with accuracy is a significant hindrance. Making any products in large forms, like ship, car, truck, bus, boat, etc., in favorable style and size have yet to be successful.

Challenge 4: (Quality Consistency)

When making high-quality products, particularly thick metal components, the rigidity in the surface of layers could be more consistent, but these are temporary problems. Quality parts are significant in the automotive, aviation, and medical industries. Maintaining constant layering and material quality in 3D printing remains problematic in areas such as aviation and healthcare devices due to a lack of uniform inspection techniques and technologies to ensure precise morphology and contamination-free materials for the best end-product outputs (Schiller, 2015).

Challenge 5: (Manual post-processing)

In actual practice, nearly all items produced by 3D printers necessitate post-processing to enhance mechanical properties, precision, and visual appeal. Metal additive manufacturing (AM) entails numerous critical phases to ensure the final part's quality and integrity. Following the printing process, removing the extra powder, performing a stress-release heating phase to minimize stretching, and removing the time-consuming support structures is critical. Additional finishing work, such as CNC machining, is frequently necessary, in addition to procedures such as hot isostatic pressing, which reduces pores and guarantees the overall integrity of the item.

Challenge 6: (Software issue)

To make a model suitable for printing, industrial 3D printing necessitates extensive design work. The design process is complex since CAD (computer-assisted design) and computer technology engineering software have not been adapted to the demands of 3D printing for many years.CAD file transfer to STL file sometimes takes much time, and slicing gets hampered and iterated. The whole process could be more user-friendly, from design models to 3D printers. To get the final 3D print product, multiple programs, software environments, and multiple file formats are required.

Challenge 7: (Workforce issue)

A fundamental challenge is the scarcity of engineers, managers, and executives who need a thorough grasp of additive manufacturing. While businesses realize the enormous potential of this technology, many need more knowledge to convert it into production effectively, hindering their ability to capitalize on additive manufacturing opportunities. As these are new technologies, experts on the technical side still need to improve. As a result, constructive ideas are not made to expand the technology (Wu et al., 2022).

Challenge 8: (Cost and pace)

Despite recent reductions in the average 3D printer cost, the whole cost of 3D printing, including materials and maintenance, remains expensive, providing a substantial obstacle to broader adoption. Furthermore, compared to traditional production processes, the pace of 3D printers could be better. More exploration and creativity will be necessary to cut prices and speed up the pace of 3D printing technology (Iftekar et al., 2023).

5. FUTURE PROSPECT OF ADDITIVE MANUFACTURING TECHNOLOGY

Traditional manufacturing techniques are restricted in terms of the quantity and intricacy of parts they can produce. As a result, expensive processes and tools are often required, leading to higher final product costs. In contrast, additive manufacturing methods can accommodate complex and customized parts, giving them a competitive edge over conventional manufacturing approaches (Jimenez et al., 2019). Additive manufacturing, also called 3D printing, builds objects by adding material layer upon layer; unlike traditional subtractive manufacturing, the material is removed from a block to shape the thing. Additive manufacturing, known as 3D printing, constructs objects by incrementally adding material layer by layer. It stands in contrast to conventional subtractive manufacturing, which involves cutting away material from a block to form the object's shape. Additive manufacturing is especially well-suited for crafting complex items that would pose difficulties or be impractical to produce using subtractive techniques.

Additionally, it reduces material wastage (Bourell et al., 2014). For example, in conventional aerospace manufacturing, titanium parts are made by machining large titanium blocks, leading to a substantial amount of waste material, often exceeding 90%, which cannot be easily reused. Additive manufacturing has the potential to diminish such waste production significantly, consequently lowering the energy consumption involved in manufacturing titanium material and parts. Additive manufacturing, a revolutionary industrial process gaining increasing acceptance across various industries, offers numerous advantages. Its capacity to generate intricate shapes and tailor-made components is a standout feature.

Additionally, additive manufacturing presents several other benefits, including quicker time-to-market for new designs, cost reduction in short production runs, decreased assembly errors, lower tool investment costs, and efficient material utilization. This disruptive technology is reshaping the manufacturing landscape by enabling the creation of intricate, personalized components that would have been challenging or impossible using traditional manufacturing methods. As the technology progresses, we can anticipate future advancements and advantages from additive manufacturing. Additive manufacturing, also known as AM, is a swiftly growing technology with the potential to revolutionize the manufacturing sector. AM allows for creating intricate shapes with customizable compositions and active functionalities, making it highly versatile across various applications (Huang et al., 2015).

Some of the most promising applications of AM encompass:

A. Personalization: AM enables the production of tailored items to fulfill the particular requirements of individual customers, proving particularly valuable in industries like medicine and aerospace, where customization is crucial.

B. Large-scale production: While AM comes with higher costs than traditional methods, it can still be employed to mass produce complex and customized items, potentially opening up new markets.

C. Sustainability: AM contributes to waste and pollution reduction by utilizing less material and energy than conventional manufacturing, as it builds only the necessary parts without generating excess waste.

