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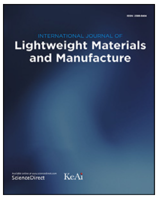

Original Article

Development of a large-scale multi-extrusion FDM printer, and its challenges

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ABSTRACT

This study focuses on the development of a large-dimensional 3D printer and its challenges in general. The major fused deposition modeling (FDM) printers focus on printing small-scale parts due to their challenges in printing large-scale objects using thermoplastic polymer filaments. A novel large-dimensional multi-extrusion FDM printer is developed at the workshop and printed several large-dimensional objects to emphasize its prospects in developing large-scale products. The printer has a print bed with a dimension of 900 mm × 1100 mm × 770 mm with respect to the length–width–height (L–W–H), respectively. There are many challenges to successfully printing large-dimensional objects using FDM technology. The experimental design elaborates on the challenges experienced during printing various large-dimensional objects. In addition, the paper focuses on the qualitative analysis of the optimal process parameters in section 4.5. Based on the experimental results, the key challenges are found to be uneven bed temperature, bending of print bed due to thermal effect, surface unsticks due to lack of adhesive force, surrounding temperature, and irregular filament feed. Experimental results also validate the key design specifications and their impact on enhancing large-scale 3D printing. The developed printer is capable of printing large-scale objects with five different thermoplastic materials using five individual extruders simultaneously. It adds a new dimension of flexible automation in additive manufacturing (AM).

1. Introduction

Additive manufacturing (AM) is a fast-growing technology in advanced manufacturing sectors. It has become more and more popular since the introduction of this technology at the end of the twentieth century. For the production of complex geometries with limited material resources, it is the most suitable technology in recent years. However, this technology has many limitations such as long product development time, and limited available materials, and mainly useful for small-scale object printing. For large-volume printing, casting is one of the most popular technologies in the manufacturing sector. It is very much necessary to focus on large-scale product development using this technology to introduce more flexible automation in manufacturing industries. AM has many advantages over conventional manufacturing technology, among them the two significant advantages are very less material waste and they can produce complex geometrical shapes.

Large-scale FDM printing technology is becoming popular in modern manufacturing industries. Due to many obstacles in printing large-dimensional objects, it is crucial to investigate further in this area. The FDM technology is very limited to small-scale objects due to several key challenges such as improper adhesion, inefficient solidification, imprecise nozzle temperature, long build time, and small build thickness.

Continuous development of digital manufacturing technologies has led to the emergence of new technologies such as AM. One of the most popular AM technologies is based on FDM or fused filament fabrication (FFF). During the FDM process, a plastic filament in the form of a wire is continuously extruded through a heated nozzle and deposited on the printer's bed in a layer-by-layer fashion. As a result, a model which began its life as a digital image appears as a physical object and it can be used as a fully functional part or just a prototype. The FDM printed parts have found their application in numerous areas of industry such as medicine [1], casting [2], education [3], etc.

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The main benefits of including AM technology in the manufacturing processes are the ability to create complex shapes, the large variety of polymers used, and material efficiency as opposed to machining. Nevertheless, it is worth mentioning that FDM–based AM has certain limitations and disadvantages. The main ones are a long time of manufacturing, the anisotropic nature of mechanical and physical properties of parts, need for post-processing such as support structure removal and surface polishing. Moreover, the sizes of printed objects are limited by the volume capacity of the machine.

If we look closely at the FDM machine market, we notice that the bulk of machines that are popular among customers have a build volume of approximately 250 mm × 250 mm × 300 mm. As for the industrial size machines, the largest FDM machines that work with plastic filaments have a build volume close to 1000 mm × 1000 mm × 1000 mm. As far as the price is concerned, there is a strikingly large difference between desktop and industrial machine configurations. Even though the market offers a range of sizes tailored to customers' needs, there is a lack of knowledge on the performance and challenges associated with printing objects of large sizes. For instance, the number of obstacles that can be encountered during the 3D printing of large parts may include problems of material or hardware-related nature. Therefore, the current research aims to explore the obstacles to 3D printing objects on a large-scale multi-extrusion FDM machine.

It is important to note that commonly found issues that are inherent to FDM–based AM, can be even more aggravated when manufacturing large parts. Namely, weak/strong bed adhesion [4], shrinkage [5], the weak bond between layers [6], and low dimensional accuracy [7]. In addition, the number of controllable process parameters on FDM technology is significantly high [8].

Large-scale 3D printing opens a new door to the manufacturing industry. This area is growing around the world. It uses various materials for various purposes including polymer composites such as PLA, ABS, Polyurethane, thermoplastic, concrete, Ti6Al4V, and other alloys.

Work on a large-scale 3D printer with polyurethane foam as the object material and shaving foam as the support material is introduced, and a six-degree-of-freedom cable-suspended robot is used to print a large object [9]. Another research presented a prototype of a large-scale material extrusion 3D printer that has been designed using thermoplastic polymers. The authors also suggested certain key design elements and their influence on improving large-scale 3D printing [10]. Podium support was created with PLA composites using a large-scale 3D printer. It showed that the tensile strength of the composites increased from 34 to 54 MPa as the poplar/PLA fiber size decreased [11].

A few research groups focused on the development of large-scale concrete printers. Some of them used a robot as their foundation adding the additional extrusion for material deposition purposes. A concrete-based large-scale printer is proposed for the utilization of deformable materials [12]. Another 3D printing system is proposed for fabricating large models by making multiple projections in each layer. A robotic arm with a six-degree-of-freedom in motion (UR10 robot arm) is used to move the printing platform for concrete manufacturing [13]. In another work, large-scale 3D printed structures such as tiles are produced using concrete materials. The work emphasized the critical design parameters such as pattern shape, width, and height [14. Others have analysed the influence of the large-scale 3D printing process on polymer concrete. Two printing orientations were compared to the control cast part to examine the mechanical performance during printing. In addition, two possible reasons for the degradation of mechanical properties were discussed, namely poor layer adhesion and material degradation [15].

In a similar metal-based 3D printing research, a large-scale and oxidation-free component (500 mm length) out of Ti6Al4V was developed under open atmosphere conditions with DED. It resulted in fine bonding and no cracks having a porosity of less than 0.1%. The printed object showed a tensile strength of up to approx. 1270 MPa and yield strength of up to 1170 MPa, which are significantly higher than the relevant specifications [16].

Concerning printing mechanical components, a group of researchers created a static large-scale truss structure with composite polymer from 3D printed connectors and PET bottles [17].

For wood-based manufacturing technology, a large dimension of 2000 mm × 580 mm pattern with six layers and around 2.5 mm thickness was printed with a gantry robot and the total length of the used filament was 174 m [18].

In electronics, a 3D printed flat disk monopole is used with 72 mm diameter curved on a 25.6 mm diameter AIREX foam cylinder, powered by a 50 Ω SMA connector and placed above a 30 × 30 cm^2 square metal reflector plane. The workpiece was printed by a large-scale 3D printer [19].

