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3D printing – A review of processes, materials and applications in industry 4.0

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ABSTRACT

3D printing, unlike other manufacturing processes, being an additive process has emerged as a viable technology for the production of engineering components. The aspects associated with 3D printing such as less material wastage, ease of manufacturing, less human involvement, very less post processing and energy efficiency makes the process sustainable for industrial use. The paper discusses numerous 3D printing processes, their advantages and disadvantages. A comprehensive description of different materials compatible for each type of 3D printing process is presented. The paper also presents the various application areas of each type of process. A dedicated section on industry 4.0 has also been included. The literature studied revealed that although the field of 3D printing has evolved to a great extent, there are still issues that need to be addressed such as material incompatibility and the cost of the materials. Future research could be undertaken to develop and modify the processes to suit a broad range of materials. To broaden the range of applications for 3D printed parts, more focus needs to be laid on developing cost effective printer technologies and materials compatible for these printers.

1. Introduction

The very basic question that comes to our mind regarding the field of manufacturing is that how do we make stuff or how do we proceed from materials into something that we want to use, buy or consume in any way. The first way to make something is subtractive manufacturing- where we begin from raw material and proceed towards the desired product. Then the next type of manufacturing is called forming- in which a block of material undergoes changes into its dimensions when force is applied. The third type of technology of making things is casting- where the material in solid form is melted into liquid form, the liquid metal is then poured into a specific mold to obtain the object. The fourth way of manufacturing is Additive manufacturing (AM) wherein the parts are developed additively layer by layer [54,56]. AM and 3D printing are umbrella words that cover a wide range of processes for creating three-dimensional prototypes and structures from digital files. The solid modelling component of Computer-Aided Design is the basis for additive technologies. This solid modelling data is used by additive models to create layers of extremely thin cross-sectional areas, which entitle manufacturing of intricate and complex shapes and surfaces that are very difficult to achieve by using conventional methods [1].

One will conclude a machine as a 3D printer if it comprises the three properties that are, three-dimensional, additive, and layer-based. An additive process is adding different substances to make the desired substance. Let's say if we want to bake cupcakes, we take an empty bowl and add ingredients, one by one until we get the finished batter, this is an additive way to make it. Another way to make a cupcake is, we can buy a big cake and cut away everything to give it the shape of a cupcake. This is a subtractive process, wherever we tend to begin from a bigger part and take away everything that's not needed. Examples of subtractive manufacturing would be manual wood carving, CNC machining or laser cutting, etc.

In 3D printing, which is basically an additive manufacturing process, we start with the fundamental design of the part we want to model [55]. The said design is created on a computer software that is attachable to 3D printers. This software then generates a special type of file to be sent to the printer. The 3D printer reads that file and creates the product by adjoining one layer over the other [22]. Almost every process in 3D printing uses layers to form a part. 3D printers read the parts as a single two-dimensional layer at a time rather than a whole single part. The working of 3D printers as shown in Fig. 1 is based on the fact that they are designed to read Standard Tessellation Language (STL) file type.

The sustainable aspects of 3D Printing such as less material wastage, less post processing and very less cost even for manufacturing complex parts makes 3D Printing a technology of the future. The other sustainable aspects include the potential of 3D printing to reuse plastics, recycle and reduce emissions. The technology is also capable of producing designs with complex and optimized geometries, which help in developing

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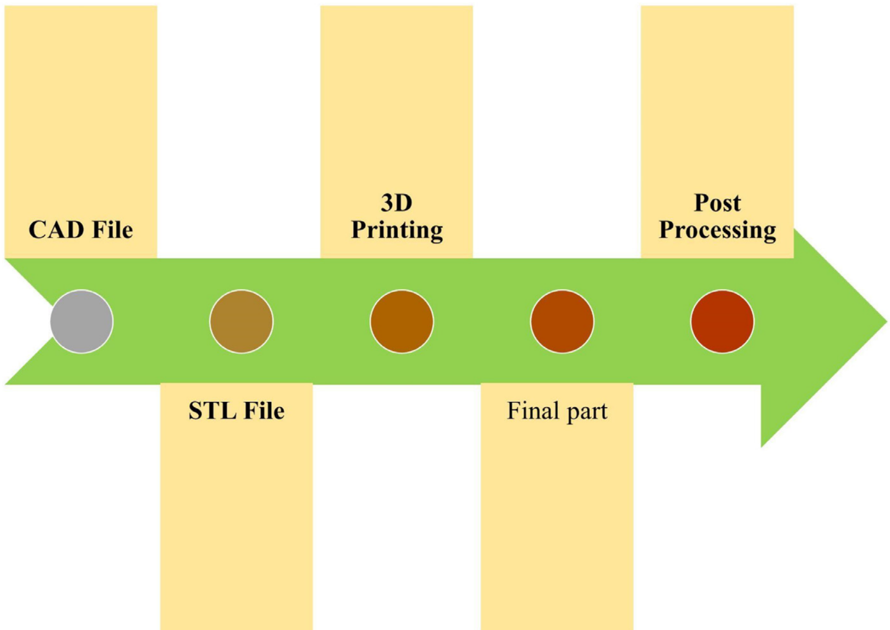

Fig. 1. Basic process of 3D printers to create 3D object.

parts with light weight and better strength to weight ratios. Therefore, the use of 3D Printing helps to produce designs which are sustainable.

