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A Review on Additive Manufacturing Process

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The new generation of manufacturing methods that extends over subtractive type is introduced by additive manufacturing. The benefit of additive manufacturing is that it directly uses 3*D* CAD models to create three-dimensional objects by adding more layers of material and joining them together. It is commonly utilized in the motor sector, aerospace industry, biomedical applications, prototyping, fashion such as creation of custom-made jewellery, accessories, and even clothing and many more. Additive manufacturing technology is extensively employed because of its numerous benefits, which include multimaterial goods, improved product ergonomics, on-demand manufacturing, short production runs, and so on. Various fabricating methods, which include rapid prototyping, stereolithography, electron-beam melting, fused-deposition modelling, 3*D* printing (3*D*P), selective laser sintering, *etc*. Understanding the complex relationships between fundamental process parameters, flaws, and the finished product of the AM process depends heavily on mechanical testing. Because of the growing use of additive manufacturing in a variety of industries, it is critical to evaluate the mechanical performance of the components created.

Key words: additive manufacturing, mechanical properties, DMLM, EBM.

Методи виробництва нового покоління, які поширюються на субтрактивний штамп, представлено адитивним виробництвом. Перевага адитивного виробництва полягає в тому, що в ньому безпосередньо використовуються 3*D*-CAD-моделі для створення тривимірних об'єктів шляхом додавання

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шарів матеріялу та з'єднання їх разом. Такий підхід широко використовується в автомобільній та аерокосмічній промисловостях, біомедицині, для створення прототипів, в моді, наприклад, для створення індивідуальних прикрас, аксесуарів і навіть одягу. Адитивне виробництво широко використовується завдяки своїм численним перевагам, серед яких — можливість виробляти багатокомпонентні товари, поліпшена ергономіка продукту, виробництво на вимогу, короткі виробничі цикли тощо. Використовуються різноманітні методи виготовлення, зокрема такі, як швидке прототипування, стереолітографія, топлення електронним променем, моделювання натоплювання, 3*D*-друкування, селективне лазерне спікання тощо. Розуміння складних зв'язків між основними параметрами процесу, недоліками та кінцевим продуктом процесів адитивного виробництва значною мірою залежить від механічних випробувань. Через зростаюче використання адитивного виробництва в різних галузях промисловости критично важливо оцінювати механічні характеристики створених компонентів.

Ключові слова: адитивне виробництво, механічні властивості, пряме лазерне топлення металу, електронно-променеве топлення.

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1. INTRODUCTION

The fundamental idea behind additive manufacturing is that it directly uses CAD-generated three-dimensional models to build three-dimensional objects by layering and fused materials. The notion that the invention of 3*D* printing has transformed the industrial world in such a manner as no other product has achieved this tremendous success over the past 35 years is supported by more than adequate statistics.

Although they were first known as rapid prototyping in the context of product development, these technologies have advanced significantly in recent years, going from manufacturing prototypes to production-ready parts. These technologies are also known as '3*D* printing', a term that MIT used for inkjet printing focused on additive manufacturing (AM), which they developed in the 1990s. As a result, these terminologies are inadequate to characterize more recent technological developments in the industry.

2. HISTORY

The fabrication of components with intricate, multiscale geometries, including interior structures, is possible with AM [1]. Moreover, multi-material AM provides programmable material heterogeneity *via* discrete layers including composition gradients [2]. The ISO/ASTM 52900:2015(E) standard specifies [3]. AM processes are defined as 'creating three-dimensional components by sequential addition of material' [4]. Seven families of AM technologies have been established, each of which is based on the way that additive processes are joined: vat photopolymerization, powder bed fusion, binder jetting, material jetting, sheet lamination, material extrusion, and directed energy deposition. [5] AM can be done in one step (referred to as 'direct') or through a number of steps (referred to as 'in-direct') [5, 6].