It is of paramount importance to identify optimal process parameters when printing large-size parts. For example, to establish adequate interlayer bonding, the printing speed might need to be increased so that the thermal gradient between layers of newly deposited and previously deposited layers is low enough to ensure proper bonding. As for the issues related to the hardware, the bed leveling should be corrected to avoid printing difficulties. To address all the possible minor and major challenges associated with printing large objects, the authors have attempted to identify:

- Optimal controllable process parameters.
- Types of defects of printed parts.
- Requirements for new machine design.

To realize all the established objectives, a large-scale customized FDM printer has been designed and numerous attempts of printing large parts have been made with different levels of success.

In brief, the paper is presented in the following order. Section 1 discusses the introduction where various areas of large-scale printer applications are discussed. Section 2 gives a short overview of the developed printer. Section 3 highlights the influence of process parameters in printing large-scale objects successfully. Section 4 explains the challenges of printing large-scale objects. Section 5 shows some examples of successful printing. And, Section 6 discusses conclusions and future works.

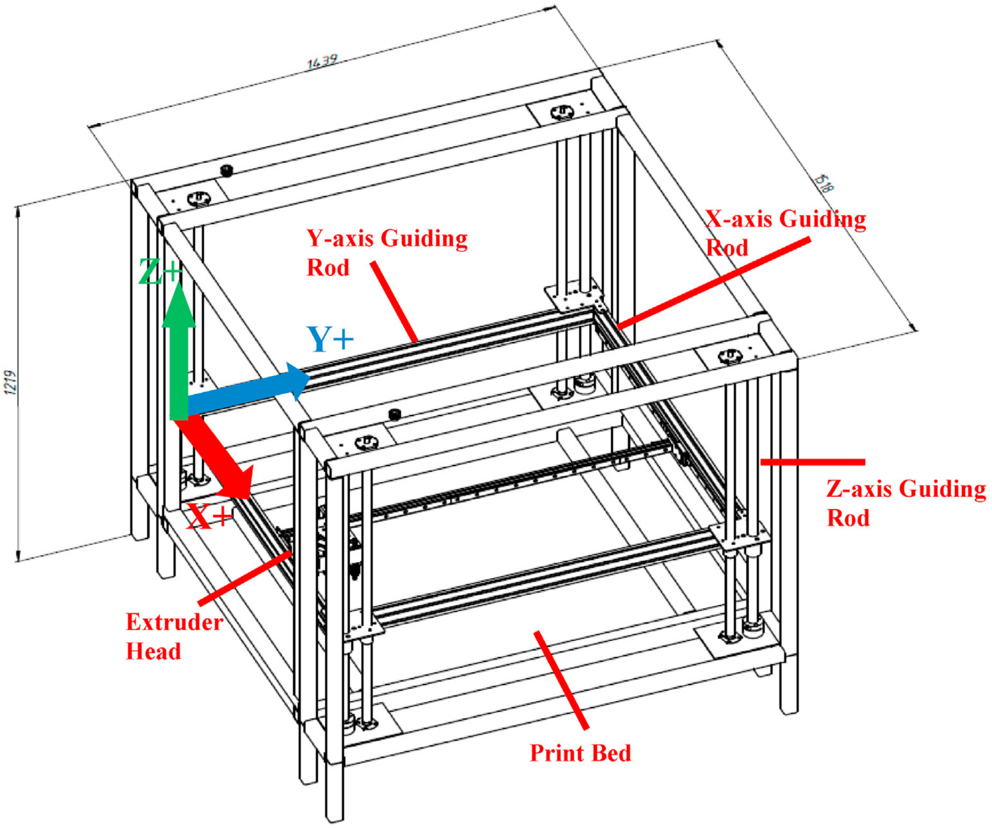
2. Large-dimensional customized printer specification

A large-scale FDM printer has tremendous potential for the aerospace, automotive, medical, food, construction, marine, and defense industries. However, up-to-date, the available large-scale printers are very limited and focus only on single extrusion-based product development. The CEO of aniwaa has indicated the presented the latest large-scale available 3D printers as shown below Table. Table 1 shows the latest development of large-scale FDM printers.

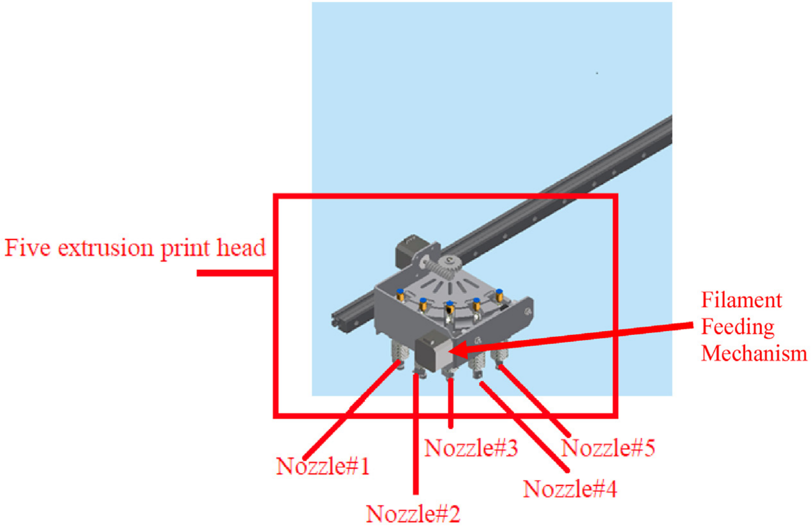
Besides the above, a large dimensional multi-extrusion FDM printer is developed at the workshop and has been patented by the Eurasian Patent Agency. The conceptual design of the printer is shown in Fig. 1. The hotbed is designed to print an object with a dimension of 900 mm × 1100 mm × 770 mm in, L–W–H respectively. Five nozzles can be used to print with five different materials

Table 1
The latest development of large-scale FDM technology.

Brand	Country of Origin	Build Volume	Build Size	Price
BLB Industries	Sweden	6000 L	2000 mm × 2000 mm × 1500 mm	$ 298,000
Tractus3D	Netherlands	1649.34 L	⌀ 1000 mm × 2100 mm	$ 59,000
3D Platform	United States	1050 L	1000 mm × 1500 mm × 700 mm	$ 49,999
BigRep	Germany	1015.08 L	1005 mm × 1005 mm × 1005 mm	$ 30,000
CreatBot	China	1000 L	1000 mm × 1000 mm × 1000 mm	$ 29,999



(a) 3D view of the developed printer



(b) Five-extrusion print head

Fig. 1. The conceptual design of the multi-extrusion large-dimensional 3D printer.

(and even with different colors, simultaneously). The filaments are fed to the extruders in real time without stopping the machine. This saves time and energy with regard to cleaning the nozzle head, unlike a single extrusion printer. Cleaning nozzle heads takes a good amount of time from opening the nozzle to re-install it to the printer. The machine has been built in such a way that it could be paused in the middle of printing a large-dimensional object which may take a few days to print. In such cases, the motors are switched off but the nozzles maintain the same temperatures which helps to avoid the materials clogging the nozzle head.