AM is a relatively nascent technology, but its potential to revolutionize traditional manufacturing industries is evident. As further advancements are made, we can anticipate even broader applications for AM. Additive Manufacturing (AM) facilitates the creation of components using functionally graded materials (FGM), a capability not easily achievable through conventional methods. Additionally, AM technology allows for creation of active materials with programmable behaviors, resulting in multifunctional parts that can sense, react, compute, and behave in various ways. It opens up new design possibilities, as arbitrary active systems with passive and active components can be manufactured. In biomedicine, AM proves valuable for fabricating biocompatible, biodegradable, and bioabsorbable tissue scaffolds.

Furthermore, it simplifies the generation of in vitro biological structures comprising viable cells and substances of a biological nature. Economically and environmentally, AM presents numerous advantages over traditional manufacturing techniques. The technology minimizes resource use, cuts costs, speeds up production, and offers a competitive edge. It enables just-in-time production, reduces inventory expenses, and enables innovative design and engineering. Beyond its industrial applications, AM holds significant potential for enhancing STEM education at all levels. With affordable 3D printing equipment availability, hands-on AM labs can engage a diverse population of students and adults, fostering interest and expertise in various fields. These AM-enabled educational programs extend beyond engineering to encompass molecular modeling in the biological sciences, orthopedic implants and tissue engineering in medicine, clothing, footwear, and jewelry design in fashion, protective gear in sports science, crime scene recreation in law enforcement and forensics, bone and artifact replication in archaeology, space and facilities planning in interior design, and scaled models in architecture (Jackson et al., 1999). Additive manufacturing (AM) has surfaced as a prominent technology as an exceedingly adaptable manufacturing technique capable of revolutionizing conventional production methods. Its capacity to create something by fabricating intricate parts with remarkable flexibility has unlocked many novel opportunities in design, research, and manufacturing. Initially relegated to producing limited, low-quality prototypes, AM's scope has significantly expanded due to recent advancements, rendering it a feasible choice for large-scale production. As AM technology advances, its profound influence on the manufacturing industry is bound to persist (Ye et al., 2015; Zastrow et al., 2020; Castelvecchi et al., 2015; Silver et al., 2019). Designers and engineers are presented with an exceptional opportunity to push the boundaries and unlock the full potential of polymer materials and composites. Due to additive manufacturing techniques, researchers now have the chance to delve into novel possibilities for producing bioinspired composites and electrodes. These materials can possess seemingly conflicting traits, like a combination of exceptional flexural strength and a complex, multi-level porous arrangement. The advent of 3D printing manufacturing has opened up unrivaled possibilities for designing intricate structures optimized for performance levels that were previously unattainable using traditional manufacturing methods. This technology encourages industrial designers to break free from conventional thinking, allowing them to envision products and components in innovative ways. As 3D printing technology expands and evolves, it promises to bring exciting developments and revolutionize manufacturing ecosystems, reaching diverse environments and reshaping global supply chains.

Additionally, it can significantly reduce production losses while bolstering local networks (Peng et al., 2020; Castelvecchi et al., 2019). Additive manufacturing (AM) is a burgeoning technology on the rise that holds the promise of transforming numerous industries. AM has already demonstrated its capabilities in the construction sector by creating large-scale structures like 3D-printed houses and bridges. Moreover, it has shown potential in producing lightweight and cost-effective metal components for jet engines compared to traditional manufacturing methods. Biomedical researchers also explore AM's potential by developing intelligent materials that respond to specific stimuli, open doors for applications like drugs, and create tissues through engineering. Nevertheless, hurdles must be addressed before widespread adoption, such as the availability and cost of innovative materials and seamless integration with other manufacturing processes. Nonetheless, the possibilities AM presents are vast, and as the technology advances further, we can anticipate a plethora of new applications emerging in the coming years (Saleh et al., 2021).

Table 1. Summary of all 3D printing processes.

AM Process Categories	Technological Description	Materials
Material Extrusion (FDM, DIW)	Material is distributed sequentially through a nozzle or aperture	Polymer, Composites, Hydrogels.
Vat Photopolymerization (SLA, DLP, CDLP, 2PL)	Light-activated polymerization effectively repairs liquid photopolymer in a vat.	Photopolymer, Ceramic, Composites, Hydrogels.
Material Jetting (Polyjet)	Droplets of material for construction are inserted selectively.	Photopolymer, Wax
Binder Jetting	To unite Powder substances, a liquid adhesive is carefully placed	Metal, Polymer, Ceramic
Powder Bed Fusion (SLS, SLM, DMLS, SHS)	Thermal energy selectively merges powder bed areas.	Metal, Polymer, Ceramic
Sheet Lamination (LOM, UAM)	Material sheets are bound together to generate an item.	Hybrids, Metallic, Ceramic
Direct Energy Deposition (EBM)	Concentrated thermal energy is utilized to melt and combine materials as they are injected.	Metal, Powder, Wire