A laser is used in the stereolithography (SL) process to harden tiny layers of UV light-sensitive liquid polymers pioneered the use of AM for commercial purposes in 1987. World's first available commercially AM machine and also the progenitor of the earlier well liked SLA 250 machine was the SLA-1, which acted like a beta testing system (SLA is an abbreviation for stereolithography apparatus). The Viper S–L–A product has long since taken the place of the SLA 250.

The first generation with acrylate resins was released in 1988. Due to collaboration with 3*D* and Ciba-Geigy, SL materials were made possible. In the same year, DuPont developed materials and the Somos SL tool. Loctite also entered in SL resin market in late 1980s, but it left the industry in 1993.

NTT Data CMET and Sony/D-MEC of Japan commercialised stereolithography variants around 1988 and 1989, respectively, before 3*D* Systems began selling SL in the US.

Solid object ultraviolet plotter (SOUP), a subsidiary of Nabtesco, was the name given to its system, while Solid Creation System was the name given to Sony/D-(now MEC's D-MEC) product (SCS). SL systems for D-MEC were no longer produced by Sony after 2007.

Asahi Denka Kogyo introduced the first epoxy resin for such CMET SL machine in 1988. The following year, DSM Desotech and Japan Synthetic Rubber (now JSR Corp.) began offering resins for such machines.

German company Electro Optical Systems (EOS) sold the very first stereolithography system in 1990.

The Mark 1000 SL system, made by Quadrax that year, utilized visible light resin. The visible light resin product was introduced the following year by Imperial Chemical Industries for use with the Mark 1000. About a year later, when Quadrax collapsed as a result of a legal dispute with 3D System, ICI ceased selling its resin. Figure 1 below depicts the timeline of developments of additive manufacturing.

3. TYPES OF AM

3.1. Powder Bed Fusion

Powder bed melting process (also known as PBF) includes direct metal laser sintering (DMLS), selective laser sintering (SLS), selective thermal sintering (SHS), and electron beam melting (EBM). This technology is used by a lot of people. Metal melting using lasers (DMLM) applies subsequent material layers over the top of freshly fused fine substance layers that are dispersed across a platform to use an electron as well as laser beam [7].

Until the component has the desired geometry, successive layers are added. Powder bed fusion produces components with excellent quality and precise resolution.

3.2. Direct Energy Deposition

Direct energy deposition melts a material as it is applied because it uses focused heat energy. For the purpose of melting the raw material, powder, wire, or filament of metal, an electron beam-gun as well as laser positioned on a 4-axis and 5-axis arm is required. Polymers, ceramics, and metals are just a few of the materials that can be employed with the procedure.

3.3. Material Extrusion

The most used AM technique is material extrusion. A heating nozzle linked to a movable arm extrudes or stretches the rolled polymer. Although beds as well as nozzles move both horizontally and vertically the molten material would be layered layer after layer [8]. By carefully controlling the temperature or by using chemical adhesives, proper bonding between layers can be achieved. This approach has low costs

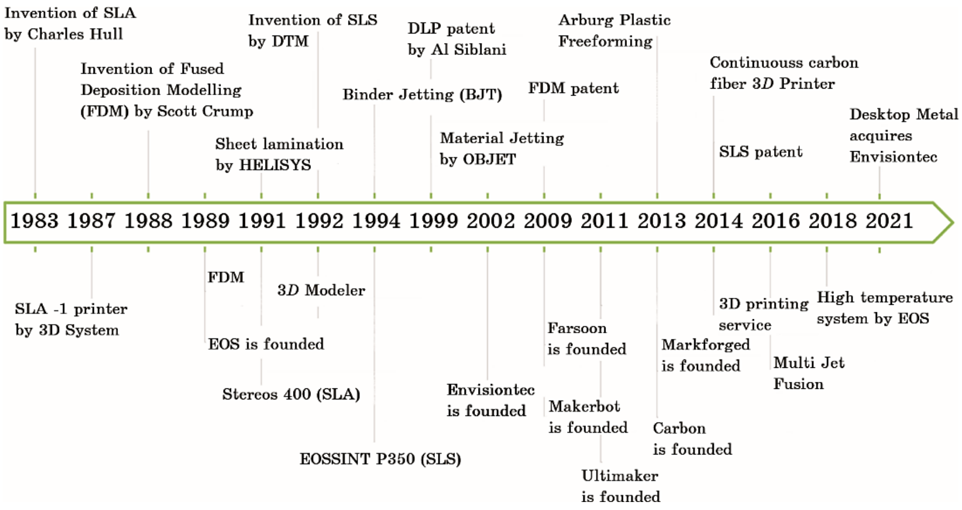

Fig. 1. Timeline of developments in AM.

and a quick turnaround time.