The (key novelty lies in our work is adding) five direct type extruders to the print head. It gives a very flexible material selection option without changing and cleaning the filament from the extruder. The materials used are PLA, ABS, BFlex, CFRP, and Nylon to create various objects successfully. Some of the materials even worked well in open-air conditions, thus robust with the surrounding temperature. It should be noted that in comparison to 3D printers listed in Table 1, the proposed design has more than twice more extruders. As opposed to Bowden-type extruders, the five extruders are of a direct kind and that allows for manufacturing both hard and flexible plastics. To decrease the weight of the print head, the design has only one filament feeding mechanism as shown in Fig. 1(b).

In general, the FDM machines that allow for multi-material manufacturing are divided into multi-nozzle and single nozzle designs. In a single nozzle setup, the materials are extruded one after another through a shared single nozzle and, therefore, several serious issues arise when utilizing a single nozzle model. The obvious problem is that the material being mixed should have the same melting temperatures. Otherwise, it will be necessary to adjust the nozzle level each time the materials switch due to thermal expansion/contraction of the nozzle. In addition, the nozzle should be evacuated from previously used filament before the new one is deposited. Nevertheless, the multi-nozzle configuration is not free of drawbacks either. Therefore, Table 2 was prepared to highlight the major advantages and disadvantages of the customized FDM machine.

As far as temperature control is concerned, Fig. 2 displays the temperatures for five nozzles and the hotbed. The temperature settings are controlled based on our equipment. For different materials, the melting temperatures are different, thus, a precise setting is necessary for each material separately. We can set them through a customized programming window or from the buttons next to the display screen. The heaters are connected under the hotbed. It takes a few minutes to reach the temperature above 50° Celsius due to the large-dimensional print bed. The print bed is made of steel alloys. Temperature control is one of the key indexes in 3D printing technology. Many important factors such as bonding between layers, filament melting, adhesion to the hotbed, and print accuracy depend on the optimal temperature settings. During the printing, several materials are used such as PLA, ABS, Bflex, Nylon, and PETG. Each material has a different melting temperature and usually, it's given in a range such as 210–230, 230–250, 180–210, etc. degrees Celsius.

Table 2
Summary of pros and cons of the customized large-scale multi-material FDM machine.

Parameter	Advantage	Disadvantage
Print nozzle	Rapid material switch; no material mix; waste is at minimum; nozzle diameter can be varied; nozzle offset calibration is not required	Filament oozing might occur for idle nozzle; calibration of all nozzles is required; idle nozzle can knock off the print
Temperature	Each nozzle can have its own temperature.	Energy consumption is higher due to the presence of multiple cooling fans, heat blocks, and large bed sizes. Need for a large enclosed chamber when printing heat-sensitive materials
Cooling	Each extruder's cooling fan can be adjusted	Bulkiness is due to the presence of cooling fun at each extruder.
Calibration	The nozzle switch mechanism allows for quick calibration	Calibration is needed if different temperatures used
Size	–	All extruders located at the moving platform occupy more space
Control panel	–	An advanced control panel is needed

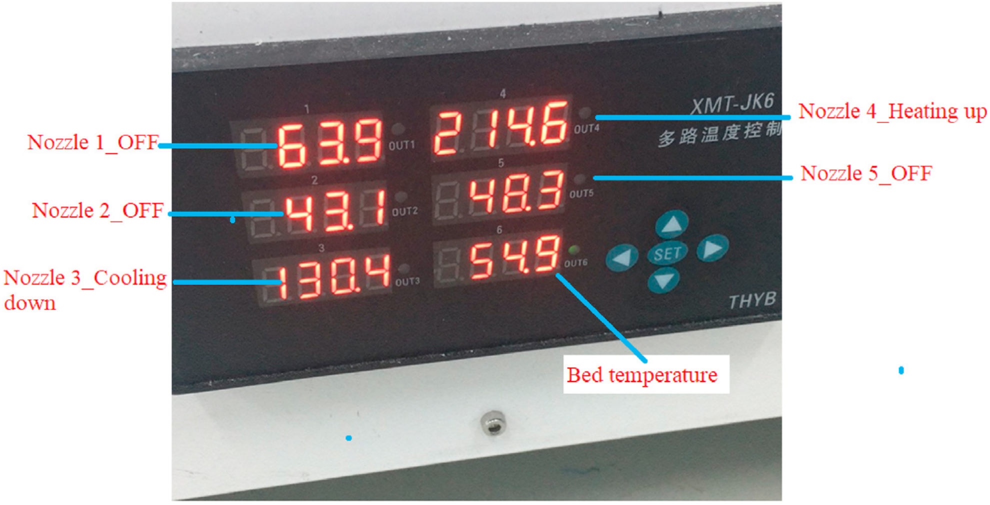


Fig. 2. The temperature monitoring system of the multi-extrusion FDM printer.

3. Major process parameters affecting the quality of the parts

3.1. Parameters affecting dimensional accuracy

Dimensional accuracy is one of the key requirements in small-scale products and it goes up to the micrometer level. However, for large-sized products, the dimensional accuracy could be compromised up to a millimeter level. Dimensional inaccuracy can be caused by two major factors: machine error and material properties. As far as machine error is concerned, the high error might be a result of high vibrations and inertial forces associated with moving heavy print heads. Therefore, choosing the correct machine kinematics is of paramount importance. In our case, the "Cartesian" type is chosen as it is the most common and easy-to-assemble type printer. The machine is classified as those that have a stationary platform with the extruder moving three-dimensionally. In any case, due to the high popularity of chosen machine configurations, it is possible to identify how bigger versions of small-scale FDM machines perform in practice. It should be noted that the movement of the print head in horizontal axes is realized through rubber belts while the *z*-axis movement is possible through lead screw rods.

As for material-related errors, they mostly occur due to polymer properties. For instance, it is well known that most popular FDM plastics tend to shrink and distort after the solidification process. Due to the phase change process, residual stresses develop in polymers and during rapid solidification, the stress is released resulting in shrinkage or warpage [20]. The most commonly used plastics such as PLA has shrinkage level of up to 3%.

Fig. 3 shows two large-dimensional products printed with the developed printer. The length of the product is 650 mm and the width is 60 mm. The part is printed to apply in a biomedical engineering application, called a human posture corrector. The blue material is PLA and the white one is Flex material. Different materials and colors are chosen to investigate printing performance for large-scale objects. Between the designed and the printed parts, there is a dimensional inaccuracy of (±)−0.8 mm with respect to the length (L−W−H), which constitutes a 0.12% error. Thus, it can be concluded that the error is attributed to material property. As for the errors in horizontal directions, their magnitudes are comparable to those found in small-scale printings.

