Fused Deposition Modeling Based 3D Printing: Design, Ideas, Simulations

Md. Hazrat Ali and Anuar Abilgaziyev

Abstract The capability of printing real three-dimensional (3D) objects from digital data is a sophisticated technology. 3D printing (3DP) technology has proliferated in the last several decades by attracting more manufacturers globally. It enables users to make parts without almost any geometrical restrictions. This chapter discusses Fused Deposition Modeling (FDM) technology, its types, applications, and prospects. It also discusses the latest introduced technologies and energy consumption in 3D printing.

1 Introduction

Additive technologies are currently one of the most dynamically correct uses of digital manufacturing. These technologies possess great prospects in the manufacturing of mechanical engineering and biomedicine products and repair work. Among all basic principles of 3D printing, the extrusion-based system where the material is selectively fed through a nozzle is the most widespread in current days.

This chapter discusses the fused filament fabrication (FFF) type of 3D printer that belongs to the extrusion-based systems in additive manufacturing. Along with the abbreviation FFF, FDM (fused deposition modeling) is also used to denote this technology. However, legally the term FDM is trademarked by Stratasys Company [1, 2]. In order to design 3D printers with these working principles, companies should use a different name.

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Currently, there are several dozens of different companies offering their products based on this technology. The wide use of FDM printing is explained by the financial reason for this type, i.e., the low cost of both printer itself and its supplies. Another reason is the wide range for printing capabilities of various types of products and the availability of components for assembling FDM printers without the support. There are three main types of FDM printers based on price and advancement: home desktop, professional and industrial ones. The FDM technique, with some modifications depending on the purpose of use, is successfully applied in many fields, such as medicine [3, 4], food [5], and even construction engineering [6, 7].

It should be noted that FFF technology has a lot of significant characteristics and features that make it possible to value its advantages over other types of 3DP technologies, namely:

- the most simple printing principle and easy implementation on the bases of standard electronic components
- relatively high resolution (up to 20 microns)
- the possibility to print simultaneously with several materials or several colors
- the possibility of using a wide range of thermoplastic materials with different characteristics (e.g., carbon-reinforced plastics, electrically conductive materials, etc.), including those that are safe for health (both during the process and the use of the finished product) and that do not require special storage and handling conditions
- implementation in the form of compact personal printing devices that do not require specific technical knowledge of installation, connection, and operation
- prototyping of objects with complex geometry and cavities that are beyond the power of other technologies
- lack of noise pollution and industrial waste requiring disposal or special places for installation
- low cost of both the devices themselves and the materials used
- the possibility of self-assembly or DIY of the printing device from a ready-made kit or a set of components
- printed products have high-performance characteristics and can be used as serial products;
- the openness of the technology and open-source hardware and software allows for the improvement and implementation of 3D printing devices in various fields.

FDM printers use a feeding mechanism to push a filament into the extrusion chamber to create a high pressure that would push out melted material through the nozzle. The feeding mechanism generally consists of two roller wheels that clamp filament. One wheel is controlled by a driving motor to generate the translation movement of the filament. The second one is to create high friction between the filament and the driving motor wheel.

The extruders are classified as a direct and Bowden extrusion based on the location of the feeding mechanism. In the direct extrusion system, the feeding

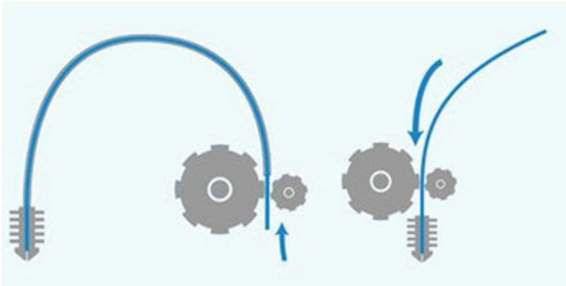


Fig. 1 Schematics of Bowden and direct extrusion systems [8]

mechanism is mounted on the moving extrusion hot-end, whereas Bowden one has the feeding mechanism located on the frame of the printer and has a Bowden cable which works as a guide for the filament is driven to the hot-end through it (Fig. 1). Bowden type extrusion makes the printer lighter, especially when the printer has more nozzles or extrusions.

2 Design Variations

The most common arrangement used for FDM is a Cartesian coordinate system. Built on Cartesian coordinates, this technology works based on three axes (X, Y, and Z). One or more of these axes move the mechanical print head of the equipment, i.e., the coordinates specified along the axes implement movement and position of the extrusion system relative to the platform (Fig. 2). Of all kinds of kinematic schemes of FDM 3D printers, the Cartesian system shows relatively high stability of results.

