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Additive Manufacturing Technologies in Dentistry (A Review)

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Abstract

Background: Significant advancements have been observed in the additive manufacturing (AM) technology industry in recent decades. Due to the inherent variations among each AM manufacturing technique, new areas of investigation continually arise and require consideration. Additionally, the novel applications of additive manufacturing present new difficulties and possibilities for targeted focus. The aim of this manuscript is to conduct a comprehensive literature review that describes the various processing methods, precision levels, types of materials utilized, and potential applications of 3D printing technology in the field of dentistry. Data: An online search was conducted on databases including Research Gate, Google Scholar, and PubMed to identify potential applications of AM technologies in the dental industry. The most relevant studies on the subject were selected, including English-language articles published between 2006 and 2022.
Conclusion: It is feasible to incorporate a variety of AM techniques in dentistry, which has led to improved workflow and acceptable clinical results. Moreover, the different technologies of 3D printing have a broad array of potential applications, enabling the development of novel and optimized techniques to produce dental products.

Introduction:

The field of additive manufacturing (AM) is rapidly developing and finding applications in manufacturing and everyday life. Its commercialization has gone by several names, including rapid prototyping (RP), layered manufacturing (LM), solid free-form fabrication (SFF), and three-dimensional (3D) printing. The 1980s saw the initial revolution of AM, and it is still developing quickly. In general, AM is a process that enables three-dimensional designs to be generated effortlessly from computer-aided design (CAD) files with minimal to no human involvement (1, 2). This method of manufacturing relies on cutting or slicing a 3D model into cross-sections, which are then printed on top of one another to create a 3D object, thereby minimizing material waste. The first applications of 3D printing were in rapid prototyping, which is the rapid manufacture of the model utilizing additive layer manufacturing (3). The application of additive manufacturing to produce intricate 3D models within the medical industry has been in practice since the 1990s. In recent times, this technology has gained significant popularity within the dental field. The creation of parts with complex geometry is an important feature of additive manufacturing. It can therefore provide an optimal solution in the field of dentistry (4, 5). For more than 20 years, subtractive computer numerically controlled (CNC) milling has been extensively used in the production of ceramic restorations. However, this technology still has some shortcomings. While the restoration is milled with dimensional precision and accuracy from CAD/CAM blocks, this technique also induces profound abrasion on the milling burs and microscopic cracks on the ceramic surface, reducing the restoration's longevity (6, 7). The restricted size, shape, and range of motion of the milling burs also results in a machining limitation for the subtractive milling process. Consequently, machining small details cannot be done so precisely. Additionally, flaws can develop along the manufactured restoration's surface area (8, 9). Previous studies have shown that different fabrication techniques can have an impact on the outcome of the manufactured products (10-15). Therefore, the understanding of novel methodologies has the potential to address certain issues that are occasionally encountered.

Additive Manufacturing Process

The initial step in the process involves the creation of a model utilizing professional computer-aided design (CAD) software. The Standard Transformation Language (STL), also known as the Standard Tessellation Language format (STL), is generally accepted as the standard file format for AM machines. Upon completion of a CAD model, it is essential to save it in STL format and subsequently transfer it to the 3D printer (16, 17). The 3D printer's parameters must be set up correctly to meet quality standards. These parameters include layer thickness, build orientation, energy provided, exposure time, and light intensity (18). The STL file is sliced into numerous horizontal layers (x-y plane) by the 3D printer. The Layer thickness, which is also known as the z-axis, determines the printer's vertical precision (19). Reducing the thickness of the film leads to enhanced surface smoothness of the printed objects, nevertheless at the expense of increased printing duration (4). Subsequent to the printing stage, post-processing assumes paramount importance, as it is dependent upon the 3D printing technique, the material employed, and the manufacturer’s instructions. Specifically, the post-printing procedure is necessary solely for light-curing technology and not for other technologies (20). Post-processing encompasses two essential steps: a rinsing procedure that eliminates any remaining resin and a post-curing process that completes the polymerization of the unpolymerized resin present between the layers (21, 22).

Advantages of Additive Manufacturing

The greatest advantage of 3D printing for the medical fields is the ability to produce customized medical equipment and products, which is particularly advantageous for the production of customized fixtures, implants, and surgical equipment (23). Additive manufacturing also has the advantage of creating parts with complex geometry and can be more productive and economical than conventional manufacturing techniques along with decreased material waste (24). Moreover, this manufacturing technique allows for passive production of restorations which is in contrast to subtractive manufacturing technique does not use milling burs which might cause cracks or surface flaws in the manufactured products (25).