3.4. Stereo Lithography

By using photo polymerization and stereo lithography, also known as SLA, models, prototypes, and patterns are built up layer after layer. The body of the sculpture is created through the photo polymerization process, in which light joins the molecular chains to create a polymer [9].

3.5. Material Jetting

Material jetting, an AM process, injects liquid wax materials onto such a build platform using an inkjet print head. Layers can be placed on top of one other while the material hardens and cools. To make $3D$ objects, print heads generally oscillate the x, y, and z axes. When this object is cooled or exposed to UV radiation, the layers will cure. This method has benefits including printing on several materials and excellent surface finishing [10, 11].

3.6. Binder Jetting

A print head with in binder injection method includes additional possibilities surrounding layers on metal powder and layers of liquid behaviour, in contrast to the material injection process. Inkjet print heads cover a thin layer of powder with a liquid binder. By gluing bits of material together, you may build pieces layer by layer. Binder injection technology can be applied to make components out of a wide range of materials and colours [12, 13].

3.7. Sheet Lamination

Laminate object manufacturing (LOM) and ultrasonic additive manufacturing are the two processes available for laminating sheets (UAM). Although LOM utilizes alternating layers on paper and adhesive, UAM connects thin metal plates using ultrasonic technology. Using LOM, it is easy to make models of objects that are perfect for aesthetic or visual modelling. This approach has low costs and a quick turnaround time [14, 15].

4. PROCESSES

4.1. Rapid Prototyping

Rapid prototyping was developed in the 1980s to create models and prototype components, reducing time and money, allowing for human involvement, and improving product development. Rapid-prototyping was invented to broaden the scope of the conditions evaluated throughout the prototyping process, and it is today utilized to create final products. CAD, CAM, and CNC allowed rapid production, enabling the printing of three-dimensional [16, 17]. Figure 2 below shows the schematic flow chart of rapid prototyping.

4.2. Electron Beam Melting

Electron beam melting (EBM) is a derivative or variant of SLS. Although this method is still quite young, it is expanding quickly. This utilizes a maximum of 60 kV to propel an electron laser beam, melting the powder in this procedure. Since the technique is designed to create metal parts, oxidation problems are avoided by operating in a high vacuum chamber. The method is very identical to SLS aside from this; a wide range of prealloyed metals can also be processed by EBM [18]. Since everything is done in a high vacuum environment, manufacturing in space is one of the method potential future applications. Figure 3 below shows the schematic representation of Electron Beam Melting EBM process.

4.3. Stereo Lithography

Stereo lithography (SL) is a liquid-based method of curing or hardening a photosensitive polymer in the presence of an ultraviolet laser. It begins with a CAD model and is transferred to an STL file [19]. A platform is built to support the overhanging structures and anchor the work. When the layer is complete, the extra water is drained and reused. MicroSL is a higher resolution technology that allows for layer thicknesses of less than 10 m. The process of converting a liquid mon-

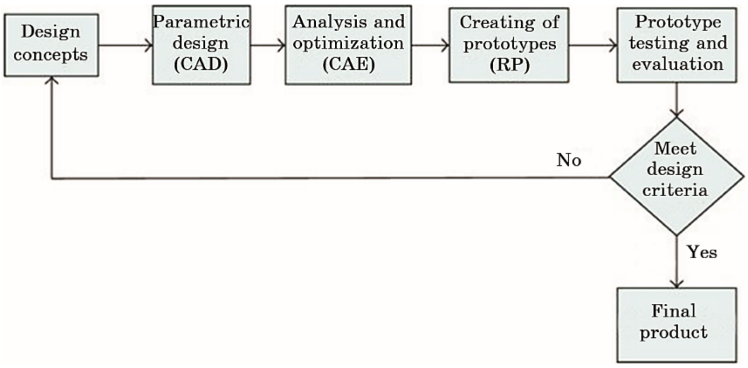

Fig. 2. Flowchart of rapid prototyping.

omer or polymer into a solidified polymer by using UV light is known as photopolymerization. Figure 4 below depicts the schematic representation of SL process.