6. CONCLUSION

The components' variable production side and structural intricacy primarily constrain traditional manufacturing. We must periodically utilize procedures and tools that increase the element's cost. Furthermore, some manufacturing methods violate a promise of sustainable production (pollution, reusing, and speed). Additive fabrication is one of the most important instruments for addressing growth and creating additional importance and high-value jobs. This article has shown various forms of additive manufacturing processes and their outlook difficulties, applications, and their prospects. Over the years, various developments and millstones have been achieved in additive fabrications. Traditional manufacturing processes are being replaced by AM, which has the potential to transform manufacturing. As industries adopt and adapt these new technologies, further research, and innovation will be inevitable to address challenges and maximize the benefits of additive manufacturing. Ongoing improvements and incorporating of these methods will result in heightened effectiveness, minimized waste, and expanded design opportunities spanning diverse industries. As this technology advances, the cost of equipment and materials employed in 3D printing manufacturing will decrease, and the range of materials that can be used will increase. It will make additive manufacturing more accessible to various industries and applications.

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Conflict of Interest

The authors declare that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

8. REFERENCES

Azam, F. I., Abdul Rani, A. M., Altaf, K., Rao, T., & Zaharin, H. A. (2018). An In-Depth Review on Direct Additive Manufacturing of Metals. IOP Conference Series: Materials Science and Engineering, 328, 012005. doi.org/10.1088/1757-899x/328/1/012005

Castelvecchi, D. (2019). Forget everything you know about 3D printing — the 'replicator' is here. Nature, 566(7742), 17–17. doi.org/10.1038/d41586-018-07798-9

Cheah, C. M., Chua, C. K., Lee, C. W., Feng, C., & Totong, K. (2005). Rapid prototyping and tooling techniques: a review of applications for rapid investment casting. The International Journal of Advanced Manufacturing Technology, 25, 308-320. doi.org/10.1007/s00170-003-1840-6.

Chen, L., He, Y., Yang, Y., Niu, S., & Ren, H. (2017). The research status and development trend of additive manufacturing technology. The International Journal of Advanced Manufacturing Technology, 89, 3651-3660. doi.org/10.1007/s00170-016-9335-4

Guo, N., & Leu, M. C. (2013). Additive manufacturing: technology, applications and research needs. Frontiers of mechanical engineering, 8, 215-243. doi.org/10.1007/s11465-013-0248-8.

Horn, T. J., & Harrysson, O. L. (2012). Overview of current additive manufacturing technologies and selected applications. Science progress, 95(3), 255-282. doi.org/10.3184/003685012X13420984463047.

Huang, S. H., Liu, P., Mokasdar, A., & Hou, L. (2013). Additive manufacturing and its societal impact: a literature review. The International journal of advanced manufacturing technology, 67, 1191-1203. doi.org/10.1007/s00170-012-4558-5.

Rosa, E. L. S. D., Oleskovicz, C. F., & Aragao, B. N. (2004). Rapid prototyping in maxillofacial surgery and traumatology. Brazilian Dental Journal, 15, 243-247. doi.org/10.1590/S0103-64402004000300015.

Negi, S., Dhiman, S., & Sharma, R. K. (2013). Basics, applications and future of additive manufacturing technologies: A review. Journal of Manufacturing Technology Research, 5(1/2), 75.

Herderick, E. D. (2015). Progress in additive manufacturing. Jom, 67(3), 580-581. doi.org/10.1007/s11837-015-1323-x.

Yang, S., & Zhao, Y. F. (2015). Additive manufacturing-enabled design theory and methodology: a critical review. The International Journal of Advanced Manufacturing Technology, 80, 327-342. doi.org/10.1007/s00170-015-6994-5.

Frazier, W. E. (2014). Metal additive manufacturing: a review. Journal of Materials Engineering and performance, 23, 1917-1928. doi.org/10.1007/s11665-014-0958-z.

Guessasma, S., Zhang, W., Zhu, J., Belhabib, S., & Nouri, H. (2015). Challenges of additive manufacturing technologies from an optimisation perspective. International Journal for Simulation and Multidisciplinary Design Optimization, 6, A9. doi.org/10.1051/smdo/2016001.

Tang, H. H., & Yen, H. C. (2015). Slurry-based additive manufacturing of ceramic parts by selective laser burn-out. Journal of the European Ceramic Society, 35(3), 981-987. doi.org/10.1016/j.jeurceramsoc.2014.10.019.

Gaytan, S. M., Cadena, M. A., Karim, H., Delfin, D., Lin, Y., Espalin, D., ... & Wicker, R. B. (2015). Fabrication of barium titanate by binder jetting additive manufacturing technology. Ceramics International, 41(5), 6610-6619. doi.org/10.1016/j.ceramint.2015.01.108.

Guessasma, S., Belhabib, S., & Nouri, H. (2015). Significance of pore percolation to drive anisotropic effects of 3D printed polymers revealed with X-ray μ-tomography and finite element computation. Polymer, 81, 29-36. doi.org/10.1016/j.polymer.2015.10.041.

Quan, Z., Wu, A., Keefe, M., Qin, X., Yu, J., Suhr, J., ... & Chou, T. W. (2015). Additive manufacturing of multi-directional preforms for composites: opportunities and challenges. Materials Today, 18(9), 503-512. doi.org/10.1016/j.mattod.2015.05.001.