3D Printing Technologies

On the basis of their distinct functional principles, 3D printing technologies are often assigned to three main groups: Powder Bed Fusion (PBF), light curing, and Fused Deposition Modeling (FDM) (26).

A. Powder Bed Fusion

The term “powder bed fusion” (PBF) technology refers to a category of AM techniques requiring a source of energy to specifically fuse or melt powder particles in order to manufacture parts layer by layer, hence achieving the intended geometry (27). The heat source could be a laser discharge, an electron beam, or ultraviolet light. Metals require a high temperature to bind their particles, owing to their remarkably high melting points. Thus, lasers and electron beams are the most prevalent kinds of heat sources used with metal AM (28).The PBF process involves the subsequent printing technologies: direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS), selective laser melting (SLM) and selective laser sintering (SLS) (26). SLM, SLS, and DMLS employ a laser beam to unite powder particles, while EBM utilizes an electron beam as its energy source (29). In contrast to the majority of other additive manufacturing techniques, this particular process utilizes the powder bed surrounding the fabricated components as a means of support, thereby facilitating the production of parts that do not require additional support structures. Consequently, the costs associated with the support structure’s material and the post-processing procedures required for support removal are eradicated. In addition to its economic implications, the removal of support structures affords greater geometric flexibility in design and a more rapid production rate for the components (30). PBF technology can be used for the production of metal frameworks removable partial denture RPD (cobalt chromium and titanium), implant supported permanent dental prostheses, customized subperiosteal titanium implants, titanium mesh for bone grafting-procedures, and cobalt chromium frames for implant impression techniques. These frameworks can be used for a variety of dental applications (26, 31, 32). Ceramics are another material that can be employed in the SLS process; however, in comparison to metals and polymers, ceramics present a greater challenge due to their higher melting point and lower plasticity. For the production of ceramics using SLS, two primary methods have been established as the standard approach. In the direct technique, the ceramic particles are fused together to produce the final sintered item, whereas in the indirect method, a polymeric binder phase is used to achieve ceramic particle fusion (33). Research investigations have been conducted on the precision and adhesion properties of Co-Cr frameworks utilizing PBF technologies. The precision of PBF as a fabrication method is determined by calculating the marginal gap between the metal framework and the abutment that has been prepared (31). Huang et al. (2015) assessed the marginal and internal fitness of metal and ceramic crowns. The study compared crowns fabricated using the conventional lost wax technique to those fabricated using selective laser melting. The results indicated that selective laser melting Co-Cr metal ceramic crowns exhibited superior marginal fit when compared to their traditionally fabricated counterparts (34). The potential application of SLS technology in the production of removable partial denture frameworks has been explored. A study conducted found that the employment of SLS as a fabrication technique for RPDs is deemed to be more accurate and yields superior mechanical properties in comparison to the traditional approach (35).

B. Light Curing

The phrase "light curing technology" refers to a category of three-dimensional printing technologies that use photosensitive resin materials which are cured and shaped under light irradiation. This technique involves three main types: stereolithography (SLA), digital light processing (DLP), and photo jet (PJ) (36).

I. Stereolithography

The Stereolithography (SLA) process employs a laser or UV light to construct the intended object in a sequential, layer-by-layer manner. The process involves the gradual descent of the build platform into a container containing photosensitive resin. Subsequently, the platform is exposed to UV light in a manner controlled by the cross-sectional configuration of each layer of the printed item. After this, the build platform moves a distance that's equal to the thickness of one layer, and the previous layer is then covered by uncured resin Fig.(1) (37). To protect the object against the sweeping motion of the build platform and the influence of gravity, supporting structures are added to the STL file before the printing process. Subsequent to printing, the object goes through a series of post-processing steps, the first of which is the elimination of any uncured resin and supporting structures, and the second of which is polymerization in an ultraviolet chamber (26, 31). SLA is the sole photocurable 3D printing method that is capable of manufacturing large scale models; nevertheless, SLA has a longer printing rate compared to DLP technique attributable to the curing induced by the motion of the laser beam, resulting in slower printing speeds for larger models. The resolution of printing is contingent upon the size of the laser beam (38, 39). The process of SLA involves the integration of ceramic particles with a photocurable resin. The viscosity of the slurry affects the strength of the structure; therefore, it is necessary to maintain a balanced ratio between the ceramic filler content and the resin matrix. Ceramic fillers possessing varying chemical compositions, for example, alumina and zirconia, exhibit desirable mechanical strength and are deemed appropriate for the fabrication of hybrid ceramic crowns (40).