Another popular schematic arrangement is Delta. In this kinematic scheme, the print head's movement occurs along with three parallel guides (Fig. 2). The change in coordinates along the Z-axis takes place when the angle between the drives changes. The workspace in printers with this system is usually much larger vertically. They also come in open and closed cases. The Delta scheme's advantages include higher printing speed but less accuracy at the model's edges than the Cartesian scheme. This is because all three attachment points are involved in the movement of the extruder. The electric motors operate simultaneously, which leads to the accumulation of errors in coordinate positioning.

A kinetic scheme like Polar is a reasonably new scheme introduced by the company of the same name, Polar. It uses a polar coordinate system. Its fundamental difference from the Cartesian scheme is that the extruder moves in the X and Y planes not linearly but in a circle relative to the platform. The platform of such a scheme of 3D printers has a circular shape, rotates in a circle, and moves entirely along one horizontal axis, and the extruder moves up and down (Fig. 3). It is faster than the Cartesian type.

3D printers with robotic arms (SCARA) are designed with a mechanical programmable arm-gripper, replaceable extruder. SCARA is a kinetic scheme designed

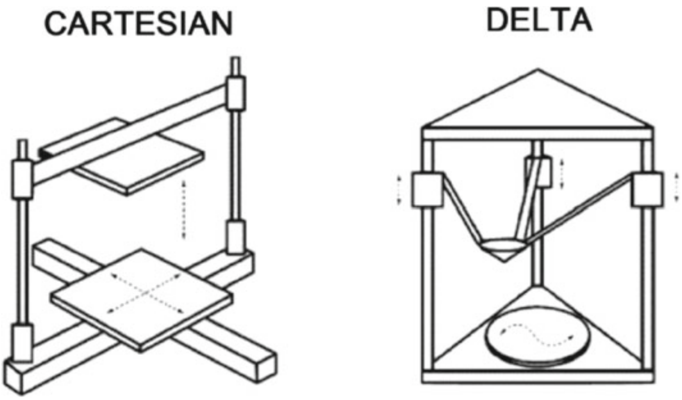
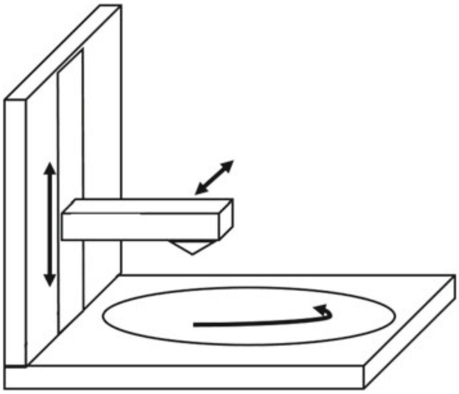


Fig. 2 Cartesian and delta type FDM printers [9]

Fig. 3 Polar type printer



for manipulators with limited mobility with increased accuracy and rigidity. In this scheme, the extruder is located at the end of the manipulator, which moves due to lever joints along the XY axes and a separate drive along the Z-axis. According to this scheme, the devices built are distinguished by very high accuracy and repeatability, low noise and vibration levels, and compactness. Among the disadvantages is the complicated software compared to the Cartesian ones.

3 Latest Process Variation and Process Mechanisms

3.1 Polymer Printing

Polymer printing is the most popular process variation among all process variations. In polymer printing, there is a wide range of available materials. The material range includes thermoplastics (e.g., ABS, PLA), engineering polymers (e.g., PA (Nylon), TPU, PETG), high-performance thermoplastics (e.g., PEEK, PEI), and other composite materials (carbon-reinforced thermoplastic, electrically conductive materials).

The polymer FDM technology is quite simple and works based on the melted polymer filament's extrusion from a coil. The extrusion system has a nozzle with a heater that melts the filament and has a feeder mechanism that generates pressure inside the nozzle to facilitate pushing the molten material out of the nozzle (Fig. 4). The constant pressure application ensures a constant flow rate, whereas the extrusion mechanism's constant movement implies even fabrication of an object's layers.

Ideally, the melted polymer material after the extrusion process should keep its shape and size. However, external factors such as gravity and tension may cause the change of the shape and size. The material also shrinks and gets porous upon the solidification process, affecting the printed parts' quality.