3.2. Mechanical properties

When it comes to the mechanical properties of FDM printed parts, the first thing that comes to mind is the issue of anisotropy. Since the manufacturing process is realized in a layer-by-layer fashion, the mechanical properties of printed parts significantly differ within one part depending on the direction of applied force. The maximum strength is achieved when the force acts along the deposited layers while interlayer bonding is the weakest part. Therefore, process parameters must be chosen in a way that beneficial conditions are established for maximum interlayer bonding strength. According to Yin et al. [21], interfacial bonding

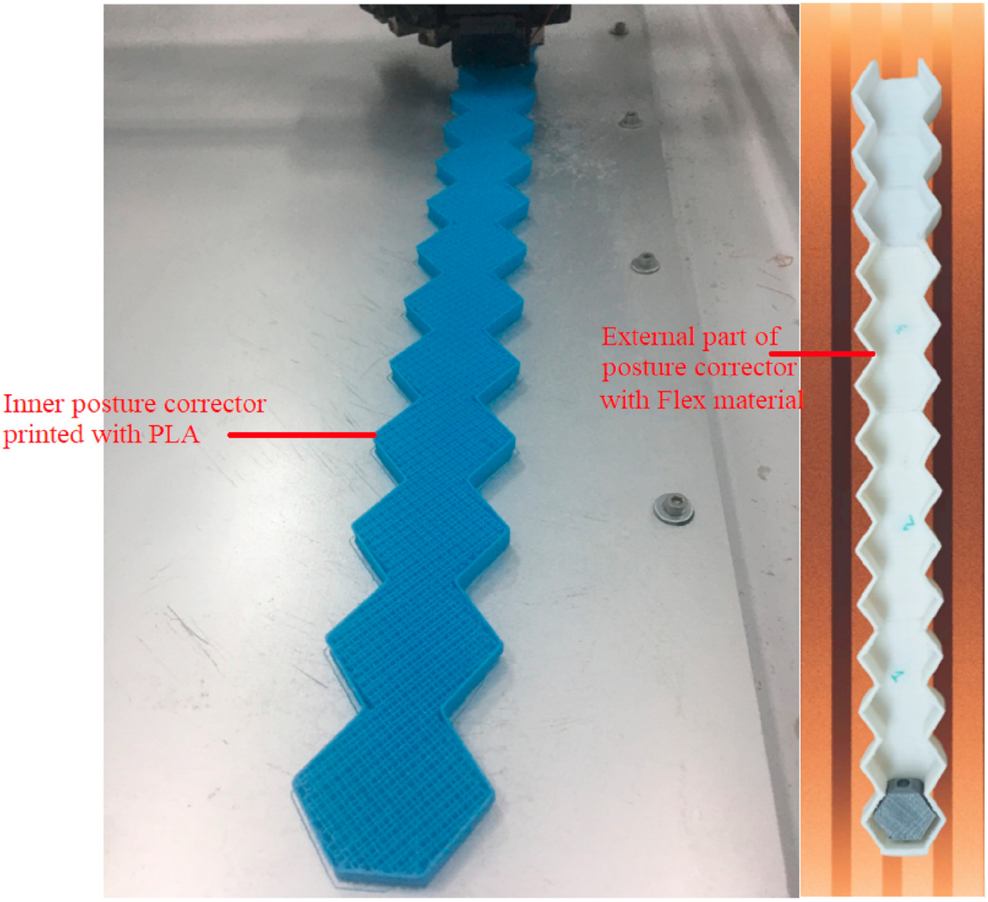


Fig. 3. 650 mm long posture corrector printed with customized FDM printer.

depends on the wetted area and the magnitude of intermolecular diffusion. In turn, the level of fusion is a function of heat. Therefore, the higher the heat supplied in the interlayer region, the higher the degree of sintering between two materials. Nonetheless, it should be noted that excessive heat can cause over-melting and distortion of the part. That is why when printing small-scale objects, it is important to cool down the print by simulating convective cooling. That is realized by setting up the cooling fans. However, the opposite scenario is true for printing large-scale objects. During printing bulky parts, the nozzle travels large distances until it comes to the point where it started. As a result, the time taken to print increases allowing for substantial cooling of the previously printed layer. Although it was reported by Brian et al. [22] that it is sufficient for a newly deposited layer to increase the temperature of the previously placed layer to the glass transition temperature, the work of Nurbol et al. [23] has demonstrated that preheating the layer before depositing on it increases the bonding strength.

Among the mechanical properties of FDM printed parts, the frequently tested criteria are bonding strength, hardness, toughness, brittleness, elasticity, and plasticity. An example in Fig. 4 shows that the bonding strength is not sufficient in a large-dimensional part, especially for a multi-material product. Fig. 4 left shows an AFO printed with PLA and Flex material, whereas, the right graph shows the PLA and PETG (materials used to print the object). As for the left graph, due to the object's shape, the Bflex material did not fully stick on the PLA giving cracks on the joint. For the right graph, the PLA was not sticking to the hotbed properly, especially on the left side.

In addition to issues related to printing large-scale objects, there is a big challenge when different materials are used to print a single object. The main obstacle is the bonding strength between the layers of the new materials. As the melting temperatures are different for different materials, with a unified temperature it is challenging to get an adequate interfacial bonding. In the case of Fig. 4, the difference between the printing temperatures of the two materials was 20 °C. (Thus, by applying an additional laser beam, the problem could be solved. When two unidentical materials are blended to make a single product, the challenges are found to be on the last surface of the first material and the first surface of the second material. Once a layer does not stick to the hotbed surface, there is a high probability to print it unsuccessfully. It will create deviation to the next layer and it keeps deviating until finishes printing the object. Thermal conduction is another factor that affects printing quality.)

3.3. Print (time) speed

Another major parameter that was observed to be of high importance is the printing speed or nozzle speed. When considering large-scale printing, the issue of time gains even more