II. Digital Light Processing

The digital light processing (DLP) technology relies on the vat polymerization technique, but it distinguishes itself from SLA through the utilization of a different light source. DLP technology employs a Digital Micromirror Device (DMD) to reflect light and project an image in layers throughout the entire platform, thereby simultaneously curing all points. The representation of each pixel is facilitated by a corresponding mirror, and the resolution of the projected image is directly proportional to the total number of mirrors employed. The micro reflectors' angles are independently controlled. The light generated via the light source is refracted through the micromirror and displayed onto the surface in a single pixel Fig.(2) (21, 37). The advantage of adopting DLP technology is that it only requires a single laser irradiation to produce a full layer, in contrast to the SLA technology, which requires progressively scanning the layer using a laser beam. The printing time can be shortened because the entire layer is cured regardless to its shape or count of pixels (26). Therefore, it possesses the benefits of high precision as well as quick production times (41) However, it should be noted that the printing of only small-sized objects is feasible due to the limited projection size, which is necessary to maintain a high level of precision (42). Each micromirror corresponds to a single image point, also known as a pixel. Due to the restricted number of micromirrors present in a DMD, enlarging the build platform leads to a proportional increase in the edge lengths along the x and y axes, which ultimately results in reduced precision (5). The utilization of DLP printing has resulted in a significant transformation in conventional 3D printing methods, as it has substantially enhanced both manufacturing speed and resolution (43). Among the earliest uses of SLA and DLP technologies was the fabrication of diagnostic casts. A systematic review has evaluated the precision of the casts produced through these methods, and the results suggest that this approach is now widely regarded as the new gold standard to generate diagnostic casts (44). Moreover, according to Tahayeri et al. (2018), the use of 3D printable restorative dental material and SLA 3D printing technique in their research yielded adequate mechanical properties that enabled the creation of provisional restorations suitable for intraoral application (45). Recently, new 3D-printed permanent materials have shown encouraging results, suggesting they could be used as permanent crown restoration (9, 46-48). Donmez and Okutan (2022) evaluated the marginal adaptation and fracture resistance of three different CAD/CAM-milled and one 3D-printed implant-supported crown restorations. Results showed that the implant-supported 3D-printed crowns had higher marginal adaptation compared with the milled crowns and also showed comparable fracture resistance values to the milled crowns (49). Kakinuma et al. (2022) studied the dimensional accuracies of permanent 3D printed and CAD/CAM-milled resin-composite crowns manufactured on two abutment-tooth shapes (ideal and sharp models). The 3D printing technique demonstrated better dimensional fitting accuracy compared to the milling technique and showed high trueness for both abutment shapes, including the sharp abutment model, which was unsuitable for the milling method (47).

III. Photo Jet

In contrast to the aforementioned methods of polymerization liquid resins at designated sites, the PJ approach involves the utilization of a photosensitive polymer inkjet. During the 3D printing procedure, the printing head traverses the X and Y axes while dispensing photosensitive resin onto the table. Simultaneously, an ultraviolet lamp generates light with the movement of the printing head to cure the photo sensitive polymer on the building surface, thereby completing one layer of printing. Subsequently, the table undergoes a downward movement along the Z-axis, and the equipment proceeds to execute the printing process repeatedly until the object is fully fabricated Fig.(3) (26). The variety of materials used in this technology, including ceramics, zirconia paste, resins, and thermoplastics, makes it stand out. The ability to print and fuse all the materials mentioned is a distinct advantage over competing technologies. Additionally, given its ability to print various materials, inkjet-based 3D printing permits the blending of materials, enabling the creation of objects with a wide range of properties (50).