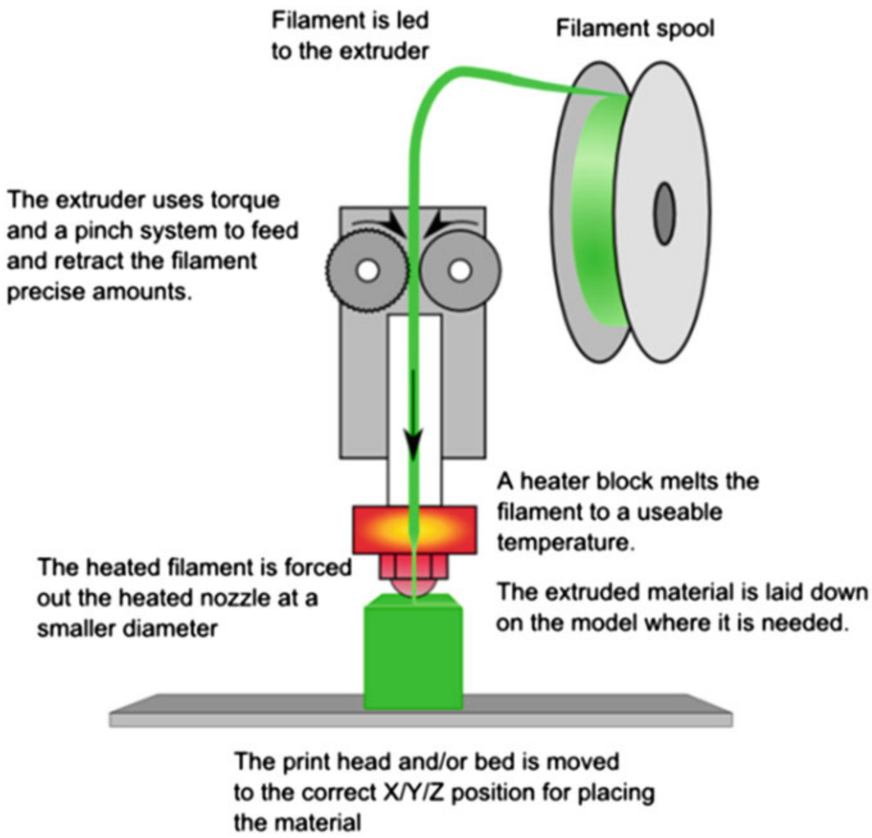


Fig. 4 Schematic of FDM [10]

A new extruder system called Gigabot X for polymers was introduced on Kickstarter by re 3D company [11]. The company believes that thermoplastics' novel extrusion system could decrease dependent on current polymer filaments and reduce material waste. The input of the extrusion system is polymer granules, not usual filaments. There is a screw inside a heated barrel in the extrusion system that drives pelletized plastics and extruded through a small nozzle (Fig. 5). The waste materials after printing can be recycled and pelletized to be reused again in the printer.

3.2 Food Printing

Currently, 3D printing technology opened new directions, even beyond food production. Further development prospects can be defined from its benefits such as sustainability, food aesthetics, and nutrition control. It helps with the demand for special food customer groups such as sportsmen, older people, pregnant women, and children.

There are three additive manufacturing techniques used in food printing, which is extrusion, selective laser sintering, and binder jetting. The extrusion system is the most popular one in food printing [5]. It is a digitized engineering solution that helps to prepare food with different designs and customized nutrition proportions. It

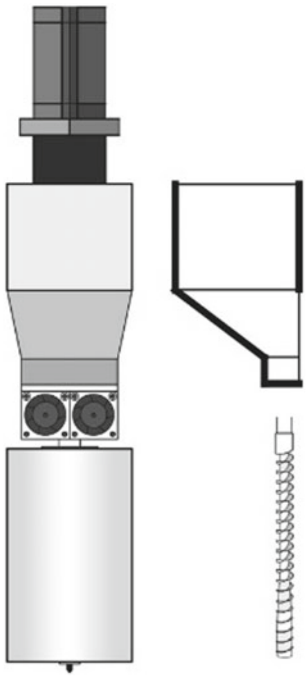


Fig. 5 Extrusion system of Gigabot X [12]

uses the same coordinate systems as FDM does Cartesian, Delta, Polar, and Scara. However, food printers use distinct extrusion systems from FDM that are syringe, air pressure, and screw-type systems.

The popularity of using the FDM system in food printing is achieved firstly due to a relatively wide range of material appropriate for the extrusion through a nozzle. Secondly, more complex designs can be achieved as it eliminates molding. Thirdly, the elimination of molding narrows the overall expenses to the cost of machines and ingredients.

Soft self-supporting edible materials such as dough, meat paste, and processed cheese can be used to create 3D printed food. The choice of the material's viscosity is crucial, enabling the material to be extruded through a tiny nozzle and strong enough to hold its structure [13].

Lipton et al. [14] successfully printed multi-material constructs of turkey meat and celery. Then the printed materials were able to be slow cooked or deep-fried. The extrusion system technique is also used to create customized 3D chocolate products [15]. Researchers from Netherland Organization for Applied Scientific Research (TNO) made use of a soft-materials extrusion system to print-rich diversity of food. They used meat purees, carbohydrates, proteins, and other nutrients from alternative sources such as algae, grass, and insects [16].