2. Types of processes in 3D printing

In order to satisfy the need for printing intricate models with high resolutions, methods of AM have been developed. Rapid Prototyping has played an important part in the advancement of AM technologies. AM Technologies are based on three main types which are sintering- whereby the temperature of the material is raised without being liquified to compose complex sharp resolution prototypes, melting- where electron beams are used to melt the powders and stereolithography- which uses a method referred to as photopolymerization, which uses an associate ultraviolet laser. This laser is dismissed over a photopolymer resin vat so that torque-resistant ceramic components are ready to encounter utmost temperatures [2]. As per ASTM (American Society for Testing and Materials), AM have been divided into seven processes which include VAT Photopolymerisation, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Direct Energy Deposition [3]. Some of the main methods have been addressed in depth in the subsequent sections focusing on the work involved in each process, benefits and drawbacks, materials used in different processes, and applications of various 3D printing processes.

2.1. Stereolithography (SL)

Era of 3D printing started in the late 20s and SL is the earliest 3D printing process ever introduced in the market and the first ever 3D printers set in motion were stereolithographic/ SL machines that were used to manufacture 3D models, 3D prototypes, 3D parts and patterns. Although many studies in the area of 3D printing were conducted in the 1970s, this process was introduced and patented by Charles Hull in 1984 [4].

Before defining the term Stereolithography, one needs to understand how the SL process works. To begin the process, a CAD file is generated on the system and this file is converted into STL file type. This STL file type provides the geometric data required by a 3D printer to manufacture an object. The four main parts which contribute to the formulation are ultraviolet (UV) curable photopolymer liquid, perforated table, laser source, and a computer to control the process. After reading the STL file type, 3D printers start working in such a way that the perforated table gets immersed in the liquid tank. As the table moves downwards, the liquid polymer encounters the table through the perforated holes. The instant the liquid comes in contact with the table, the UV laser hits the upper surface of the photo liquid polymer making it hardened instantly. This table then again moves downward, to create a layer-by-layer geometry and each consecutive layer is fused starting with the base layer. After the completion of the last layer, the 3D printed part is immersed into another resin so that the 3D printed model gets separated from the liquid polymer. After this process, the bonding between all the layers gets strong in that particular resin and this 3D printed model is now allowed to bake in a UV curing oven. Inside this oven, at the predetermined temperature, all the layers harden up, strength increases, and the desired surface finish is obtained. Thus, all these processes finally lead to the finished object. Now, we are in a position to define the term SL, stereolithography (SL) is outlined as a method of 3D printing during which liquid photopolymer is born-again into 3D objects with the assistance of a Stereolithographic/ SL machine.

2.2. Fused deposition modelling (FDM)

FDM is a procedure that uses thermoplastic filament that has been parched to its melting point and then thrust out layer upon layer toform a 3D object [5,50]. FDM technology was introduced by Scott Crump during the early Nineteen Nineties by Stratasys INC, USA introduced this. The 3D printers used for FDM contain a support base that is related to some degree of freedom and it has an arrangement such that it will move in a vertical direction. Aboard with the bottom plate, there's an associate extruder that connects the filament and is liable for heating of the filament up to its freezing point and so extrudes it layer by layer with the assistance of a nozzle to form the required object. The extruder has the supply to maneuver in all three directions (x, y and z). The reason that it's called fused deposition modeling is that the adjacent layers get consolidated to one another whereas deposition is completed by the extruder and therefore the 3D printer is liable for modeling of the item [57]. Counting on the surface end needed, the ultimate product is dipped in resin as similar in the SL method.

2.3. Powder bed fusion (PBF)

A PBF process uses a thin layer of powder to build a plate and energy source, such as a laser or an electron beam fuses, to fuse the powder in accordance with the geometry of the component made [6]. This process allows the laser to selectively deliquesce powders layer-by-layer, resulting in three-dimensional sections. PBF processes unfold pulverized material over the antecedently joined layer, preparing it for the subsequent layer's process, resulting in a distinct rather than continuous output (nevertheless every layer is conjoined to vicinal layers). A hopper delivers the pulverised powder, which is then spread evenly over the powder bed to create platform space by a roller or brush. Conditions of processes and content used determine the best thickness of each sheet of unfolding powder. Selective Laser Sintering (SLS), Electron Beam Melting (EBM) Selective Laser Melting (SLM), Direct Metal Laser Melting (DMLM) and Direct Metal Laser Sintering (DMLS) are all names of Powder Bed Fusion (PBF) [6].

2.4. Selective laser sintering (SLS)

Dr. Carl Deckard and Dr. Joe Beaman of the University of Texas at Austin invented this method in the mid-nineteen eighties [7]. Selective Laser Sintering (SLS) is a rapid prototyping method that enables the creation of detailed geometry by consolidating consecutive powdered material layers over one another [8]. The solidification of layers takes place with the help of CO_2/ Nitrogen lasers counting on the sort of surface end and fusion needed. During this method, the chemical compound powder is employed for the aim of producing the object. The powder may be of thermoplastic, ceramics, glasses, metals, etc. If the powder used is created from metal, then this method is thought of as Direct Metal Laser Sintering (DMLS). SLS printers are composed of two chambers, the transfer of power takes place from the first chamber to the second one, where actual manufacturing occurs. The powder is heated at a temperature below the melting point of the equivalent substance. The leveler or roller present at the top surfaces the powder by forming layers. After the manufacturing gets completed, finishing operations are required.