C. Fused Deposition Modeling

Fused deposition modelling (FDM) printing, which is also referred to as fused filament fabrication (FFF), is a manufacturing process that involves the construction of a three-dimensional object through the sequential deposition of extruded molten polymers onto a building platform (51). The standard form of the print material is filamentous in nature. FDM printers typically employ waxes and polymers as substrates. To fabricate an object, it is necessary for filaments to traverse a heated nozzle and be extruded in a sequential manner onto a build platform that moves along the z-axis. The nozzle exhibits motion along both the x and y axes to configure the configuration of every individual cross-sectional stratum, and the substance undergoes immediate solidification upon its extrusion from the nozzle Fig.(4) (7, 52). Several thermoplastics are frequently utilized for FDM applications, such as polylactic acid

(PLA), polycarbonate, polyamide, and acrylonitrile-butadiene-styrene copolymers. Polylactic acid (PLA) is a material that exhibits superior ecology and suitability for application within the oral cavity (53). Robocasting, also known as direct ink writing, is a technological variation that utilizes the process of cold extrusion to propel a ceramic slurry through the printing nozzle. The green object that has been printed is subsequently subjected to sintering in order to achieve the desired density and strength (54). Ideally, the ceramic slurry would be extruded through the nozzle at a moderate pressure, maintain its shape during deposition, exhibit minimal deformation, and achieve high density upon sintering (7). The main advantage of FDM is its low cost and that various types of material can be printed using this technique. Broadly speaking, any material that is capable of being extruded has the potential to be selected. However, the surface smoothness and overall quality of the objects produced with FDM are lower in comparison to those produced using other methods (4). The effective use of robocasting technology in the production of ceramic dental crowns has the potential to have a promising opportunity for future applications. However, it is necessary to make modifications to critical factors such as nozzle height, pH, and viscosity of the ceramic slurry in order to effectively carry out the robocasting process of green ceramic objects (31). The processing parameters were investigated by Wang et al. (2006) for robocast porcelain crowns. The surface texture of additive manufacturing (AM) crowns was found to be within the range of 20 to 50 µm, which is considered clinically acceptable (55). For the fabrication of extraoral maxillofacial prothesis (for example, nasal or ear protheses), 3D printing can be used to manufacture extraoral prothesis either directly by printing the prosthesis or indirectly by printing a prosthesis molds (56). SLA, DLP, photo jet, SLS, and SLM have all been employed to obtain extraoral prothesis however FDM can only replicate the macro anatomy but cannot accurately reproduce the micro anatomy of facial structures due to the staircase effect which is more evident in FDM (57).

Accuracy of Additive Manufacturing Technology

It is imperative to possess an understanding of the distinctions between specific terminologies utilized in additive manufacturing procedures, which are: resolution, precision, and trueness. A 3D printer's resolution refers to the smallest feature that can be accurately reproduced by the printer and is unique for every technology and 3D printer. The determination of a 3D printer's resolution should be specified for each x, y, and z-axis in units of micrometers or dots per inch (dpi), with the z-axis generally corresponding to the layer thickness. Precision or repeatability refers to the capacity of a 3D printer to produce components with consistent 3D dimensions, or the degree of proximity between replicated printed objects. Trueness pertains to the difference between the dimensions of the designed component and the printed object (31, 58). Discrepancies may be integrated at each stage of the dental digital process. In addition, the selection of technology, 3D printer model, and material for additive manufacturing of the desired item can have a significant impact. The resolution capabilities of printers utilizing identical technology may exhibit variations. Every printer is provided with an established resolution, as determined by the manufacturer. In addition, it is important to note that each material possesses a unique activation range of wavelength, power, and exposure time required for its production on 3D printers. Hence, it is imperative to note that not all additive manufacturing materials are universally compatible with all additive manufacturing printers (59).

Various factors, including laser speed, intensity, angle, building direction, total number of layers, shrinkage between layers, amount of supportive material, and postprocessing procedures, may impact the precision and trueness of the printed item (60-62).

I. Build Orientation

The precision and durability of the finished object are impacted by its build orientation setting. Using SLA technology, Alharbi et al. (2016) found that crowns fabricated at an angle of 120 degrees had the best combination of dimensional precision and accuracy (63). According to Ryu et al's (2020) findings, the recommended optimal build angles for achieving ideal internal fit of 3D-printed crowns using the DLP system are 150° and 180° (64). Hada et al. (2020) conducted an assessment of the accuracy and precision of dentures produced via SLA technology using photosensitive resin. The study found that the accuracy and precision of the printed dentures were influenced by the direction of printing, with the 45-degree direction exhibiting superior accuracy compared to the 0 and 90-degree directions (65).