Currently, many researchers and companies are focusing on improving the extrusion type of food printing. The majority of current 3D printers can print unique and complex shapes without controlling at the macro-nutritional level. Combining these two values to the final food is very significant. It needs to be addressed to improve food printing technology to have a healthy life and the growing population's sustenance.

3.3 Live-Cell Printing

Extrusion-based system printing is also used to extrusion living cells, which is also known as bioprinting. It is already used in tissue engineering to print parts such as cells, tissues, bones, cartilage, bi-layered skin [17], artificial organs [18]. In bioprinting, bioink is the material dispensed by extrusion or a deposition system controlled by a computer. There are three types of deposition systems in bioprinting: neumatic, piston-driven, and screw-driven extrusion systems [17].

The main challenge of bioprinting for use in medicine is biocompatibility and non-toxicity of materials. The main materials that have been successfully applied are hydrogels and composite materials. 3D bioprinters offer faster fabrication of drugs at a lower cost.

Visser et al. [19] used in-air microfluidics to print biostructures with living cells. This technique can help to fabricate micro-building blocks that could be a major boost in tissue engineering advancement, and it will be able to fix the damaged tissues. Cubo et al. [20] with collaboration with BioDan, developed an extrusion-based 3D printer capable of fabricating functional human skin.

4 Printing Methods and Technologies

According to Ali et al. [21], in 2016, there were only a few technologies available that can perform multi-material and multi-color printing, and their performances were relatively poor. Companies and researchers have often designed dual or multi-extrusion systems to fabricate multi-material parts simultaneously. They just literally increased the number of nozzles and extrusion systems to facilitate multi-color and/or multi-material printing. This method of solving mono-color printing is not practical since adding more nozzles requires more heaters and more feeding motors, making the printer bulky and heavy. This slows printing speed and print volume significantly. Moreover, this solution consumes high energy and limits the number of materials and/or colors depending on the number of nozzles installed. Multi-extruders also decrease the printing area, which is available for single-nozzle printing.

Nevertheless, currently, there are many proposed novel systems proposed by different research groups and companies that attempted to tackle these issues.

4.1 *Single-Nozzle Multi-material Printers*

There have been proposed reinforced polymer material printing for FDM printers to improve the mechanical properties of printed objects [22]. Tian et al. [23] developed a novel fabrication approach technique is particularly suitable for reinforced composite plastic materials that consist of polylactic acid as the matrix and carbon fiber. The extruder head has only one nozzle but two inputs for two different filament materials (Fig. 6).

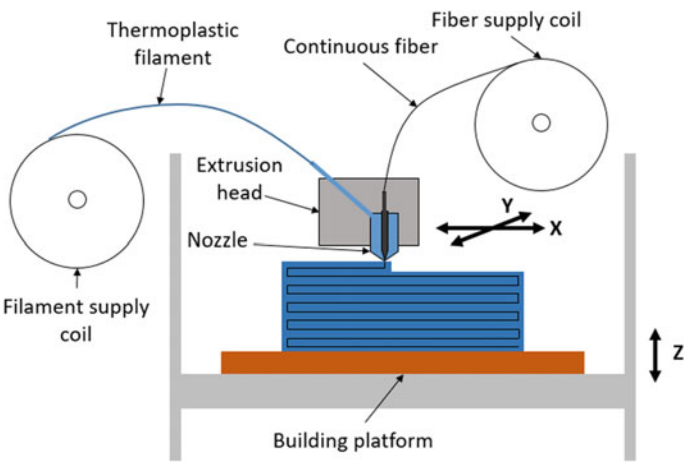


Fig. 6 Schematic of FDM 3DP for continuous carbon-reinforced PLA composites

This method is performed by providing matrix and fiber filaments simultaneously. The major challenge is the bonding between the two materials.

4.2 Multi-nozzle Printers

Ali et al. [21, 24] have proposed a novel multi-extrusion system for five different material/color FDM printing. They utilize only two motors for the whole feeding mechanism. This novel system's main feature is that there is only one feeding mechanism for the whole system. In order to drive the specific filament, it rotates and switches to the needed filament. The extrusion system consists of five nozzles and only one feeding motor, so it is much lighter than conventional multi-material systems.

4.3 Full-Color Printers

Some companies have already proposed new systems to design full-color FDM printers.

Da Vinci Color Mini 3D printer introduced by Taiwanese company XYZPrinting can print full-color objects. The printer utilizes CMYK inkjet technology that enables to produce infinite color palette. The printer uses a special color-absorbing PLA filament and mixes magenta, cyan, and yellow ink droplets to print objects with millions of colors. This 3D printer is the world's first full-color FDM 3D printer (Fig. 7) [25].