4.4. Selective Laser Sintering

A powder is fused or sintered using a laser of carbon dioxide in this three-dimensional printing method. The temperature within the chamber has nearly reached the material's melting point. For each layer that the design called for, the laser fuses the powder in a precise location. When a layer is done, a piston that controls the bed lowers it by the same amount as the layer thickness, causing the particles to float around loosely. Materials that could be employed in this procedure include a wide range, including: metals, metal alloys, metal and polymer mixtures, and metal and ceramic alloys are among the materials that can be used. Acrylic styrene and polyamide (nylon) are two examples of polymers that could be utilized; they almost exactly match the mechanical characteristics of the injected portions. Composites or reinforced polymers can be created by combining polyamide and fiberglass. Metals like copper could be used to reinforce them as well. A binder is important for metals. This might be a polymer binder that will be removed later, or it could be a mix of metals with varying melting tem-

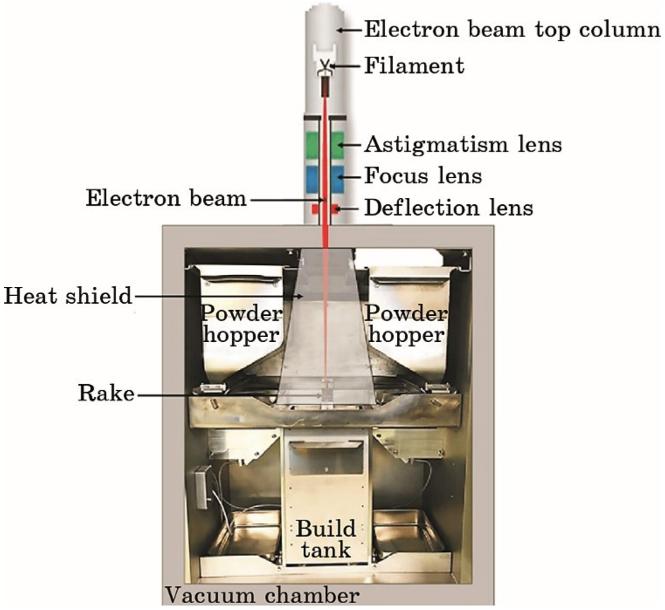

Fig. 3. Schematic representation of electron beam melting.

peratures. Alumina components with high strength can be constructed using the organic binder polyvinyl alcohol. The variety of materials that can be used is one of this technology's key benefits. Powder left over can be recycled. The limitations of accuracy due to material particle size, force the need to conduct the process in an inert gas atmosphere to prevent oxidation, and the requirement that the procedure is carried out at a constant temperature close to the melting point are the drawbacks. This technology is also known as direct metal laser sintering. Figure 5 below depicts the schematic representation of SLS process [20–22].

4.5. 3*D*P

The 3*D*P process is an MIT-licensed method for printing data from a CAD drawing by spraying a water-based liquid binder over a starch-based powder. When the binder is blasted, the powder particles are cemented together in a powder bed. 3*D*P refers to this technology because it is similar to the inkjet printing process used for two-dimensional printing on paper. This method can work with a wide range of polymers [23–25].