2.5. Binder jetting (BJ)

Binder Jetting uses a modified version of Inkjet technology. Massachusetts Institute of Technology (MIT) introduced this process [9]. Instead of using lasers to bind this process, it uses an inkjet to bind the objects. It uses a 2D printer technology in inkjet and goes up in layers forming a 3D project. In this process, with the help of a printhead, moving on two axes, a liquid binder is precisely deposited. This process also begins like any other 3D printing process, that is by creating a 3D drawing and then importing it into printer software. Since constant supply is required during printing, thus, a dispenser ensures that supply by placing powder in it that is to be used. Following the application of a powder sheet of varying thickness, the printing head attaches the binder according to the specification. Before continuing onto the subsequent layer, the solvent containing the binder is desiccated using fluorescent or electric lamps. After that, the powder bed is de-escalated and a new sheet of powder is applied. The binder is then placed in a furnace after the completion of the cycle. Factors such as temperature and time required are dependent on the nature of the binder used. The metals and ceramic parts must undergo sintering, in-filtration, heat treatment, or hot isostatic pressing before being used. However, most of the metals and plastic materials do not require any post-processing and are ready to use as soon as they come out of the printing systems [10,11].

2.6. Direct energy deposition (DED)

Unlike alternative 3D printing processes, this method is employed for repair and maintenance instead of producing components. DED methods make it easier to create materials by melting material when it is deposited [12]. The equipment used for the DED process consists of the deposition head which is an integration of energy source and two powder feed nozzles. In this process, either the metal powder is fed or a thin wire can also be fed. The particular part which is to be fabricated is kept on a platform and in some cases, inert gas tubing is also present. The direction of the deposition head (which is depositing the powder beam and conjointly the laser beam) is a 4 or 5 axis machine. The DED process uses a centered heat supply (electron beam or laser) and then as it solidifies, the material is affixed layer by layer, repairing and making new material objects on the already present products.

2.7. Laminated object manufacturing (LOM)

Helisys Inc.(now Cubic Technologies) in 1991 headquartered in California, commercialised LOM [13]. It is a rapid prototyping process that fabricates models by paper, plastic, or metal laminates which are successfully epoxied together, and therefore the desired form of the item or model is cut employing a laser cutter. The process starts with a sheet joined to a substrate with a heated roller and maneuvering a laser or a mechanical cutter, the following layers are cut accurately and then glued successively i.e (forming followed by bonding) or vice versa (i.e bonding followed by forming) [1]. The platform which has the completed layers move downwards and the contemporary sheet of metal is rolled into the position while the platform goes back to its original position to receive the next layer. The method is to be continued till the prototype is produced. UAM may be a subset of LOM that combines lamination with ultrasonic metal seam connection and CNC milling [14]. Table 1 below comparatively lists down the processes, advantages and disadvantages associated with it.

3. Classification of materials used in various 3D printing processes

After going through the various types that are incorporated into 3D printing the next question that comes to our mind is what are some of those materials that are used in these processes and what are the viability of those materials, what kind of properties do they provide, and for which process and applications we use them. Therefore, based on these parameters material aspects have been elaborated in the following sections specific to each 3D printing process.

3.1. Materials used in stereolithography

Stereolithography, as the term itself explains, is an optical manufacturing method in which UV rays are applied to liquid monomers, also called photopolymer resin, to tie them together to form polymers (enabling them to cross-link together). These polymers are then solidified layer by layer to keep the pattern according to our wishes.

In a method called photopolymerization, SL uses a UV laser to curate liquid resin into hardened plastic [15].

Stereolithography consists of additives namely stabilizers, flexibilities, monomers/oligomers, solvent, photo-initiators, and reactive diluents etc. Table 2 groups together, the materials and their properties along with their applications [16].

3.2. Materials used in fused deposition modeling

These materials have resistance to UV radiation, hardness, translucency, and biocompatibility, among other characteristic properties. This is a widely used AM process that needs a continuous filament which uses thermoplastic content as input [16]. Table 3 details the properties and applications of several material classes and their examples.

3.3. Materials used in selective laser sintering

A laser is used in this method as the power source for the sintering of granulated material (usually polyamide or nylon), as detailed by a three dimensional model the laser is automatically directed at predefined places in space, binding the material together in order to create a

Table 1
Comparison of benefits and limitations of different processes in 3D printing.

S.No.	Process	Advantages	Disadvantages
1	Stereolithography	High surface finish. Complicated parts can be easily manufactured. High accuracy. High thermal durability. 3D printed parts made by this process can serve as patterns for casting.	Less surface area is exposed to Laser (about 0.15mm) which makes it a slow process. High initial investment cost. Overhanging parts are difficult to manufacture. The photosensitive resin is difficult to handle.
2	Fused Deposition Modelling	High surface finish. Less initial investment cost. Complex shapes can be easily made. No scrap generation. High flexibility	A slow process, although the time taken depends on the part to be manufactured. Quality is not as good as SL or SLS.
3	Powder Bed Fusion	Low cost. No external support is required. Wide material choice. Powder recycling.	Post-processing is required. Weak structural properties of materials formed by this process. Time-consuming process.
4	Selective Laser Sintering	Complex parts which cannot be manufactured by the above two processes can be manufactured easily using SLS. Does not require any external support. Suitable for mass production. Good accuracy and precision.	The high cost of manufacturing Requires post-processing Large surfaces, tiny holes are difficult to manufacture accurately.
5	Binder Jetting	High resolution. High surface finish. No need for post-processing. Printing can be done over a large area. Multiple printings at one time.	Limited materials are available. Low part strength. The substrate is required for printing.
6	Direct Energy Deposition	Denser parts creation is possible. Allows directional solidification which enhances features. Utilized effectively for repairing and refurbishing components.	Time-consuming process. Poor resolution and surface finish. Limited material is available.
7	Laminated Object Manufacturing	External support is not required. Inexpensive. Quick process. Suitable for large parts.	Post-processing is required Poor dimensional accuracy. Poor surface finish Complex parts are difficult to manufacture.