Lee, J. S., Cha, H. D., Shim, J. H., Jung, J. W., Kim, J. Y., & Cho, D. W. (2012). Effect of pore architecture and stacking direction on mechanical properties of solid freeform fabrication-based scaffold for bone tissue engineering. Journal of Biomedical Materials Research Part A, 100(7), 1846-1853. doi.org/10.1002/jbm.a.34149.

Takezawa, A., Kobashi, M., & Kitamura, M. (2015). Porous composite with negative thermal expansion obtained by photopolymer additive manufacturing. APL Materials, 3(7). doi.org/10.1063/1.4926759.

Hossain, K. R., Lyu, Y., Yao, X., Yang, Y., Jiang, P., & Wang, X. (2023). Tribological and mechanical properties of fabricated soft materials with a podium mesostructured. Tribology International, 187, 108673. doi.org/10.1016/j.triboint.2023.108673

Ligon, S. C., Liska, R., Stampfl, J., Gurr, M., & Mülhaupt, R. (2017). Polymers for 3D Printing and Customized Additive Manufacturing. Chemical Reviews, 117(15), 10212–10290. doi.org/10.1021/acs.chemrev.7b00074

Kumar, V., & Dutta, D. (1997). An assessment of data formats for layered manufacturing. Advances in Engineering Software, 28(3), 151–164. doi.org/10.1016/s0965-9978(96)00050-6

Griffiths, C., Howarth, J., De Almeida-Rowbotham, G., Rees, A., & Kerton, R. (2016). A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing. Journal of Cleaner Production, 139, 74–85. doi.org/10.1016/j.jclepro.2016.07.182

Rejeski, D., Zhao, F., & Huang, Y. (2018). Research needs and recommendations on environmental implications of additive manufacturing. Additive Manufacturing, 19, 21–28. doi.org/10.1016/j.addma.2017.10.019

Hossain, K. R., Jiang, P., Yao, X., Wu, J., Hu, D., Yang, X., ... & Wang, X. (2023). Additive Manufacturing of Polymer-Based Lubrication. Macromolecular Materials and Engineering, 2300147. doi.org/10.1002/mame.202300147.

Jiang, J., & Fu, Y. F. (2020). A short survey of sustainable material extrusion additive manufacturing. Australian Journal of Mechanical Engineering, 21(1), 123–132. doi.org/10.1080/14484846.2020.1825045

Crivello, J. V., & Reichmanis, E. (2013). Photopolymer Materials and Processes for Advanced Technologies. Chemistry of Materials, 26(1), 533–548. doi.org/10.1021/cm402262g

Pagac, M., Hajnys, J., Ma, Q. P., Jancar, L., Jansa, J., Stefek, P., & Mesicek, J. (2021). A Review of Vat Photopolymerization Technology: Materials, Applications, Challenges, and Future Trends of 3D Printing. Polymers, 13(4), 598. doi.org/10.3390/polym13040598

Tumbleston, J. R., Shirvanyants, D., Ermoshkin, N., Janusziewicz, R., Johnson, A. R., Kelly, D., Chen, K., Pinschmidt, R., Rolland, J. P., Ermoshkin, A., Samulski, E. T., & DeSimone, J.

M. (2015). Continuous liquid interface production of 3D objects. Science, 347(6228), 1349–1352. doi.org/10.1126/science.aaa2397

Huang, B., Hu, R., Xue, Z., Zhao, J., Li, Q., Xia, T., Zhang, W., & Lu, C. (2020). Continuous liquid interface production of alginate/polyacrylamide hydrogels with supramolecular shape memory properties. Carbohydrate Polymers, 231, 115736. doi.org/10.1016/j.carbpol.2019.115736

Tesavibul, P., Felzmann, R., Gruber, S., Liska, R., Thompson, I., Boccaccini, A. R., & Stampfl, J. (2012, May). Processing of 45S5 Bioglass® by lithography-based additive manufacturing. Materials Letters, 74, 81–84. doi.org/10.1016/j.matlet.2012.01.019

Hossain, K. R., Jiang, P., Yao, X., Yang, X., Hu, D., & Wang, X. (2023). Ionic Liquids for 3D Printing: Fabrication, Properties, Applications. Journal of Ionic Liquids, 100066. doi.org/10.1016/j.jil.2023.100066.

Zheng, L., Kurselis, K., El-Tamer, A., Hinze, U., Reinhardt, C., Overmeyer, L., & Chichkov, B. (2019). Nanofabrication of High-Resolution Periodic Structures with a Gap Size Below 100 nm by Two-Photon Polymerization. Nanoscale Research Letters, 14(1). doi.org/10.1186/s11671-019-2955-5

Zhao, Y., Zhu, J., He, W., Liu, Y., Sang, X., & Liu, R. (2023). 3D printing of unsupported multi-scale and large-span ceramic via near-infrared assisted direct ink writing. Nature Communications, 14(1), 2381. doi.org/10.1038/s41467-023-38082-8.