The Polish company OVE collaborating with the American company Memjet has developed a full-color FDM 3D printer (Fig. 8). OVE printer uses a transparent PLA filament, and after printing one layer, the platform is moved to the side where the printing object is painted by Memjet printhead [26].

The PlaySmart 3D printer by Polaroid has an option to print with multiple colors. It has only one nozzle, and it has a smart software that pauses the printing process to allow the user to change the filament to the needed color [28].

4.4 Parallel FDM Printing

Parallel FDM printing is a novel method of printing where multiple independently printing extruders are used simultaneously. This approach allows us to achieve a high printing speed proportional to the number of printing elements. Before designing a 3D printer using FDM parallel printing technology, developing the printer design and the parallel printing algorithm for independently moving extruders is necessary.

Fig. 7 Da Vinci Color Mini 3D printer [25]

Fig. 8 OVE printer [27]

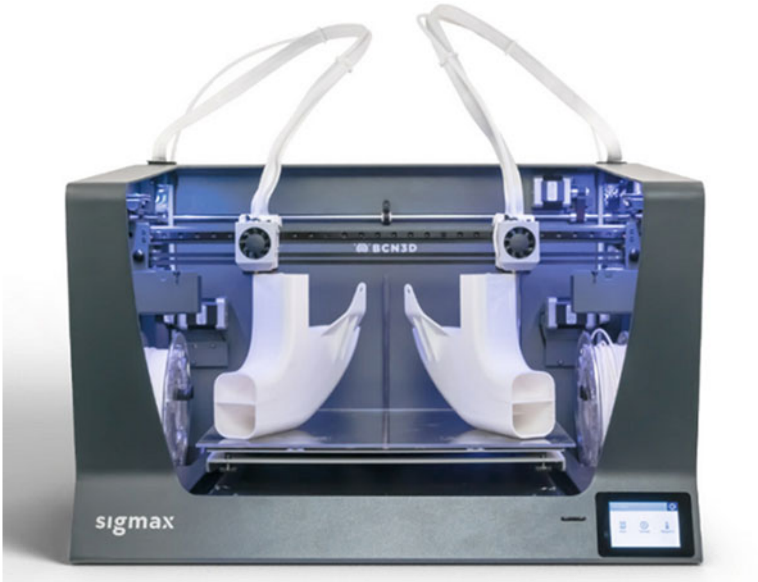


Fig. 9 Sigmax printer [30]

The Spanish company BCN3D Technologies made available to the public all the drawings and instructions necessary for self-assembly of the latest proprietary 3D printer FDM BCN3D Sigmax [29], equipped with two extruders with parallel kinematics (Fig. 9). A distinctive feature of all Sigma 3D printers is parallel-kinematics: the devices are equipped with two extruders with an independent X-axis stroke, making it possible to simultaneously print two identical parts, or mirror models, for example, halves of an assembled product.

Different extruders can print different plastic colors to produce different colored layers of the model, making it much easier to change the plastic required with a single extruder. Each extruder has its printable area, resulting in two main areas.

Before this, only one extrusion system at a time was used as the standard for FDM printing. Some designs have multiple extruders moving together and printing separately at different times. There are printers with two extruders (MakerBot Replicator 2X, WANHAO Duplicator 4X, etc.). The main extruder grows the central part of the model, and the additional one prints the supporting structures using soluble plastic. These printers can also be used for double-color printing. However, these multiple extruders were assembled in one extrusion system and could not print two different parts in parallel.

5 Simulations

Otepbergenov et al. [31] conducted a study to analyze a customized ankle-foot orthosis for patients to rehabilitate from the foot drop disease. For their study, the researchers used a multi-material FDM 3D printer. They changed the high stress concentrated regions with Nylon 12 material to reduce the stress and make a longer lifetime for the orthosis. They performed experimental and numerical FEA analyses. Figure 10 shows simulation results, and the force applied is on the zone with the red color in the figure.

Figure 11 shows the obtained experimental results.

The results showed significant improvement by decreasing the equivalent stress by nearly 50% and decreasing total deformation by 35% and 70%.

Sabyrov et al. [32] created a flexible neck orthosis design using an FDM printer for rehabilitation with regular usage. The digital model of the patient allowed them to design the neck orthosis with high accuracy.

The finite element analysis method found in ANSYS software was used to assess the model's mechanical behavior. The numerical simulation approach shows an applied force on the object and consequent displacement and load distribution along with the model. The initial step begins with setting filament parameters in the software. Thermoplastic elastomer (TPE) material has both features of plastic and rubber. TPE fabricated orthosis includes strong, flexible, and durable properties.