II. Layer Thickness

The precision of printers is enhanced as the layer thickness is reduced from 100 to 50µm. The findings indicate that there is a positive correlation between accuracy and the reduction in layer thickness. According to SLA and DLP manufacturing technologies, the cured resin is formed in a layer-by-layer manner. However, in cases where there are irregular borders in the printed object, the layers are not directly positioned on the z-axis or x-y plane. In such instances, the quantity of discrete points on the edge is determined by the thickness of the layer. Reducing the thickness of the layer will result in the generation of finer points, leading to the creation of a more refined and intricate surface, thereby enhancing the precision of the print. On the contrary, a thicker layer exhibits a reduced number of distinct points and an increased distance between them, leading to a noticeable staircase artefact at the boundary that impacts the overall precision (66). A study conducted by Zhang et al. (2019) compared the precision of dental models produced through different 3D printing technologies. The study involved the use of three different DLP printers as well as an SLA printer, with varying layer thicknesses of 20, 25, 30, 50, and 100 µm. The study determined that a layer thickness of 50 µm is optimal for DLP technology and observed that the precision of printing with SLA technology improved as the layer thickness decreased. The findings indicate that DLP technology exhibited superior printing precision in layers with thicknesses of 100 µm and 50 µm. Conversely, the SLA printer exhibited the lowest precision at a layer thickness of 100 µm (67).

The phenomenon known as the "staircase effect" can be observed on the surface of a printed object due to the uneven overlapping of printed layers. The additive manufacturing process of layer-by-layer fabrication may result in a ladder effect on the final product. However, by adjusting the layer thickness to the greatest resolution, this effect can be mitigated. It is important to note that this adjustment may significantly increase the printing time of the object (68).

III. Post-processing.

Effective post-processing techniques can enhance the quality and efficiency of printed samples. It is imperative to execute the manufacturer’s postprocessing procedures with great care to prevent any potential discrepancies in the printed object. In their study, Jindal et al. (2020) employed a 405nm light source consisting of 13 poly-directional light-emitting diodes to perform post-curing of clear dental aligners. Their findings indicate that subjecting the resin to a curing time of 15-20 minutes at a temperature range of 40-80°C resulted in a significant enhancement of its ability to withstand pressure loading (69). Furthermore, one of the main causes of error that has been noticed in 3D printed restorations is the excessive use of alcohol rinsing and inadequate eliminating of uncured resin. This can lead to restorations having poor accuracy (70).

Conclusion

At present, subtractive milling is the most commonly employed computer-aided manufacturing protocol in dentistry. However, as the precision and range of applications of additive manufacturing improve, it will likely be utilized in dentistry more frequently in the future. Additive manufacturing technologies have demonstrated efficacy across various manufacturing fields and offer numerous benefits in the processing of dental structures in comparison with subtractive technologies. These advantages involve a reduction in production steps, resulting in a decrease in total manufacturing duration, a decrease in the usage of consumables and raw materials, and the ability to produce intricate dental components.

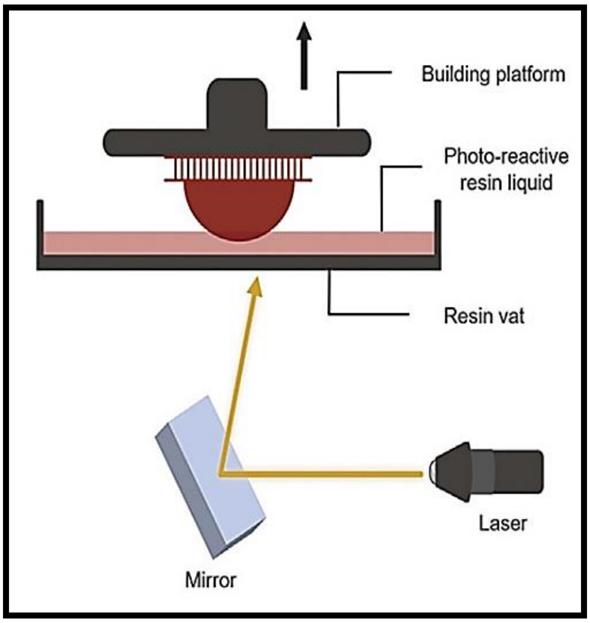

Fig. (1): Stereolithography 3D printing procedure (37).