Table 2
Materials, properties and applications in SL method.

Materials	Properties	Applications/ Industries
DC 100	Lesser shrinkage with higher accuracy.	Used for the casting of patterns for pieces of jewelry.
DC 500	Like wax in nature and can easily burn out.	For the making of precise and thinner wire patterns of jewellery which can't be easily copied using methods for molding rubber.
DL 350	Highly flexible and resistant to fatigue and chemicals etc. Similar to polypropylene.	Used to produce parts for industrial as well as general purposes.
DL 360	Strong and transparent in nature.	Produces parts for general purposes and industrial uses which require transparent properties.
AB 001	Provides good strength and stiffness and electrical characteristics.	Used for producing parts that are strong and smooth in nature.
GM 08	Highly flexible, strong and elastic, along with transparency comprises its nature.	Produces parts that don't require further finishing operations.
DM 210	Great surface qualities and including ceramic-type properties.	Used for jewellery patterns that require liquid silicone that can be extracted quite easily from rubber.

strong structure. It is comparable to Selective laser melting (SLM), working on the same principle but requiring different technical conditions. This laser is used over powders which have lesser melting or sintering temperature, on the other hand, a liquid binder is otherwise used. SLS is used with various polymers, alloys, and metal powders while SLM is generally applicable in case of certain metals like steel and aluminum [25]. Table 4 presents a comparative study of materials incorporated in this process.

3.4. Materials used in powder bed fusion

The method consists of fine layers of quiet minute particles of powder, which are dispersed and tightly bound on a platform [1]. PBF is one of the rapid manufacturing processes in which a thermal source for example a laser is used to initiate partial or complete merging between particles of powder and is rolled over with a roller or blade re-coater to further smoothen the powder layer. The combining process of the PBF method includes melting and sintering [16]. Examples of PBF methods are SLS process [30,31], Electron Beam Melting (EBM) method [32,33], and selective laser melting (SLM) method. The materials, properties, and applications incorporated in PBF are mentioned below in Table 5 and Table 6 [16].

3.5. Materials used in binder jetting

Binder jet AM process that is also known as "Powder bed and inkjet" & "drop-on-powder" printing. Their examples of material are summarized in Table 7 below [16].

3.6. Materials used in direct energy deposition

In one fundamental aspect, the operating concept of a DED process differs from that of PBF in that, here the high dense and powerful laser concentrates on a steady stream of powdered material that are laid down on the substance itself instead of a layer of metallic powder that are pre-deposited [16]. The following Table 8 presents the comparative study of materials and their properties [34].

3.7. Materials used in laminated object manufacturing

The two major types of sheet lamination methods are defined as follows, first one is such that in this process laser is used to cut the material sheets and the process is known as Laminated Object Manufacturing (LOM) or the second one in which these sheets are joined by ultrasound

Table 3
Materials, properties, and applications in FDM method.

Material class	Materials	Properties	Applications
Thermoplastic Polymer	Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS), ABSi, High Density Polyethylene (HDPE), Polyphenylsulfone (PPSF), Polycarbonates (PC), Polyethylene terephthalate glycol-modified (PETG), Ultem 9085, Polytetrafluoroethylene (PTFE), Polyether Ether Ketone (PEEK), Recycled Plastics, Acrylonitrile Styrene Acrylate (ASA), Nylon 12, etc.[16]	Properties associated with this include toughness and strength, UV stability, good chemical resistance, and high fatigue resistance along with the high impact strength. They possess high tensile and flexural strength etc.[16]	Because of their great thermal resistance properties, they are suitable for aerospace and aerodynamics application.
Polymer Matrix Composites	Glass Fiber Reinforced plastic (GFRP), Carbon Fiber Reinforced Polymer (CFRP).[17]	Compatibility with toughness, ductility, yield strength, etc.	Constructional applications.
Ceramic Slurries and Clay	Alumina, Zirconia, Kaolin.[18]	Chemical and physical stability, heat resistance, and compatible thermal conductivity, strength and hardness.	General purpose uses along with the applications in dental field as well.
Green Ceramic/ Binder Mixture	Zirconia, Calcium phosphate.[19]	Resistance to chemicals and corrosion, great compatibility with respect to fracture toughness, hardness, wear-resistance, and thermal resistance good frictional behavior, lower electrical and thermal conductivity and non-magnetic in nature etc.[20]	Structures suitable for bone substitute scaffolds[19], and for making piezoelectric components.
Green Metal/ Binder Mixture	Stainless steel, Titanium, Inconel.[21]	Providing binder viscosity, flowability, greater sintered density, leads to the homogeneous microstructure of parts.[21] Results in strong, light and corrosion resistant properties etc.	For the manufacturing of mechanical parts used in tooling and fixtures etc.
Food pastes	Sugars and Chocolates	Flowability	Cooking
Biological Materials	Bioink [23]	Easy to print, with desired mechanical properties, can be easily biodegraded, and we can easily install modifiable functional groups on the surface, the better ability of post-printing maturation, biologically compatible and capable of retaining the 3D printed structure after it is printed.[24]	Bioprinted organs and scaffolds.