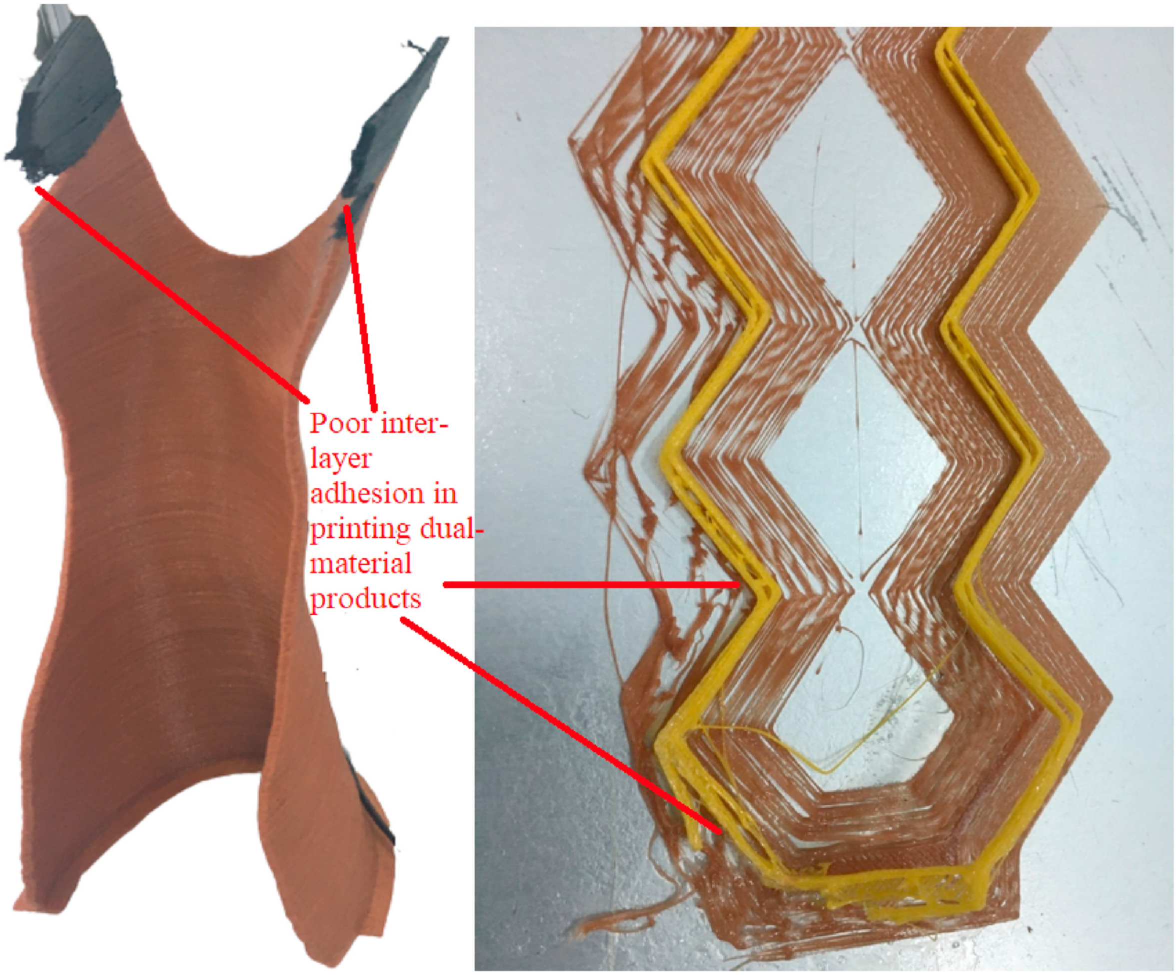


Fig. 4. Highlights the adhesion failure and its effect on the mechanical properties.

importance. On one hand, the speed of printing should be increased to partially compensate for the time lost on printing large volumes of material. On the other hand, high speed creates the risk of initiating high vibrations for the massive print head and other machine parts. In addition, as was mentioned in the previous section, the issue of heat-driven diffusion is important for generating quality parts. The slower the nozzle moves, the more heat is supplied from the hovering nozzle. Moreover, the rapid moving of the nozzle creates conditions for greater convective cooling which is not in favor of heat-driven diffusion. To identify optimal printing time and conditions for large object manufacturing, numerous trial printings were performed. For instance, Fig. 5 shows the example of the successful manufacturing of a prosthetic hand (Flex) and skeleton (PLA). The prosthetic hand took about 27 h and the skeleton took about 29 h using a print speed of 22 mm/s and nozzle diameter of 0.5 mm. As can be seen, choosing a slow printing speed is favored for the reasons described above.

(Build time depends on several factors such as nozzle dimension, filament feed rate, and printing speed. When it is required to have a fine surface, it is better to keep the above parameters on the average scale but it may take a long time to finish the product. Based on the part dimension, printing time varies. The product build time is calculated using the below formula:

$$\text{Printing time} = \frac{\text{Original layer thickness}}{\text{Altered layer thickness}} \times \text{Average print time per layer}$$

As for the combination of optimal process parameters, Table 3 contains some of the important printing parameters which lead to manufacturing successfully parts shown in Fig. 6. From Table 3, we can see that for flexible polymers the first layer's line width was set at 150%. This is done to improve the adhesion of the print to the bed.

Table 3
FDM process parameter values for successful printing.

Printer setting	Posture corrector (Flex)	Prosthetic hand (PLA)
Printing speed	22 mm/s	25 mm/s
Retraction speed	40 mm/s	40 mm/s
Layer Height	0.2 mm	0.2 mm
First Layer Extrusion Width	150%	100%
Shell Thickness	0.8 mm	1 mm
Infill Overlap	5%	5%
Infill Pattern	Grid	Grid
Nozzle Temperature	240 °C	250 °C
Bed Temperature	58 °C	58 °C

3.4. *Optimal process parameters*

Optimal process parameters are selected by tuning the printing conditions. For the developed machine, the PLA material requires a nozzle temperature of 230 °C, and print speed is 22 mm/s; the ABS material requires a nozzle temperature of 250 °C and print speed is 22 mm/s and for the Bflex material, the nozzle temperature is 240 °C and print speed is 22 mm/s. It was observed that a printing speed is 30 mm/s also works well but for a large-dimensional part, it is better to reduce the speed to have a stable printing condition. Fast speed may cause oscillation during printing and if it causes deviation to one of the surfaces, it is very unlikely to get the precise print dimension. With the optimal process parameters, successful products could be developed as shown in Fig. 6.

3.5. *Printing parameter tuning*

Table 4, 5, and 6 show the tuned printing parameters for successfully printing large objects such as insole, prosthetic hand, and posture correctors. Parameters were chosen based on the types of materials used in printing those parts. Many other parameters were

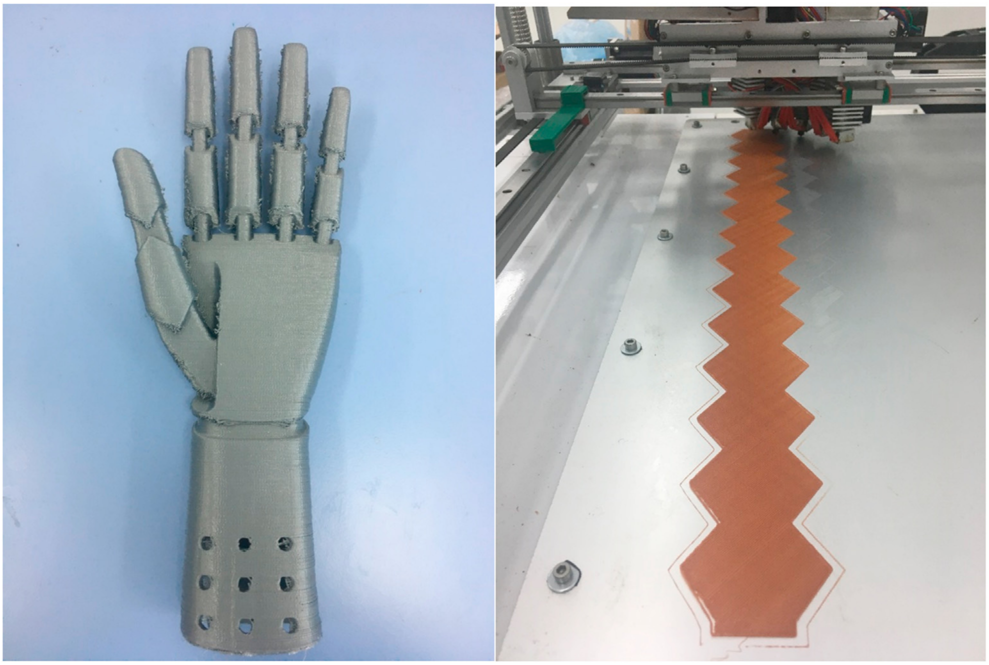


Fig. 5. Long printing time (27 h) for successful printing of large-object.