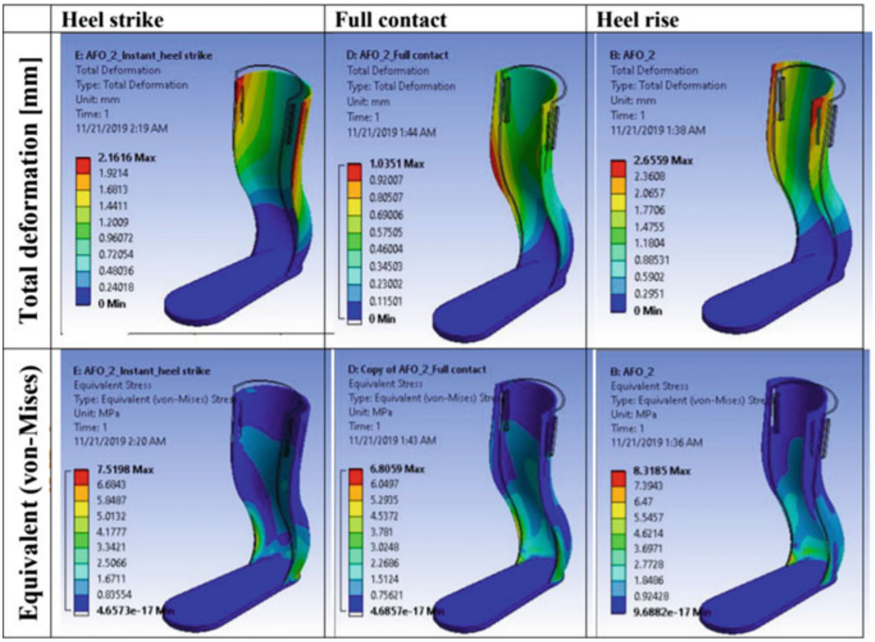


Fig. 10 Simulation results at each gain instance [31]

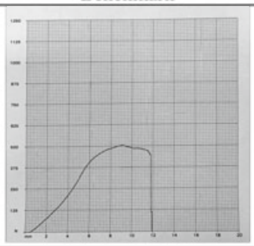
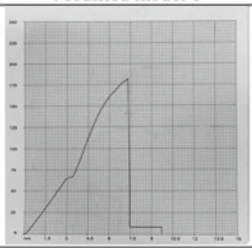
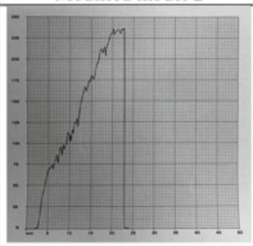
	Benchmark	Modified model 1	Modified model 2
Graph of load vs. deformation			
Ultimate load	505 N	183 N	237 N
Max. deform.	12 mm	7.5 mm	23.5 mm

Fig. 11 Experimental results of the compression testing [31]

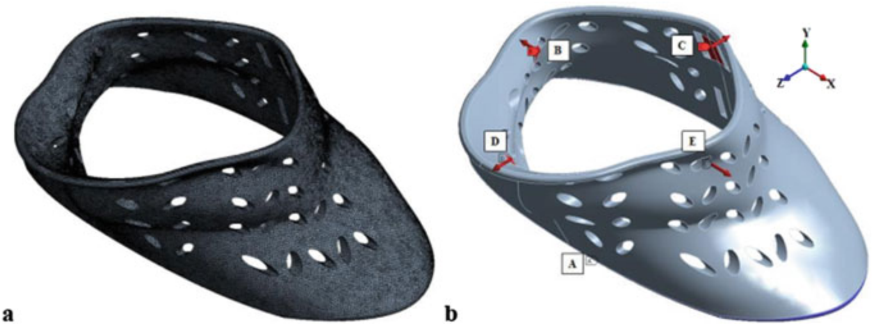


Fig. 12 **a** mesh view of the design model and **b** applied force directions and boundary conditions [32]

The purpose of numerical assessment is to observe how the neck orthosis behaves under an applied force. The fine mesh formed by 799,699 elements and 1,208,407 nodes ensure accurate simulation (see Fig. 12a).

Figure 12b illustrates the directions of forces; the letter "B" and "E" corresponds to lateral bending (left and right side of orthosis). Extension force relates to the letter "C" and the backside of the model. To the forward part of the neck is applied the flexion force ("D").

The model's lower edge was chosen as a fixed boundary, indicated with the letter "A" and blue color region. The value of forces applied from the inner surface for flexion, extension, and lateral bending are 210, 190, and 165 N, respectively.

The influence of the applied force on stress distribution is represented in Fig. 13 in the iso-color view. On the left side of Fig. 13a is shown a color-bar, where the

Fig. 13 Stress distribution along the model: **a** front, **b** left-side, and **c** back views [32]

highest pressure is represented with red color, whereas the lowest corresponds to blue color. The unit of stress parameter is "MPa". It could be seen that the region most affected by pressure is the backside of the model, while on the left and the front side, the effect is minor.