Table 4
Materials, properties, and applications in SLS method.

Laser	Materials	Properties	Applications
CO2/N2	Polymers including Polyamides [26], Polycarbonates, Polystyrene (PS), Thermoplastic Elastomer (TPE), Polyaryletherketone (PAEK)	Characterized by an ideal sintering behavior like a semi-crystalline thermoplastic [26], high toughness, thermal stability, etc.	Prototype making in the early design process, automobile parts, hardware, etc.
Nd:YAG	Ceramics	Great hardenability, mechanical strength, better thermal and chemical stability, and usable thermal, electrical, optical, and magnetic characteristics.[27]	Aeronautics, biomedical, metallurgical application.[28]
Yb-Fiber	Glasses such as fused Silica, Borosilicate Glasses.[29]	Chemical resistance, thermal stability, etc.[29]	Glass filters, medical and chemical field.[29]
	Metals	Good thermal conductivity hence, used in case of selective laser melting	Varied applications in various industries.

Table 5
Materials, properties and applications in SLM method.

Materials	Properties	Applications
Titanium (Ti)	Resistance to Corrosion and thermal expansion with great biological compatibility, along with the high strength and lower density.	Its applications are included in but not limited to design, medical, automotive, aerospace, marine industry, and jewelry industries, etc.
Stainless Steel	Increased resistance to wear and tear, corrosion, along with compatible ductility, hardness, and hardenability.	These materials have extensive application in automotive industry, maritime and medical technology, toolmaking and in varied areas of mechanical engineering.
Aluminium (Al)	Light metal with lower density and better electrical conductivity along with alloying properties and easy to process abilities.	These components are used in aerospace engineering, automotive industry, in the area of prototype construction, marked with complicated geometries.
Cobalt-Chrome	Biologically compatible, with increased hardness, corrosion resistance with comparable strength and ductility.	In the medical and dental field, and industries requiring greater thermal resistant properties for example in jet engines.
Nickel based alloys	Great weldability and hardenability along with the resistance to corrosion and outstanding mechanical strength.	Used in aerospace engineering and fields requiring thermal resistant properties also have applications in tool making.

Table 6
Materials, properties and applications in EBM method.

Materials	Properties	Applications
Titanium	Resistance to Corrosion and thermal expansion with great biological compatibility, along with high strength and lower density.	Building of prototypes for aerospace and racing fields, in the marine, chemical industry and also used in medical applications such as orthopedic implants and prosthesis.
Cobalt- Chrome	Increased strength and wear resistance, biologically compatible, with thermal capabilities.	In power generation, orthopedics, aerospace and dental fields.

Table 7
Materials, properties and applications in BJ method.

Materials	Properties	Applications
Stainless steel	Resistant to heat and corrosion with greater tensile strength.	Used for parts of pump, drilling and mining machinery.
Ceramic beads	Highly permeable as well as better thermal properties.	Steel alloys are casted using this and can also be used for printing of cores that have to bear high metallostatic forces and subsequent stress conditions during casting.
Inconel alloy	Supplementing the product with good mechanical properties and even greater density.	Used for the manufacturing of gas turbine blades, for producing steam generators used in pressurized nuclear water reactors, seals and also in pressure vessels, these are widely applicable in the aerospace industry.
Iron	Provides better mechanical properties and is also excellent wear resistant.	Applications are in the production and repairing of automotive components, tooling, and also in machine tools, along with this they are also popular in decorative hardware.

Table 8
Materials, properties and applications in DED method.

Materials	Properties	Applications
Titanium	Resistance to corrosion and thermal expansion with great biological compatibility, along with high strength and lower density.	Used for repairing works in the automation and aerospace industry.
Aluminium	Light metal with lower density and better electrical conductivity with alloying properties and easy to process abilities.	Filling of cracks and refitting of manufactured parts.
Stainless steel	Resistant to heat and corrosion with greater tensile strength.	Repairing of turbine engines, and other such complex applications.
Copper	Malleable, ductile, and better surface finish.	Industrial applications.
Inconel, Ceramics	Good mechanical properties and greater density.	Aerospace, biomedical applications.

Table 9
Materials, properties and applications in LOM method.

Materials	Properties	Applications
Polymer	Good thermal conductivity, adhesive bonding.	Paper industry.
Composites	High modulus, low density, excellent resistance to fatigue, etc.	Paper industry etc.
Ceramics	Chemical and physical stability, resistance to heat, and compatible thermal conductivity, strength, and hardness.	Foundry and forging industries.
Paper	Good conductor of electricity.	Electronics industry.
Metal Filles Tapes, Metal Rolls	Better mechanical properties.	Applicable in smart structures.

and the process is described as ultrasonic additive manufacturing (UAM) [16]. The following Table 9 is the culmination of some of the materials along with their properties and applications [1].

4. Applications of 3D printing

Each of the processes discussed so far is of utmost use to achieve the manufacturing of products in the least possible time with minimum wastage. Also, the processes aid in forming complex structures with supreme quality at enormous ease. Industries are being modernized and revolutionized with the help of 3D printing. The mode of manufacturing is gradually shifting from traditional to non-conventional processes (3D printing). It requires intensive knowledge of materials and their respective properties. With the current knowledge of materials and processes, some modifications have been done in the traditional techniques using 3D printing. In this section, we will discuss in brief some of those applications of various processes discussed so far. Fig. 2 collectively lays out the applications discussed in the text.