Saadi, M. A. S. R., Maguire, A., Pottackal, N. T., Thakur, M. S. H., Ikram, M. M., Hart, A. J., ... & Rahman, M. M. (2022). Direct ink writing: a 3D printing technology for diverse materials. Advanced Materials, 34(28), 2108855. doi.org/10.1002/adma.202108855.

Guo, C., Ge, W., & Lin, F. (2015). Dual-Material Electron Beam Selective Melting: Hardware Development and Validation Studies. Engineering, 1(1), 124–130. doi.org/10.15302/j-eng-2015013

Murr, L. E., Gaytan, S. M., Ramirez, D. A., Martinez, E., Hernandez, J., Amato, K. N., Shindo, P. W., Medina, F. R., & Wicker, R. B. (2012). Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies. Journal of Materials Science & Technology, 28(1), 1–14. doi.org/10.1016/s1005-0302(12)60016-4

Gu, D. D., Meiners, W., Wissenbach, K., & Poprawe, R. (2012). Laser additive manufacturing of metallic components: materials, processes and mechanisms. International Materials Reviews, 57(3), 133–164. doi.org/10.1179/1743280411y.0000000014

Gaytan, S. M., Murr, L. E., Medina, F., Martinez, E., Lopez, M. I., & Wicker, R. B. (2009). Advanced metal powder based manufacturing of complex components by electron beam melting. Materials Technology, 24(3), 180–190. doi.org/10.1179/106678509x12475882446133

Körner, C. (2016). Additive manufacturing of metallic components by selective electron beam melting — a review. International Materials Reviews, 61(5), 361–377. doi.org/10.1080/09506608.2016.1176289

Duda, T., & Raghavan, L. V. (2018). 3D metal printing technology: the need to re-invent design practice. AI & SOCIETY, 33(2), 241–252. doi.org/10.1007/s00146-018-0809-9

Zhang, D., Sun, S., Qiu, D., Gibson, M. A., Dargusch, M. S., Brandt, M., Qian, M., & Easton, M. (2018). Metal Alloys for Fusion-Based Additive Manufacturing. Advanced Engineering Materials, 20(5). doi.org/10.1002/adem.201700952

Subhedar, P. (2018). Additive Manufacturing: A next gen fabrication. International Journal of Current Engineering and Technology, 8(01). doi.org/10.14741/ijcet.v8i01.10893

Stavropoulos, P., & Foteinopoulos, P. (2018). Modelling of additive manufacturing processes: a review and classification. Manufacturing Review, 5, 2. doi.org/10.1051/mfreview/2017014

Dev Singh, D., Mahender, T., & Raji Reddy, A. (2021). Powder bed fusion process: A brief review. Materials Today: Proceedings, 46, 350–355. doi.org/10.1016/j.matpr.2020.08.415

Kok, Y., Tan, X., Wang, P., Nai, M., Loh, N., Liu, E., & Tor, S. (2018). Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review. Materials & Design, 139, 565–586. doi.org/10.1016/j.matdes.2017.11.021

Bahnini, I., Rivette, M., Rechia, A., Siadat, A., & Elmesbahi, A. (2018). Additive manufacturing technology: the status, applications, and prospects. The International Journal of Advanced Manufacturing Technology, 97(1–4), 147–161. doi.org/10.1007/s00170-018-1932-y

Sélo, R. R., Catchpole-Smith, S., Maskery, I., Ashcroft, I., & Tuck, C. (2020). On the thermal conductivity of AlSi10Mg and lattice structures made by laser powder bed fusion. Additive Manufacturing, 34, 101214. doi.org/10.1016/j.addma.2020.101214

Lu, Q., Nguyen, N., Hum, A., Tran, T., & Wong, C. (2020). Identification and evaluation of defects in selective laser melted 316L stainless steel parts via in-situ monitoring and micro computed tomography. Additive Manufacturing, 35, 101287. doi.org/10.1016/j.addma.2020.101287

Zadi-Maad, A., Rohib, R., & Irawan, A. (2018). Additive manufacturing for steels: a review. IOP Conference Series: Materials Science and Engineering, 285, 012028. doi.org/10.1088/1757-899x/285/1/012028

Gülcan, O., Günaydın, K., & Tamer, A. (2021). The State of the Art of Material Jetting—A Critical Review. Polymers, 13(16), 2829. doi.org/10.3390/polym13162829

Tino, R., Leary, M., Yeo, A., Kyriakou, E., Kron, T., & Brandt, M. (2020). Additive manufacturing in radiation oncology: a review of clinical practice, emerging trends and research opportunities. International Journal of Extreme Manufacturing, 2(1), 012003. doi.org/10.1088/2631-7990/ab70af.