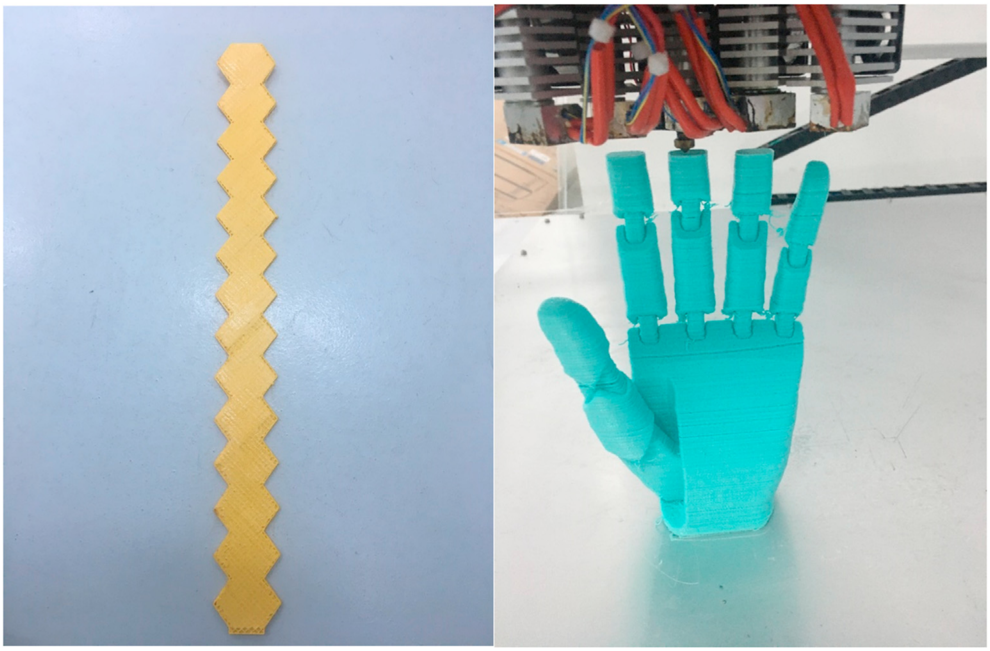


Fig. 6. Successful printing depends on the optimal parameters selection.

Table 4
Parameter settings for printing an insole with Flex material.

Printer setting	Value
Printing speed	22 mm/s
Retraction speed	40 mm/s
Layer Height	0.2 mm
First Layer Extrusion Width	150%
Shell Thickness	0.8 mm
Infill Overlap	5%
Infill Pattern	Grid
Nozzle Temperature	240 °C
Bed Temperature	58 °C

Table 5
Parameter settings for printing a prosthetic hand with PLA.

Printer setting	Value
Printing speed	25 mm/s
Retraction speed	40 mm/s
Layer Height	0.2 mm
First Layer Extrusion Width	100%
Shell Thickness	1 mm
Infill Overlap	5%
Infill Pattern	Grid
Nozzle Temperature	250 °C
Bed Temperature	58 °C

Table 6
Parameter settings for printing a long posture corrector with BFlex material.

Printer setting	Value
Printing speed	22 mm/s
Retraction speed	40 mm/s
Layer Height	0.2 mm
First Layer Extrusion Width	100%
Shell Thickness	1 mm
Infill Overlap	5%
Infill Pattern	Grid
Nozzle Temperature	240 °C
Bed Temperature	58 °C

set before and finally, the below tables generated the expected outputs in printing large-dimensional parts.

4. Challenges in printing large-dimensional parts

The key challenges are uneven bed temperature, bending of print bed due to thermal effect, surface unstick due to lack of adhesive force, and irregular filament feed.

4.1. Uneven bed temperature

As the print bed has a dimension of 900 mm × 1100 mm × 770 mm in L–W–H, control of heating throughout the whole bed is tedious and time-consuming. Often, the central area has the highest temperature whereas the peripheral areas have the lower temperature. There is a deviation between them of approximately 2 °C. Thus, heat is not proportionally distributed around the hotbed. To solve the problem, 4 to 8 heaters could help to heat it up to 100 °C. In addition, the thin scotch tape could be used to level the print bed surface as shown in Figs. 7 and 8. Once the printing is done, the tape should be removed carefully so that the first layer of the product remains intact. Adding a support structure may help to solve the surface distortion problem.

4.2. Bending of print bed due to the thermal effect

As discussed in the previous section, thermal conduction creates an uneven expansion of the print bed. The central area expands more than the peripheral areas due to the location of the heater. The central area is usually higher than the other areas due to the thermal effect which reaches the center faster. This creates three problems: first, the bed does not evenly expand; second, the temperature distribution throughout the print bed is not uniform, and third the proper adhesion problem. To solve the above problems, various types of glues, and tapes were used including thermal ones. The tape has a negative effect on the bottom surface of the product unless the support structure/layer is applied to the print setting. The effect of bending is shown in Fig. 9(a) and (b).

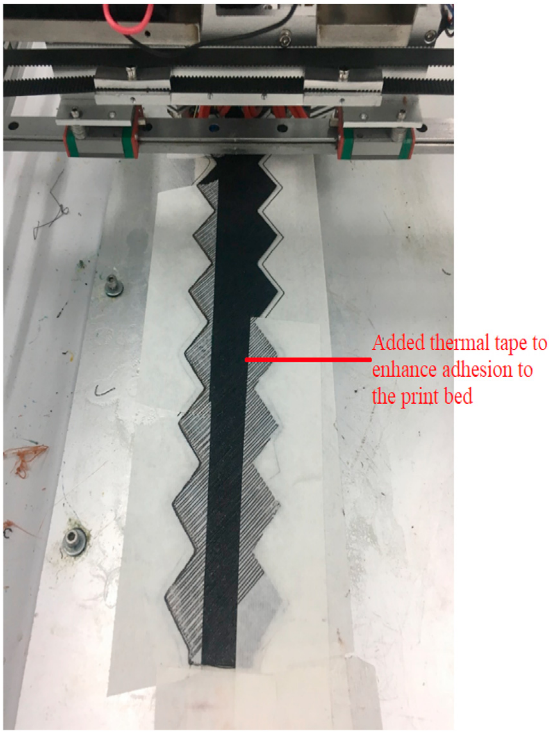


Fig. 7. Effect of uneven hotbed temperature.