4.1. . Applications of stereolithography

4.1.1. Fabrication of heart valve scaffold

Tissue engineering of heart valves is reflected in a new experimental principle to manufacture viable and functional heart valve tissue from autologous cells. In order to make a heart valve scaffold, a polymeric material is used. SL is an integral technique of tissue engineering of the heart valve. It forms feasible tissues which are capable of growing inside the human body just like the actual tissues. The stereolithic models are created using X-ray computed tomography and other software to create biodegradable and biocompatible scaffolds. These are human-like and accepted by the human body easily. Presently, non-living mechanical valves are used which do not have the ability to grow thus the chances of a body rejecting them are high. Thus, this new technique overcomes these limitations [35].

4.1.2. Fabrication of lithium disilicate glass-ceramic for dental applications

Natural teeth, resulting in a certain degree of translucency, partly refract, absorb and relay light. The lack of transparency in metal ceramics in the previous field is particularly noticeable and therefore unfavourable, leading to the creation of all-ceramic bridges. Materials made of glass and ceramic are usually used in the dental industry for personalized and cosmetic restorations. It is usually processed with the AM technology processing of lithium disilicate providing highly dense (>99 percent), complete ceramic components that meet the criteria for dental restoration use. Lithium disilicate glass-ceramic is synthesized by using the melting technique in the SiO2-Li2O-Al2O3-K2O-P2O5 glass system and heated treatment samples at the crystallization temperature of that glass. The fabricated glass has excellent mechanical properties, such as high strength, which allows for repeatable printing and de-binding of crowns and bridges, especially in the anterior tooth area [36].

4.2. Applications of fused deposition modeling

4.2.1. Drug delivery

The term "drug distribution" refers to nanoparticle-based procedures, formulations, systems, and technologies that are used to safely distribute medicinal substances within the body as required to achieve the desired therapeutic result while remaining healthy. In the manufacture of individualized tablets, FDM based 3D printing provides major advantages such as simplification of manufacturing processes, enhancements of inherent properties, and distribution of dosage types. FDM is an inexpensive 3D printing technique based on extrusion that produces solid geometries by depositing layer-by-layer materials. Since FDM is a thermo-based process, heat transfer characteristics and melted polymer rheol-

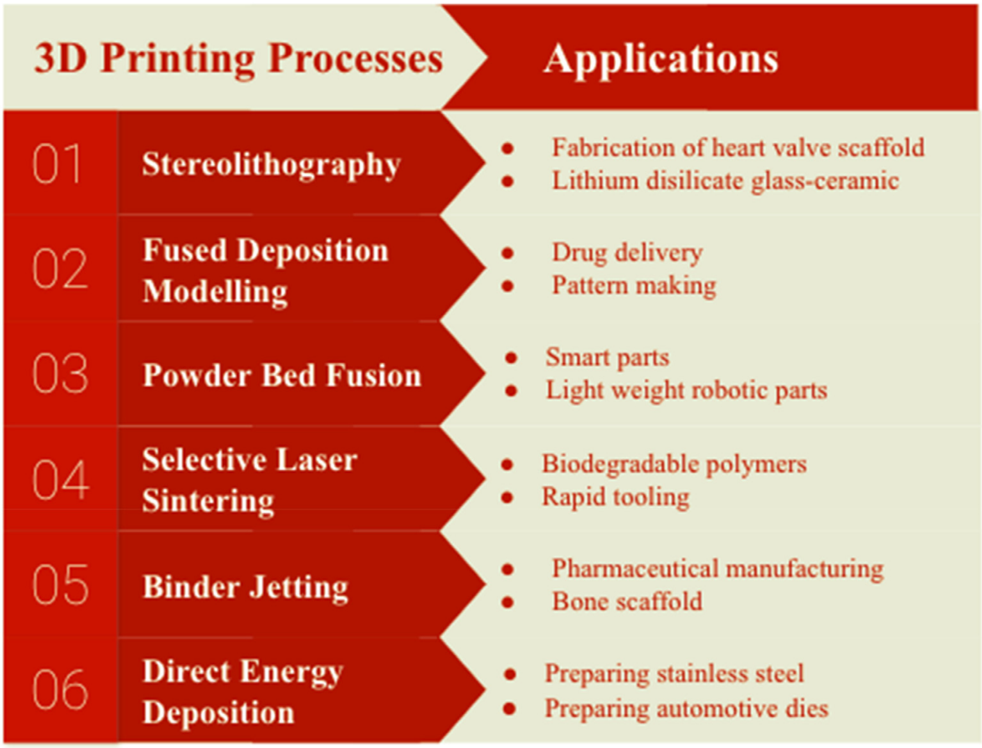

Fig. 2. Various applications of 3D printing processes.

ogy are critical factors to consider when selecting a material for the job. Thermoplastic polymers dominate FDM applications due to their low melting point. The most widely used polymers are polyvinyl alcohol for FDM drug delivery systems [37,38].

4.2.2. Production of patterns for investment casting

Nowadays, the specifications of the users are premium quality of the inexpensive components that too in a reduced span of time, which is a major challenge such that the operating parameters of the respective machines need to be streamlined. The FDM process has been used effectively in industrial casting to produce wax and wax forms at reasonable prices. In investment casting and component assembly, it's crucial to have a good surface finish and dimensional precision. The mould duplicates whatever surface state the master pattern presents. As a result, in order to manufacture good castings, the master pattern created by FDM must have a good surface finish. The most popular non-wax material used to produce casting patterns in FDM is styrene-acrylonitrile-butadiene. The wax and Acrylonitrile Butadiene Styrene patterns created using the FDM system have both proved to be effective at burning out the ceramic shell with minor improvements to the foundry's normal processes. Wax gates and vents are connected by foundry by ABS pattern in investment casting and are made as an integral part of the pattern [39].