4.6. Fused Deposition Modelling

Fused deposition modelling (FDM) is an additive manufacturing technology in which a thin plastic filament is fed into a machine where a print head melts and extrudes it in thicknesses of 0.25 mm or less. This technique makes use of acrylonitrile butadiene styrene (ABS), PC-ABS

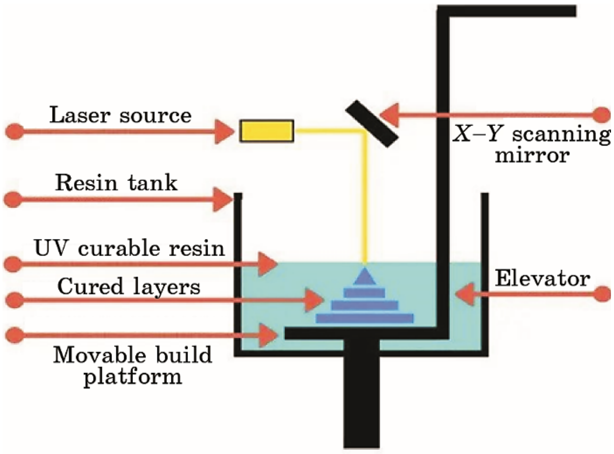

Fig. 4. Schematic representation of stereo lithography.

blends, polycarbonate (PC), polyphenylsulfone (PPSF) and PC-ISO, a medical grade PC. The key benefits of this technique are that there is no need for chemical post-processing, no resins must be cured, and the equipment and supplies are less expensive, resulting in a more cost-effective procedure [26].

The downside is that the z-axis resolution is low when compared to other additive manufacturing technologies (0.25 mm), necessitating a finishing process if a smooth surface is desired, and it is a time-consuming process that can take days to construct large complex items. Some models provide two time-saving modes: a completely dense and scant mode, which saves time but significantly reduces mechanical characteristics [27–30]. The schematic representation of FDM process is depicted in Fig. 6 below.

4.7. Laminated Object Manufacturing

A part is constructed layer by layer using LOM process, which incorporates both additive and subtractive processes. Sheets are the materials used in this technique. The layers are joined together by applying pressure, heat, and a thermal adhesive covering. Carbon dioxide laser is used to influence the material to the shape of each layer depending on the 3D model information in the CAD and STL files [31]. This method's advantages include its low cost, lack of the need for post-processing

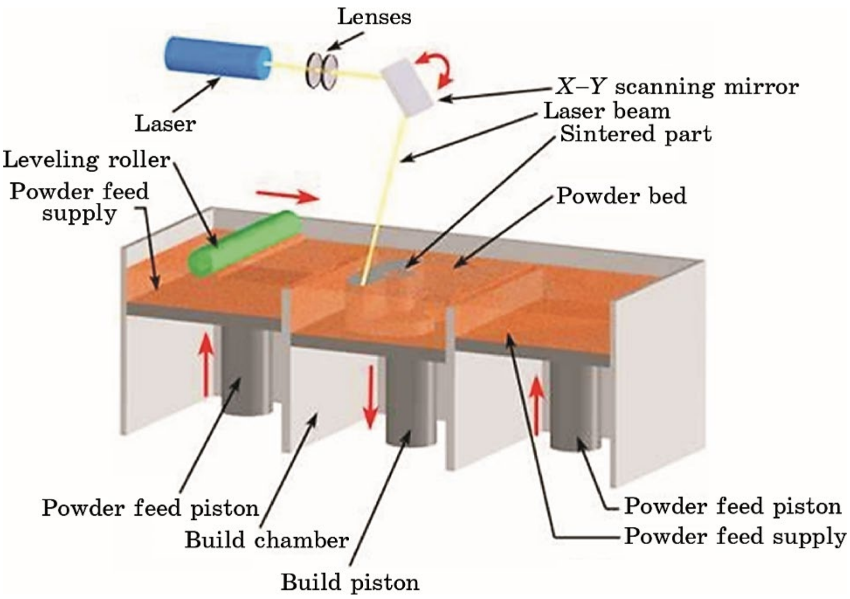

Fig. 5. Schematic representation of selective laser sintering.

and otherwise initialisation of supporting structures, sudden loss of distortion rather than phase switch throughout the process, but rather ability to produce large parts. Low surface definition, directional dependence of the material for machinability, and waste of the fabrication material are the drawbacks. Figure 7 below depicts the Schematic representation of LOM process.