Pilipović, A., Baršić, G., Katić, M., & Rujnić Havstad, M. (2020). Repeatability and Reproducibility Assessment of a PolyJet Technology Using X-ray Computed Tomography. Applied Sciences, 10(20), 7040. doi.org/10.3390/app10207040

Quan, H., Zhang, T., Xu, H., Luo, S., Nie, J., & Zhu, X. (2020). Photo-curing 3D printing technique and its challenges. Bioactive Materials, 5(1), 110–115. doi.org/10.1016/j.bioactmat.2019.12.003

Dilag, J., Chen, T., Li, S., & Bateman, S. A. (2019). Design and direct additive manufacturing of three-dimensional surface micro-structures using material jetting technologies. Additive Manufacturing, 27, 167–174. doi.org/10.1016/j.addma.2019.01.009

Sireesha, M., Lee, J., Kranthi Kiran, A. S., Babu, V. J., Kee, B. B. T., & Ramakrishna, S. (2018). A review on additive manufacturing and its way into the oil and gas industry. RSC Advances, 8(40), 22460–22468. doi.org/10.1039/c8ra03194k

Elkaseer, A., Chen, K. J., Janhsen, J. C., Refle, O., Hagenmeyer, V., & Scholz, S. G. (2022). Material jetting for advanced applications: A state-of-the-art review, gaps and future directions. Additive Manufacturing, 60, 103270. doi.org/10.1016/j.addma.2022.103270

Li, M., Du, W., Elwany, A., Pei, Z., & Ma, C. (2020). Metal Binder Jetting Additive Manufacturing: A Literature Review. Journal of Manufacturing Science and Engineering, 142(9). doi.org/10.1115/1.4047430

Wang, Y., & Zhao, Y. F. (2017). Investigation of Sintering Shrinkage in Binder Jetting Additive Manufacturing Process. Procedia Manufacturing, 10, 779–790. doi.org/10.1016/j.promfg.2017.07.077

Chen, H., & Zhao, Y. F. (2016). Process parameters optimization for improving surface quality and manufacturing accuracy of binder jetting additive manufacturing process. Rapid Prototyping Journal, 22(3), 527–538. doi.org/10.1108/rpj-11-2014-0149

FRYKHOLM, R., TAKEDA, Y., ANDERSSON, B. G., & CARLSTRÖM, R. (2016). Solid State Sintered 3-D Printing Component by Using Inkjet (Binder) Method. Journal of the Japan Society of Powder and Powder Metallurgy, 63(7), 421–426. doi.org/10.2497/jjspm.63.421

Utela, B., Storti, D., Anderson, R., & Ganter, M. (2008). A review of process development steps for new material systems in three dimensional printing (3DP). Journal of Manufacturing Processes, 10(2), 96–104. doi.org/10.1016/j.jmapro.2009.03.002

Meteyer, S., Xu, X., Perry, N., & Zhao, Y. F. (2014). Energy and Material Flow Analysis of Binder-jetting Additive Manufacturing Processes. Procedia CIRP, 15, 19–25. doi.org/10.1016/j.procir.2014.06.030

Gokuldoss, P. K., Kolla, S., & Eckert, J. (2017). Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines. Materials, 10(6), 672. doi.org/10.3390/ma10060672

Do, T., Kwon, P., & Shin, C. S. (2017). Process development toward full-density stainless steel parts with binder jetting printing. International Journal of Machine Tools and Manufacture, 121, 50–60. doi.org/10.1016/j.ijmachtools.2017.04.006

Nandwana, P., Elliott, A. M., Siddel, D., Merriman, A., Peter, W. H., & Babu, S. S. (2017). Powder bed binder jet 3D printing of Inconel 718: Densification, microstructural evolution and challenges☆. Current Opinion in Solid State and Materials Science, 21(4), 207-218. doi.org/10.1016/j.cossms.2016.12.002

Mostafaei, A., Neelapu, S. H. V. R., Kisailus, C., Nath, L. M., Jacobs, T. D., & Chmielus, M. (2018, December). Characterizing surface finish and fatigue behavior in binder-jet 3D-printed nickel-based superalloy 625. Additive Manufacturing, 24, 200–209. doi.org/10.1016/j.addma.2018.09.012

Mirzababaei, S., & Pasebani, S. (2019). A Review on Binder Jet Additive Manufacturing of 316L Stainless Steel. MDPI. doi.org/10.3390/jmmp3030082

Ziaee, M., & Crane, N. B. (2019, August). Binder jetting: A review of process, materials, and methods. Additive Manufacturing, 28, 781–801. doi.org/10.1016/j.addma.2019.05.031

Romedenne, M., Pillai, R., Kirka, M., & Dryepondt, S. (2020). High temperature air oxidation behavior of Hastelloy X processed by Electron Beam Melting (EBM) and Selective Laser Melting (SLM). Corrosion Science, 171, 108647. doi.org/10.1016/j.corsci.2020.108647

Galati, M. (2021). Electron beam melting process: A general overview. Additive Manufacturing, 277-301. doi.org/10.1016/B978-0-12-818411-0.00014-8

Svetlizky, D., Das, M., Zheng, B., Vyatskikh, A. L., Bose, S., Bandyopadhyay, A., Schoenung, J. M., Lavernia, E. J., & Eliaz, N. (2021). Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications. Materials Today, 49, 271–295. doi.org/10.1016/j.mattod.2021.03.020

Greer, C., Nycz, A., Noakes, M., Richardson, B., Post, B., Kurfess, T., & Love, L. (2019) Introduction to the design rules for Metal Big Area Additive Manufacturing. (2019, February 25). Introduction to the Design Rules for Metal Big Area Additive Manufacturing - 27, 159-166. doi.org/10.1016/j.addma.2019.02.016