4.3. Applications of powder bed fusion

4.3.1. Direct metal laser sintering in order to fabricate lightweight robotic structural parts

One of the AM techniques, direct metal laser sintering (also known as laser powder bed fusion), utilizes a laser source to manufacture near-net-shaped parts directly by using CAD data by melting various layers together. Metals formed via near-net type processing technologies yield materials that are almost identical to the final size and shape, requiring just a few finishing steps. This approach is used in an aluminum alloy to manufacture robotic lightweight components. Thanks to the very fine microstructure, very interesting mechanical properties, such as high hardness and strength have been achieved. In a single development stage, the lightweight finger exoskeleton with the joints was manufactured. It is also shaped with all the mechanical properties that are desired [40].

4.3.2. Fabrication of smart parts using PBF

Energy device modules with embedded sensors or smart components can be a route to feedback on the performance of the real-time system and in situ monitoring during operation. Due to improvements in the component design needed for sensor positioning, conventional surface contact or cavity sensors increase the risk of disrupting the regular functioning of energy systems. Smart parts manufacturing using AM technology will make it possible to flexibly incorporate a sensor into a structure without sacrificing the structure and/or functionality. The layer-by-layer approach enables sensors to be mounted inside a part at any desired location, providing unparalleled access to previously inaccessible areas within the volume of a part. Issues such as component registration and bond strength of the interface resulting from the stop-and-go process are also being studied to further refine the process of smart part manufacturing. AM technology will revolutionize the design of metal parts by enabling embedded sensors to add functionality within sensitive areas of a part that are usually exposed to high temperatures [41].

4.4. Applications of direct energy deposition

4.4.1. Repairing stainless steel

For manufacturing 316L stainless steel parts, PBF, a 3D printing technology, is frequently used. Where these PBF pieces are seriously degraded or worn during operation, traditional repair processes can help. However, there are many disadvantages to these techniques, such as the formation of a large zone that is affected by heat and repair defects. In contrast, DED gives strong metallurgical bonds, minimal dilution, and a small heat-affected region. Due to uneven nucleation, the microstructure of the restored region consists predominantly of complex dendrite structures. Also, the deposition zone micro-hardness is greater than that

Table. 10
3D printing process, applications, materials, benefits and drawbacks.

Methods	Materials	Applications	Benefits	Drawbacks
Fused Deposition Modelling	Continuous filaments of thermoplastic polymers, fiber-reinforced continuous polymerics.	Rapid prototyping of advanced composite parts and toys.	Reduced cost, increased speed, easy to use.	Poor mechanical properties, confined materials.
Powder Bed Fusion	Compressed fine powder components, limited polymerics, metals & alloys .	Medicinal, electronic, aviation and lightweight structures.	High resolution, good quality.	Prints slowly, expensive cost, high porosity.
Laminated Object Manufacturing	Polymer,metal-filled tapes, ceramics, metal rolls and composites.	Paper making, foundry sector, smart structures.	Reduced tooling, economical, perfect for generating larger systems.	Low consistency of the surface and dimensional precision, manufacturing restriction of complicated forms.
Direct Energy Deposition	Alloys and metals in the form of wire or powder, polymers and ceramics.	Aerospace, retrofitting, repair, cladding, biomedical.	Low cost and time, good mechanical properties, accurate regulation of composition, outstanding for repair	Low accuracy, poor surface finish, limitation for complex printing with fine details & shapes.
Stereolithography	A photo-active resin monomers, polymer- ceramics hybrid.	Biomedical models.	High resolution, premium-quality results.	Very few materials, prints slowly, expensive costs.
Selective Laser Sintering	Nylon, thermoplastic, flame retardant nylon.	Electronics, packaging, connectors.	Durable functional parts with high complex geometries.	Thermal distortion, rough surface, shrinking, and warping of fabricated parts.
Binder Jetting	Metals, sand and ceramics that are granular in shape.	Fabrication of full-color prototype and wide sand casting cores and moulds.	Low-cost, quick, simple and cheap.	Low density, shrinkage without infiltration.

of the original hot-rolled specimens and is comparable to the PBF specimens [42].

4.4.2. Repairing automotive dies

Tungsten inert gas (TIG) welding has long been used to restore dies used in the manufacture of vehicle engines, but it only lasts 20.8 percent of the original die life span before needing to be repaired again. A hybrid repair method has been developed, which entails removing damaged areas and then reconstructing them additively using powder-blown DED. The DED-repaired die lasted the same amount of time as the original die. Since further maintenance was needed earlier, DED repair limited the need for emergency repairs and unplanned downtime on the line. The restored DED dies now last as long cycles as the original die, thanks to this invention [43].

4.5. Applications of selective laser sintering

4.5.1. Applications for rapid tooling

Rapid development has emerged as a primary enabler for shortening product time to market and as a productivity-boosting technique. The SLS process is one of the most common rapid prototyping techniques. The SLS approach is used to quickly prototype the modules using a variety of techniques. The material used for the manufacture of tooling inserts is copper polyamide (they are cheaper than the other materials), on the other hand all the nylon-based materials are used to make prototypes for manufacturing or parts with functional features like hinges, chips, and so on. The SLS technique used to create copper polyamide tooling inserts can be used to make a limited number of pre-production parts using the same material and manufacturing methods as the final production parts. Effective use of the rapid instrument process requires detailed knowledge of design characteristics [44].