4.8. Prometal

A three-dimensional printing method called prometal is used to create injection tools and dies. Stainless steel is utilized in this powder-based method. The printing process begins whenever the liquid binder is jetted onto steel powder. The particles are stacked in a powder bed, which is moved by feed and build pistons, which provide material with each layer and lower the bed when a layer is done. After completion, the leftover powder needs to be cleaned up. There is no need for post processing while creating a mould. Sintering, infiltration, and finishing operations are necessary when creating a functional part [17]. During the sintering process, a portion would be heated to 350°F for 24 hours, in a 60% porosity specimen, hardening the binder and fusing it with the steel. The sculpture is infused with bronze powder during the infiltration process after being heated to over 2000°F in an alloy of 60% stainless steel and 40% bronze. In the production of rocket nozzles, tungsten carbide powder sintered with zirconium copper alloy was

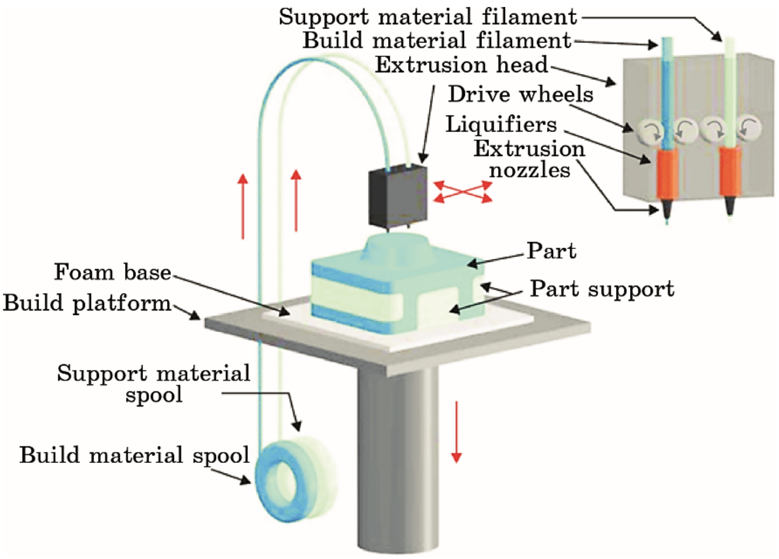

Fig. 6. Schematic representation of fused deposition modelling.

used; this method has also been used with other materials, and the results have been superior to CNC-machined parts made of the same material.

4.9. Polyjet

Using inkjet technology, this additive manufacturing method creates physical models. The inkjet head travels in the x and y axes once each layer is complete, depositing a photopolymer that is later cured by UV lamps. Due to the 16 m layer thickness that may be produced with this process, the created components have superior definition [32]. However, when compared to processes such as stereolithography and selective laser sintering, the items produced by this method are less durable. A gel-type polymer supports the overhang features, which are then water blasted once the process is complete. This method creates pieces in a variety of colours. The Schematic representation of polyjet printing process is depicted in Fig. 8.

4.10. Laser Engineered Net Shaping

Using this method of additive manufacturing, metal powder that is injected into a specified location is melted to make a part. It is heated by a powerful laser beam until it melts. The substance solidifies as it cools. The procedure is carried out in an argon-filled sealed chamber. This procedure allows for the use of a wide variety of metals and metal alloys, such as stainless steel, tool steel, titanium-6 aluminum-4 vanadium, nickel alloys and copper alloys [33]. You can also utilize alumi-