Heralić, A., Christiansson, A. K., & Lennartson, B. (2012). Height control of laser metal-wire deposition based on iterative learning control and 3D scanning. Optics and Lasers in Engineering, 50(9), 1230–1241. doi.org/10.1016/j.optlaseng.2012.03.016

Rodrigues, T. A., Duarte, V., Miranda, R., Santos, T. G., & Oliveira, J. (2019). Current Status and Perspectives on Wire and Arc Additive Manufacturing (WAAM). Materials, 12(7), 1121. doi.org/10.3390/ma12071121

Wysocki, B., Maj, P., Sitek, R., Buhagiar, J., Kurzydłowski, K., & Święszkowski, W. (2017). Laser and Electron Beam Additive Manufacturing Methods of Fabricating Titanium Bone Implants. Applied Sciences, 7(7), 657. doi.org/10.3390/app7070657

Selema, A., Ibrahim, M. N., & Sergeant, P. Metal Additive Manufacturing for Electrical Machines: Technology Review and Latest Advancements. Energies 2022, 15, 1076. doi.org/10.3390/en15031076.

Reichardt, A., Dillon, R. P., Borgonia, J. P., Shapiro, A. A., McEnerney, B. W., Momose, T., & Hosemann, P. (2016). Development and characterization of Ti-6Al-4V to 304L stainless steel gradient components fabricated with laser deposition additive manufacturing. Materials & Design, 104, 404-413. doi.org/10.1016/j.matdes.2016.05.016.

Obikawa, T., Yoshino, M., & Shinozuka, J. (1999). Sheet steel lamination for rapid manufacturing. Journal of Materials Processing Technology, 89–90, 171–176. doi.org/10.1016/s0924-0136(99)00027-8

Stefaniak, A., Du Preez, S., & Du Plessis, J. (2021). Additive Manufacturing for Occupational Hygiene: A Comprehensive Review of Processes, Emissions, & Exposures. Journal of Toxicology and Environmental Health, Part B, 24(5), 173–222. doi.org/10.1080/10937404.2021.1936319

Srinivas, M., & Babu, B. S. (2017). A critical review on recent research methodologies in additive manufacturing. Materials Today: Proceedings, 4(8), 9049-9059. doi.org/10.1016/j.matpr.2017.07.258

Sonmez, F. O., & Hahn, H. T. (1998). Thermomechanical analysis of the laminated object manufacturing (LOM) process. Rapid Prototyping Journal, 4(1), 26–36. doi.org/10.1108/13552549810197541

Mekonnen, B. G., Bright, G., & Walker, A. (n.d.) (2016). A Study on State of the Art Technology of Laminated Object Manufacturing (LOM). 28th International Conference on CARs & FoF 2016 (pp. 207-216). doi.org/10.1007/978-81-322-2740-3_21

Chiu, Y., Liao, Y., & Hou, C. (2003). Automatic fabrication for bridged laminated object manufacturing (LOM) process. Journal of Materials Processing Technology, 140(1–3), 179–184. doi.org/10.1016/s0924-0136(03)00710-6

Ahn, D., Kweon, J. H., Choi, J., & Lee, S. (2012). Quantification of surface roughness of parts processed by laminated object manufacturing. Journal of Materials Processing Technology, 212(2), 339-346. doi.org/10.1016/j.jmatprotec.2011.08.013.

Hehr, A., & Norfolk, M. (2019). A comprehensive review of ultrasonic additive manufacturing. Rapid Prototyping Journal, 26(3), 445-458. doi.org/10.1108/RPJ-03-2019-0056.

Zhang, Y., Jarosinski, W., Jung, Y. G., & Zhang, J. (2018). Additive manufacturing processes and equipment. In Additive manufacturing (pp. 39-51). Butterworth-Heinemann. doi.org/10.1016/B978-0-12-812155-9.00002-5

Graff, K. F., Short, M., & Norfolk, M. (2010). Very high power ultrasonic additive manufacturing (VHP UAM) for advanced materials. In 2010 International Solid Freeform Fabrication Symposium. University of Texas at Austin. doi.org/10.26153/tsw/15165.

Uriondo, A., Esperon-Miguez, M., & Perinpanayagam, S. (2015). The present and future of additive manufacturing in the aerospace sector: A review of important aspects. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 229(11), 2132–2147. doi.org/10.1177/0954410014568797

Wang, Y. C., Chen, T., & Yeh, Y. L. (2018). Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors - The International Journal of Advanced Manufacturing Technology. SpringerLink. doi.org/10.1007/s00170-018-1927-8

Kumar, L. J., & Krishnadas Nair, C. G. (2016). Current Trends of Additive Manufacturing in the Aerospace Industry. Current Trends of Additive Manufacturing in the Aerospace Industry | SpringerLink. doi.org/10.1007/978-981-10-0812-2_4