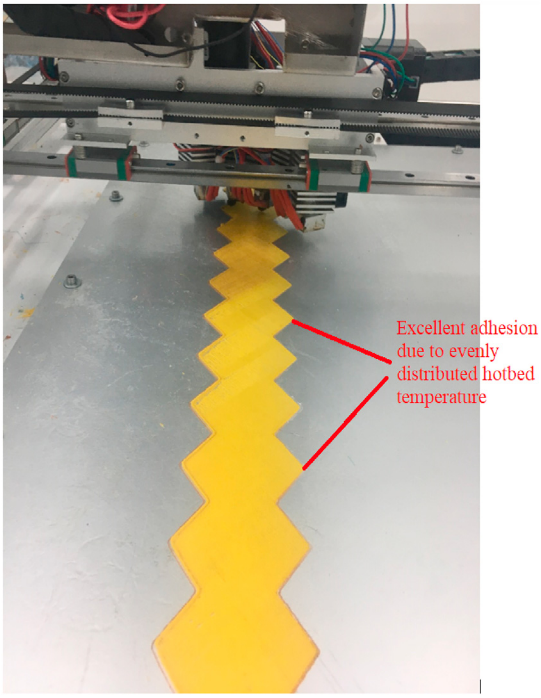


Fig. 8. Impact of optimal hotbed temperature.

4.3. *Surface lacks adhesion*

As discussed in the previous section, adhesion problems may happen due to two main reasons, namely that the temperature between the material and the bed is not optimal, and the gap between the nozzle and the print bed is more than it requires. Thus, when the material comes out of the nozzle, it does not touch the exact surface position rather it continues to the next position where it can slightly touch the surface. The touching force should also be precise otherwise; too much force will clog the nozzle head and the material will not extrude through the nozzle. This kind of adhesion problem happens depending on the print bed material, the gap between the surface and the extruder, and the bed temperature. Fig. 10 highlights the effect of lack of adhesion to the surface. In general, a sufficiently long time of bed heating helps to reach a uniform temperature and prevent the aforementioned issues.

4.4. *Vibration/swinging in printing vertical direction*

The vibration is another challenge in printing thin long objects. The images shown are various trials while printing a long object (300 mm–650 mm) vertically. When the support adhesion is not strong, it usually bends after printing 200 mm in the vertical direction. Even if the adhesion is strong, due to the total load, a distortion was observed after printing about 300 mm in the vertical direction. Once the top layer starts to deviate, the rest of the layers won't print in the right position. Thus, dimensional inaccuracy starts while dropping the printing accuracy becomes more pronounced along with surface roughness. When printed with hard materials, the top surface broke down. On the other hand, printing with Flex and soft materials does not create fracture rather it creates deviation and dimensional inaccuracy. Printing a bigger object with a diameter of 50 mm and above would work with a proper material selection. Fig. 11(a)–(d) show the printed samples in the vertical direction using different materials.

4.5. *Irregular filament feed*

Another big challenge is the material feed rate. The material feed rate needs to be consistent, otherwise, due to overflow of the material, filament retraction might occur during the process and if it is unsuccessful, the scenario would be as shown in Fig. 12(a)–(c). The material was soft and flexible, thus, due to the excessive material feeding force, the filament came out to the open platform of the printbed. Once a small portion comes out of the heater, the printing process needs to stop immediately, otherwise, the filament would keep accumulating on the workbench. In the developed printer, we have an option to modify it manually but it is not recommended always. This process can be corrected by pausing the printer and starting printing from the layer it did not print successfully. If it is noticed immediately, it could be corrected. If it is unnoticed for some time, then it could be tedious to find the original layer where the print started to be unsuccessful.

4.6. *Support structure printing initial layers*

The initial layer is a crucial point of successful printing. If the initial layer does not stick to the print bed, the printing process will be unsuccessful due to a lack of adhesion. Selecting a perfect adhesion layer is very important in FDM printing. In most cases, if the first layer remains stable, the printing process goes well unless there are other disturbances in the whole printing process. Fig. 13 shows two samples of the printing initial layer that are not properly attached to the print bed. This might happen due to

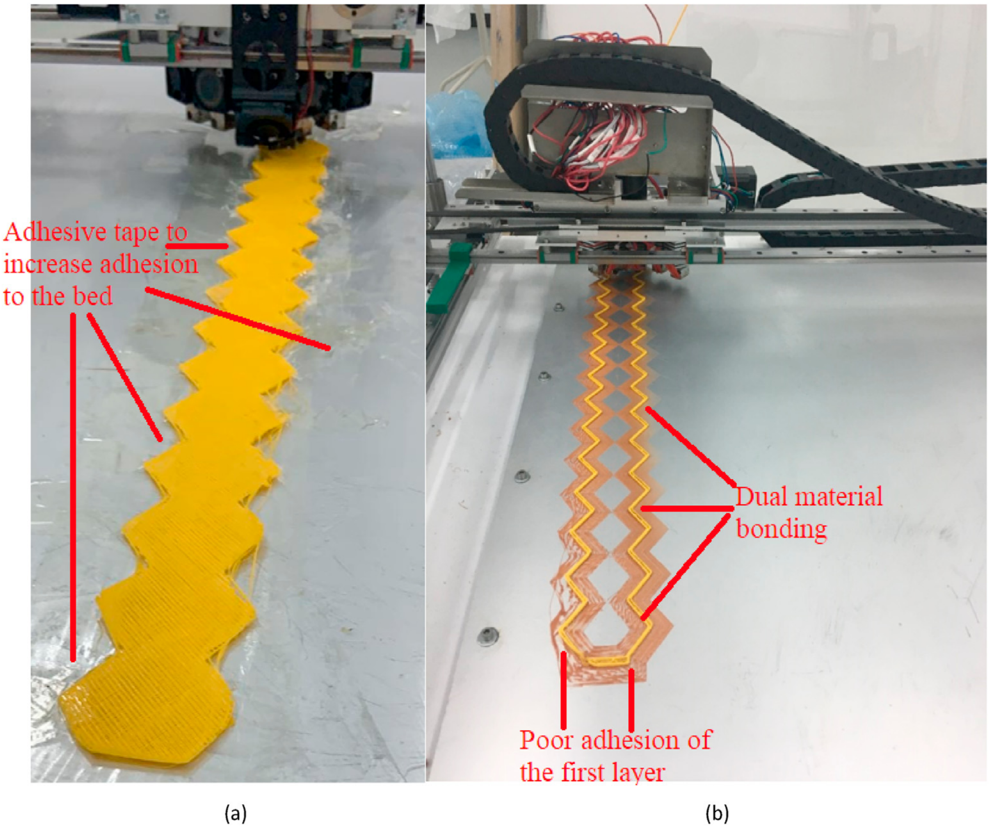


Fig. 9. Print bed/Hotbed bending scenario (a–b).