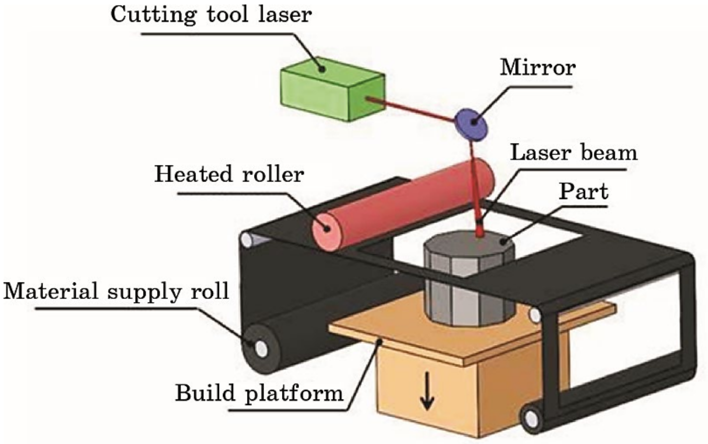

Fig. 7. Schematic representation of laminated object manufacturing.

na. Additionally, this method is utilized to fix sections that would be difficult or expensive to fix using another method.

The residual strains caused by uneven cooling and heating operations, which are significant in high-precision processes such as repairing turbine blades, could pose a problem in this process.

5. BENEFITS

The additive manufacturing provides massive benefits in different industrial sectors.

Multi-material goods: they enable the simultaneous use of many materials in the same solid during product manufacturing. The technique appears to overcome one of the present restrictions on the weight/mechanical strength when assessed by adding new features or reducing production costs [34].

Lite-weight goods: they make it possible to create items with tailored features and functionality, such as lighter products for cost, strength, or weight reasons. A model can be filled with various levels of porosity using some additive manufacturing techniques without changing the material.

Product ergonomics: by customizing each person's precise anthropometric features (prostheses), the design of the components can interact with the user to a greater extent without necessarily influencing the production costs.

Comprehensive mechanisms: they make it possible to create mechanisms that are fully integrated into the finished product and don't re-

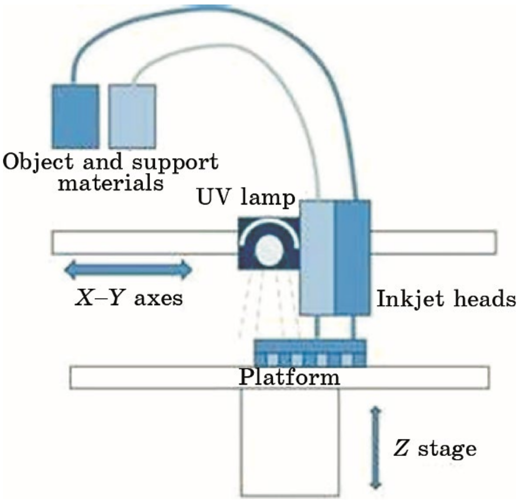

Fig. 8. Schematic representation of polyjet printing process.

quire further assembly or adjustments, such as a journal bearing, a roller bearing, a spring and its support, and a screwed-on worm gear.

Rapid prototyping: compared to traditional production methods, AM can quickly manufacture functioning prototypes, enabling designers and engineers to test and improve their designs.

On-demand manufacturing: AM can manufacture parts as needed, doing away with the need for vast inventories and cutting down on the time and expense of supply chain management.

A quicker timeframe for the commercialization of new designs: if AM is used to produce the finished product rather than just prototypes, many of the current launch and validation procedures might be drastically shortened. Another advantage is that it provides tremendous flexibility when it comes to adjusting to continuing changes in market demand.

Short runs of production: the size of the run may be so small as to only affect production costs on a per-unit basis (if and when the depreciation of the equipment is not considered). The lack of a need for tooling is one of the features that makes this possible and is a significant improvement over traditional production techniques.

Errors in assembly are reduced, as are the costs involved. It is possible to purchase pre-assembled parts; the only extra element is the quality control examination.

Reduction in assembly errors and the expenses associated with them: it is possible to purchase pre-assembled parts, and the quality assurance inspection is the only additional step [34].

Hybrid production technique: combining multiple production processes is always an option. Combining AM techniques with traditional techniques would be intriguing in this situation to maximize the benefits of both and They can be especially helpful for enhancing surface quality by lowering the 'stepping effect' generated along by AM methods when combined with mechanical material removal. A backwards hybridization process is also achievable, involving the use of subtractive manufacturing techniques to begin with a block before adding those very complex traits that provide significant value *via* AM.