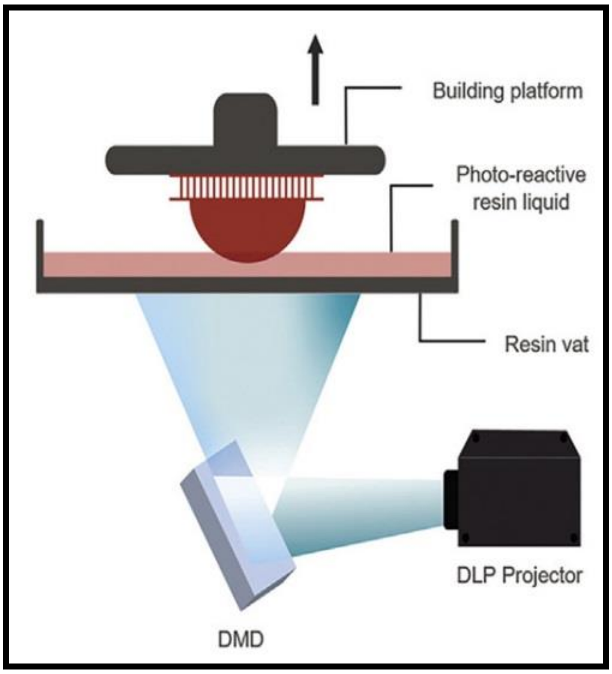

Fig.(2): digital light processing 3D printing procedure (37).

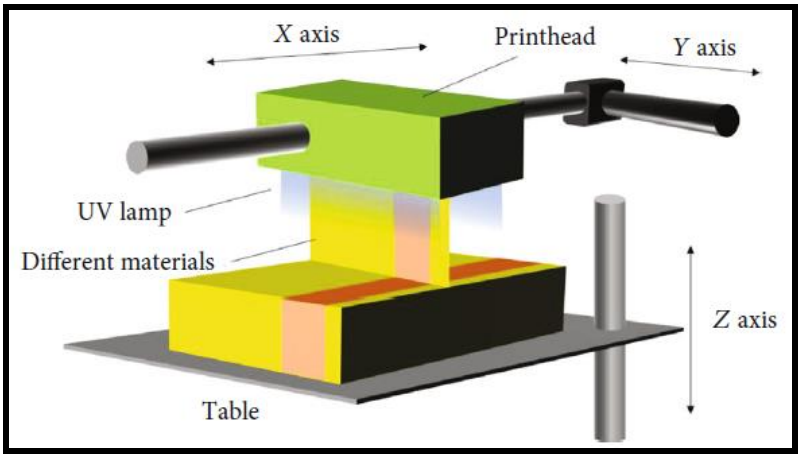

Fig.(3): Photo jet 3D printing technique (26).

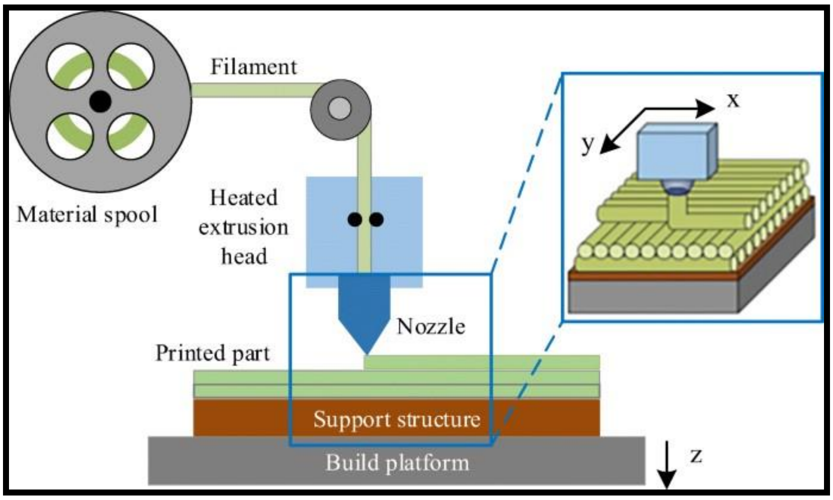

Fig.(4): Fused deposition modeling 3D printing technique (52).

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