Figure 14 shows that the maximum displacement caused by applied force is 1.4685 mm. Similar to stress distribution, the highest total displacement occurred on the backside of the model. The left side has almost 0.5 mm enlargement, while deformation on the front side is negligible.

According to simulation analysis, it can be concluded that the weakest part of the model is the backside region. Nevertheless, the small deformation value is reasonably small. Moreover, on the nape side are oriented rectangular holes for Velcro, designed for comfortable dressing. During wear, the printed neck model could be regulated and tied comfortably.

The model was tested via ANSYS software, which highlighted the orthosis's durability under an applied force.

Ali and Batai [33] researched the sandwiched structures' deformation and mechanical strength with a honeycomb cover. Face sheets were made of ABS, whereas honeycomb core was made of PLA material.

ANSYS is used to study the sandwich structures' mechanical properties with various cores under the bending load ranging from 200 to 2000 N. To be more specific; the load is line load. The boundary conditions and meshing are shown in Fig. 15. The load is applied to the indenter while the bottom of the support is fixed. Moreover, the mesh size is 1 mm. In this study, stress distribution on the sandwich structures is characterized using Von-Mises stress. Simultaneously, total deformation is taken as another indication of the mechanical behavior while subject to the bending loads (Fig. 16).

According to the stress distribution on the sandwich structures with various cores, the sandwich composite with honeycomb core presents relatively lower maximum stress than the one with the solid plate core of the same weight as its, while the composite structure with the core of the same thickness as its shows a bit

Fig. 14 Deformation (displacement) along the model: **a** front, **b** left-side, and **c** back views [32]

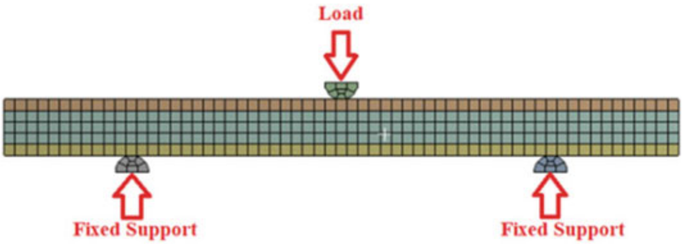


Fig. 15 3-point bendings (boundary conditions and meshing): each fixed support is located 10 mm away from the nearest free end [33]

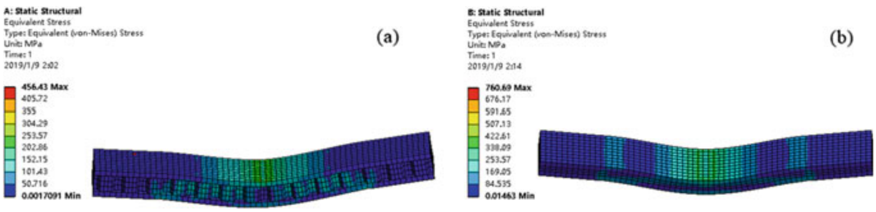


Fig. 16 Von-Mises stress distribution under the load of 1 kN: **a** sandwich structure with honeycomb core stress distribution, and **b** sandwich structure with solid plate core with a thickness of 1.08 mm stress distribution [33]

higher maxim stress value than it. Figure 17 shows the sandwich structure with a honeycomb core (SH) deforms more than the SSP (3 mm) having the same weight. SH's deformation pattern is even closer to the structure's deformation pattern with the same thickness's solid core.

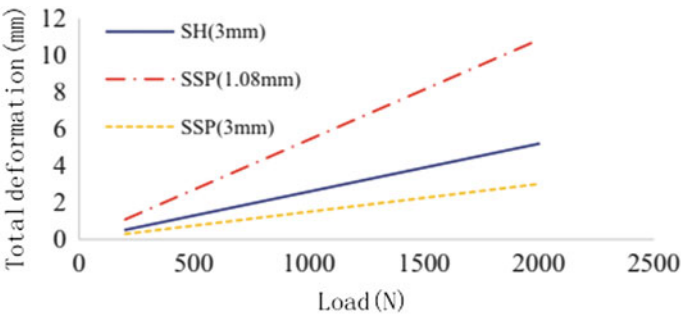


Fig. 17 Maximum total deformation of the sandwich composites under the bending loads from 200 to 2000 N [33]