Maximum material utilization: little material waste is produced. Recycling is simple and may be done with any waste.

A more sustainable manufacturing process: a more environmentally friendly manufacturing process avoids the direct use of significant amounts of hazardous chemicals.

6. LIMITATIONS

When deciding which technology is best suited to the needs of the product to be created, it is important to keep in mind that additive manufacturing techniques do have some disadvantages [35].

An effect known as stepping effect is created during additive layer production. The drawbacks of these phenomena include a very rough surface quality and difficulties in forming geometric forms. As a result, circular cross-sections must normally be formed into shafts and holes during manufacturing. The piece's roundness would not be acceptable if they were not. Alternatively, and setting roundness aside, arranging the component in a different direction may be advantageous based upon the application, it might be engrossing to design an upside-down sliding axis that prevents ‘interlocking’.

Small production runs can benefit greatly from some technologies because the manufacturing process itself might be labour-intensive. As the manufacturing run reaches a certain scale, conventional technologies may still be used even though they have a number of limitations, particularly geometrical ones.

Some technologies’ materials might not be appropriate for the product being created.

Material layering produces anisotropic materials. Many industrial components are acted by several forces, which stress the material, and are designed to use the least amount of material; it is possible that the components’ performance in relation to the forces they must withstand while in service is adequate.

The bulk of additive manufacturing techniques still yield higher tolerances than conventional manufacturing techniques, namely those relying on material removal.

7. APPLICATIONS

Prototyping: rapid prototyping is one of the applications of additive manufacturing. It allows designers to quickly create and test product concepts, reducing the time and cost of the development process [19].

Aerospace: AM is being used to create lightweight and complex aerospace components which are difficult to produce by the methods of traditional manufacturing. It also enables the production of parts with intricate internal structures, such as fuel nozzles and turbine blades.

Medical: AM is used in the medical field to create customized implants and prosthetics for patients. It allows for precise and personalized designs that can match the specific needs of each individual.

Automotive: the automotive industry is using additive manufacturing to create lightweight parts and components that can improve fuel efficiency and reduce emissions. It also enables the production of customized parts for vehicles.

Fashion: AM is being used in the fashion industry to create unique and innovative designs. It allows designers to create custom-made jewellery, accessories, and even clothing with intricate patterns and shapes.

Architecture: AM is being used to create intricate and unique architectural models and designs. It allows architects to create complex models quickly and easily, which can help in the planning and construction process.

Education: AM is being used in education to teach students about design and engineering concepts. It allows students to create prototypes and models of their designs, which can help them had better understand the design process.

Food: AM is being used in the food industry to create custom-shaped food products. It allows chefs and food designers to create unique and intricate designs using edible materials.

Jewellery: AM is being used in the jewellery industry to create complex and intricate designs, which are difficult to produce using traditional methods. It allows for the production of custom-made and personalized pieces.

Art: AM is being used by artists to create unique and intricate sculptures and art pieces. It allows artists to create complex shapes and structures, which might be impossible or difficult to produce using traditional methods.

8. CONCLUSIONS

To conclude, AM has transformed the way we think about production and design. New opportunities have been made possible by this technology in a number of sectors, including healthcare, aircraft, and fashion. AM provides unrivalled flexibility and customization possibilities because of its ability to construct complicated shapes and maximize material utilization.

However, AM, like any nascent technology, has limitations and obstacles. Some of the difficulties that still need to be addressed include a lack of uniformity and the need for more effective quality control methods. Furthermore, the high cost of equipment and materials, as well as the requirement for qualified operators, continue to be substantial impediments to general use.

Nonetheless, the advantages of AM greatly exceed the drawbacks. It is expected that as technology advances and costs fall, it will become a more common manufacturing technique. It could change how things are produced and created, making them more effective, sustainable, and fitted to the needs of people and industries. Overall, it is a technology that contains the potential to revolutionize the manufacturing sector, with effects felt in a variety of industries and applications.

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