4.5.2. Selective laser sintering of biodegradable polymers for tissue engineering applications

Tissue Engineering (TE) has progressed due to the potential to use biological substitutes to repair destroyed or damaged tissues. It is an area of biomedical engineering that is increasing in depth and relevance. Temporary three-dimensional scaffolds are often used to direct cell proliferation in anchorage-based cell types. Because of their potential to produce structures of complex macro- and micro-architectures, computer-controlled manufacturing techniques like Rapid Prototyping (RP) procedures have been recognised as having an advantage over traditional manual-based scaffold manufacturing techniques. Despite the enormous RP processing capacities for scaffold building, commercially available RP modelling materials are not biocompatible and are not ideal for direct use of scaffold development. Poly Ether Ether Ketone (PEEK), Poly Vinyl Alcohol (PVA), Poly CaproLactone (PCL), and Poly L-Lactic Acid (PLLA), as well as a bioceramic, hydroxyapatite, are among the biocompatible polymers being produced. The parameters of the SLS technique have been tweaked to work with these materials. A scanning electron microscope is used to examine SLS-fabricated scaffold specimens. The micrographs show that they can be used to make TE scaffolds and that the SLS method can create highly porous scaffolds for TE applications [45].

4.6. Applications of binder jetting

4.6.1. Binder jet in pharmaceutical manufacturing

Binder jet printing is the pharmaceutical industry's most promising three-dimensional printing technique to date. In 2015, the Food and Drug Administration (FDA) revised the binder jet process to facilitate the production of Spritam (the first 3D printed tablet) as an alternative mass manufacturing technique. Over the next decade, binder jet printing is expected to have a major effect on formulation production. Binder jet printing, in particular, has the benefit of allowing manufacturers to produce oral dosage forms with a wide range of release characteristics, from rapid dissolution to controlled release platforms. Despite its positive characteristics, it does have some drawbacks [46].

4.6.2. Bone scaffold and implant application of binder jet process

Scaffolds are biocompatible three-dimensional structures that mimic the extracellular matrix's properties (mechanical support, cellular activity, and protein production) and provide a platform for cell attachment and bone tissue growth. Their findings are based on chemistry, pore size, pore volume, and mechanical ability. Stainless steel and tricalcium phosphate are combined to produce a hybrid d and used in various volume fractions to make sections of various densities using the Binder Jet AM technique. Metals and alloys, ceramics, and polymers are the most popular biomaterials for implants. Calcium phosphates have the greatest biocompatibility and properties similar to natural bones. However, they have poor fracture toughness and tensile strength that limits their application to bioimplants. The main manufacturing strategy for the binder jet process is as follows: (a) The CAD file is separated into layers, and an STL file is generated from each layer. (b) A thin spread of powder sprinkled over the surface of a powder bed marks the start of each layer; (c) A binder material selectively binds particles where the product is to be formed using ink-jet printing technology; (d) A piston that covers the powder bed and lowers the part-in-progress so that the next powder sheet can be extended and selectively joined; (e) This layer-by-layer procedure continues until the component is complete; (f) After thermal treatment, the unbound powder is separated and the metal powder is sintered together.[47].

Table 10 lists the various 3D Printing applications, benefits and drawbacks associated with various 3D Printing technologies [48,49].

5. 3D Printing and industry 4.0

The 4th Industrial revolution or Industry 4.0 encompasses a variety of technologies and this German concept is going to change the manufacturing industry. It involves the various concepts such as inter-machine communication, Internet of Things (IoT) so as to enable automation and develop machines with minimum technical intervention by humans [51,52]. Keeping in view the technical aspects of 3D printing and the goals of Industry 4.0, 3D printing is an important component in the concept of Industry 4.0. Further, the recent advancements in the area of 4D Printing wherein development of smart materials has become possible has further increased the role of additive manufacturing in the industry 4.0. While the concept of Industry 4.0 also involves digitalization of industries, 3D printing can play a vital role in the industry 4.0 scenario. Industry 4.0 also aims to develop an industrial set up wherein, the systems are autonomous and there is sufficient interconnectivity amongst the employees, machines, suppliers and the end users. In the aforementioned discussion, we have included the different materials, processes and technologies related to 3D Printing. The various benefits of 3D Printing such as digital data transfer, remote access, need for minimum human intervention, ability to develop complex geometries and smart materials, less wastage, less post processing requirement shall help to achieve the goals of Industry 4.0 [53].

6. Conclusions

3D printing being a sustainable technology has a potential to replace conventional technologies.

3D Printing apart from being cost effective is also environment friendly, hence can help to mitigate the adverse effects of industrialization on the environment.

Based on the literature studied it can be concluded that a number of 3D printing technologies have evolved having different materials compatible with them. Each 3D printing technology is associated with different advantages and disadvantages.

Apart from the capability to handle complex and intricate shapes, 3D printed parts require very less post processing.

Amongst the 3D Printing technologies, FDM is the most common technology but is more suited for polymeric materials. The powder based technologies such as SLS face various issues such as difficulty in transportation and storage of powders.

7. Future recommendations

Future studies can be undertaken to improve the 3D printing process and to make the processes more efficient and compatible with a wide variety of materials.

The effect of various process parameters in different technologies can be studied on the mechanical properties of the developed parts.

The applications of these parts can be widened by making the 3D printing processes more user friendly, efficient and cost effective.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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