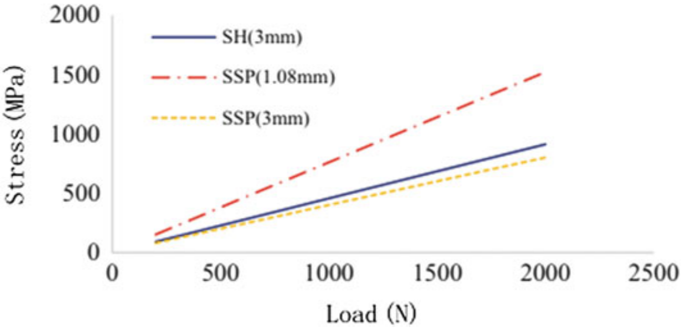


Fig. 18 Maximum Von-Mises stress on the sandwich structure of different cores under the loads from 200 to 2000 N [33]

As shown in Fig. 18, SH undergoes significantly less stress than SFP (1.08 mm) under the loading from 200 to 2000 N. While they differ in thickness, they are the same in weight. It can be inferred that honeycomb core undergoes less stress than the solid plate core of the same weight. As for SSP (3 mm) and SH (3 mm), these two specimens are of the same thickness, while the SSP (3 mm) is three times heavier than the SH (3 mm). Despite this, they demonstrate more or less the same stress resistance performance. Therefore, while keeping the same mechanical performance, the honeycomb structure can substitute heavier solid structures.

6 Energy Efficiency

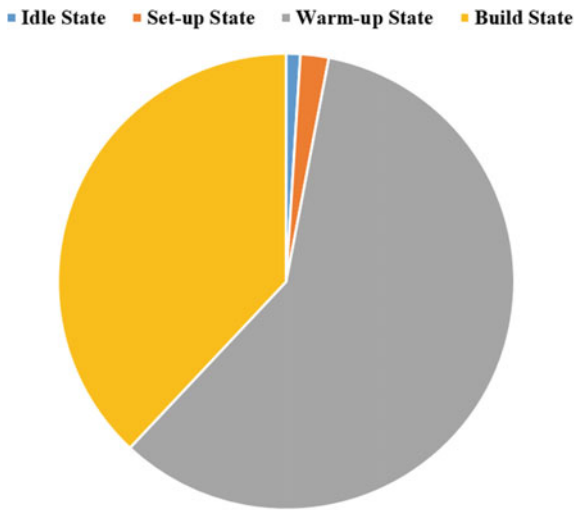
The traditional manufacturing systems use a high amount of energy and water and produce high-level waste materials, which negatively impacts the environment. Therefore, there is a need for more sustainable manufacturing processes with less energy consumption. 3DP is one of the solutions that minimize waste of materials in the production of 3D objects. Even the material used to support overhanging parts or complex geometries removed after parts are printing can be recycled to be reused again with filament extruder equipment. Meanwhile, traditional subtractive manufacturing machines remove materials from a block, leading to more material waste in the production process. The ratio of waste materials with the final part material can get up to 19:1 [34]. However, some people argue that waste materials can be recycled to be reused again. Even though it is, the recycling process demands lots of energy and resources, which impacts the environment.

3D printing impacts the environment comparatively lower than traditional manufacturing methods due to less energy usage. According to Kreiger et al. [35], 41–64% of energy reduction occurs during the manufacturing of polymer products with low-cost FDM 3D printers. Moreover, the fabrication of objects with 3D printers does not require any extra special tooling as traditional manufacturing does, and it makes 3D printers more sustainable than the other one [36].

On the other hand, some researchers have disagreed with these points. For instance, Kurman et al. [37] stated that 3D printing uses an extremely high amount of electrical energy, according to researchers at Loughborough University. The researchers compared the energy consumed to manufacture similar objects by industrial 3D printers and injection molding machines. The estimation showed that the 3D printer uses 50–100 times more electrical than the other one. Other authors stated that FDM printing affects human health and the environment when printing with ABS and PLA materials, and it generates 1.61×10^{10} ea/min and $4.27–4.89 \times 10^{8}$ ea/min emissions [38].

3DP needs energy and material as consumables in order to fabricate 3D objects. Usually, the whole needed energy is converted from electrical energy, and it is divided into three groups: thermal, mechanical, and auxiliary energies [39]. The energy distribution of FDM sub-processes [40] is shown in Fig. 19.

Fig. 19 Energy distribution of the FDM process



7 Conclusion

Additive manufacturing is already widely applied in various areas as a manufacturing technique, and it facilitates the production processes of fabrication of parts. FDM is one of the first invented 3D printing technologies and keeps on to be one of the most popular techniques because of its key advantages: the most simple and easy-to-use printing principle, variety of materials, and low cost.

This book chapter discusses a review of FDM 3D printing technology in terms of technologies and energy consumption. Lots of researches were conducted on the invention of strong materials and multi-material or multi-color printing. Results revealed that FDM is a promising technology with high potential. However, researchers still need to carry out on topics of limitations of the technology in order to fully make FDM technologies to be a practical, reliable, and effective solution.

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