Bahnini, I., Rivette, M., Rechia, A., Siadat, A., & Elmesbahi, A. (2018). Additive manufacturing technology: the status, applications, and prospects. The International Journal of Advanced Manufacturing Technology, 97(1–4), 147–161. doi.org/10.1007/s00170-018-1932-y

Mok, S. W., Nizak, R., Fu, S. C., Ho, K. W. K., Qin, L., Saris, D. B., Chan, K. M., & Malda, J. (2016). From the printer: Potential of three-dimensional printing for orthopaedic applications. Journal of Orthopaedic Translation, 6, 42–49. doi.org/10.1016/j.jot.2016.04.003

Chang, R., Emami, K., Wu, H., & Sun, W. (2010). Biofabrication of a three-dimensional liver micro-organ as an in vitro drug metabolism model. Biofabrication, 2(4), 045004. doi.org/10.1088/1758-5082/2/4/045004

Kang, H. W., Lee, S. J., Ko, I. K., Kengla, C., Yoo, J. J., & Atala, A. (2016). A 3D bioprinting system to produce human-scale tissue constructs with structural integrity. Nature Biotechnology, 34(3), 312–319. doi.org/10.1038/nbt.3413

Hager, I., Golonka, A., & Putanowicz, R. (2016). 3D Printing of Buildings and Building Components as the Future of Sustainable Construction? Procedia Engineering, 151, 292–299. doi.org/10.1016/j.proeng.2016.07.357

Sakin, M., & Kiroglu, Y. C. (2017). 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. Energy Procedia, 134, 702–711. doi.org/10.1016/j.egypro.2017.09.562

Schiller, G. J. (2015). Additive manufacturing for Aerospace. In 2015 IEEE Aerospace Conference (pp. 1-8). IEEE doi.org/10.1109/AERO.2015.7118958.

Iftekar, S. F., Aabid, A., Amir, A., & Baig, M. (2023). Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review. Polymers, 15(11), 2519. doi.org/10.3390/polym15112519

Jiménez, M., Romero, L., Domínguez, I. A., Espinosa, M. D. M., & Domínguez, M. (2019). Additive Manufacturing Technologies: An Overview about 3D Printing Methods and Future Prospects. Complexity, 2019, 1–30. doi.org/10.1155/2019/9656938

Bourell, D. L., Rosen, D. W., & Leu, M. C. (2014, March). The Roadmap for Additive Manufacturing and Its Impact. 3D Printing and Additive Manufacturing, 1(1), 6–9. doi.org/10.1089/3dp.2013.0002

Huang, Y., Leu, M. C., Mazumder, J., & Donmez, A. (2015). Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering, 137(1). doi.org/10.1115/1.4028725

Jackson, T., Liu, H., Patrikalakis, N., Sachs, E., & Cima, M. (1999). Modeling and designing functionally graded material components for fabrication with local composition control. Materials & Design, 20(2–3), 63–75. doi.org/10.1016/s0261-3069(99)00011-4

Yu, K., Ritchie, A., Mao, Y., Dunn, M. L., & Qi, H. J. (2015). Controlled Sequential Shape Changing Components by 3D Printing of Shape Memory Polymer Multimaterials. Procedia IUTAM, 12, 193–203. doi.org/10.1016/j.piutam.2014.12.021

Zastrow, M. (2020). 3D printing gets bigger, faster and stronger. Nature, 578(7793), 20–23. doi.org/10.1038/d41586-020-00271-6

Castelvecchi, D. (2015). Chemical trick speeds up 3D printing. Nature. doi.org/10.1038/nature.2015.17122

Silver, A. (2019). Five innovative ways to use 3D printing in the laboratory. Nature, 565(7737), 123–124. doi.org/10.1038/d41586-018-07853-5

Peng, M., Shi, D., Sun, Y., Cheng, J., Zhao, B., Xie, Y., Zhang, J., Guo, W., Jia, Z., Liang, Z., & Jiang, L. (2020). 3D Printed Mechanically Robust Graphene/CNT Electrodes for Highly Efficient Overall Water Splitting. Advanced Materials, 32(23). doi.org/10.1002/adma.201908201

Saleh Alghamdi, S., John, S., Roy Choudhury, N., & Dutta, N. K. (2021). Additive Manufacturing of Polymer Materials: Progress, Promise and Challenges. Polymers, 13(5), 753. doi.org/10.3390/polym13050753.

Schelly, C., Anzalone, G., Wijnen, B., & Pearce, J. M. (2015). Open-source 3-D printing technologies for education: Bringing additive manufacturing to the classroom. Journal of Visual Languages & Computing, 28, 226-237. doi.org/10.1016/j.jvlc.2015.01.004.

Wu, H., Mehrabi, H., Naveed, N., & Karagiannidis, P. (2022). Impact of strategic control and supply chain management on recycled plastic additive manufacturing. Journal of Cleaner Production, 364, 132511. doi.org/10.1016/j.jclepro.2022.132511.

Zhai, Y., Lados, D. A., & LaGoy, J. L. (2014). Additive manufacturing: making imagination the major limitation. Jom, 66, 808-816. doi.org/10.1007/s11837-014-0886-2.