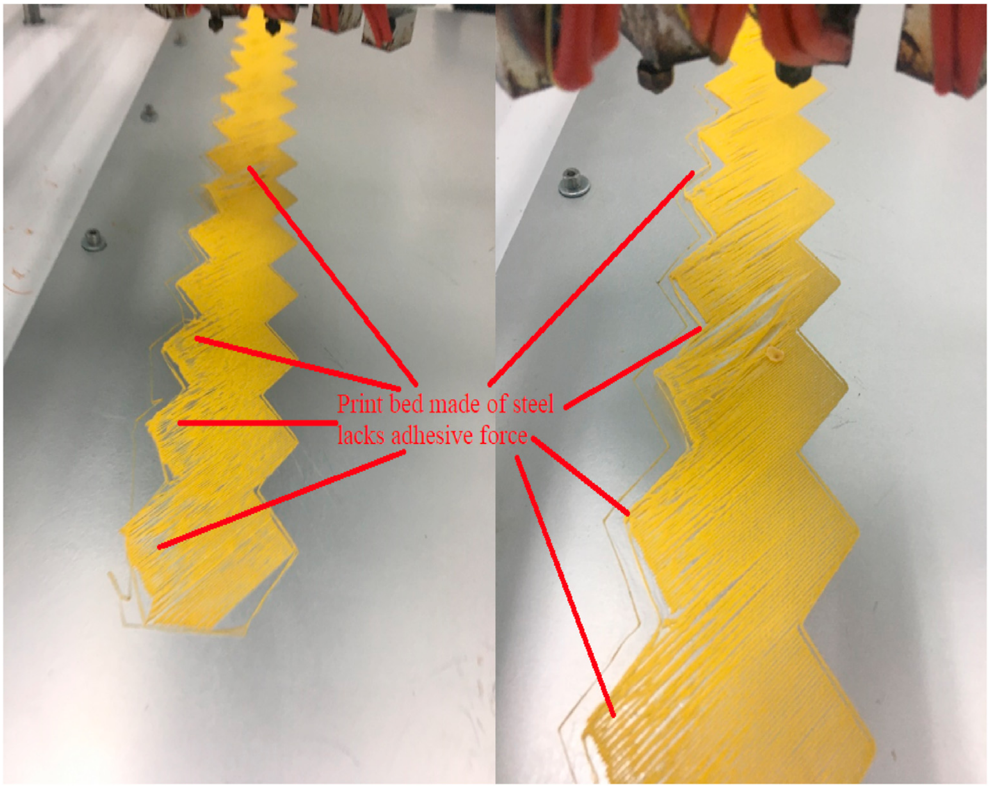


Fig. 10. Adhesion problem due to the effect of temperature and material properties.

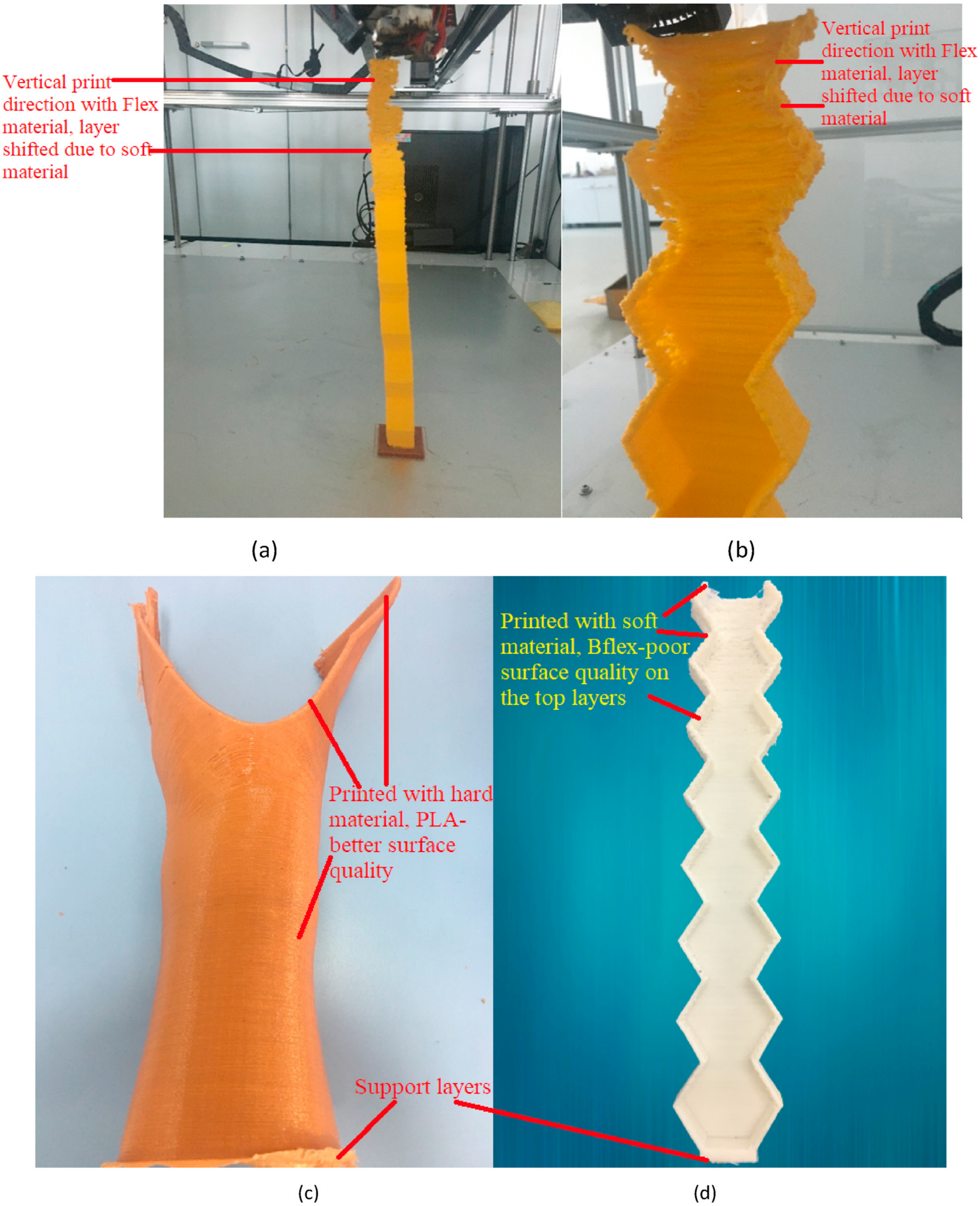


Fig. 11. Printed samples in the vertical direction and their deviation.

inappropriate bed temperature and large layer thickness. If the gap between the nozzle and bed is too much then the first layer will not adhere to the surface.

The support structure is a crucial point of successful printing. If the support structure does not stick to the surface, the printing process will be unsuccessful due to a lack of adhesion. Selecting a perfect support structure is very important in FDM printing. In most cases, if the support structure remains stable, the printing process goes well unless there are other disturbances in the whole printing process. Fig. 13 below shows two samples of support structures that are not properly sticky to the printed surface. The causes may happen due to the print bed temperature and the distance between the nozzle and the bed. If the gap between the nozzle and bed is too much then the first layer will not print in the

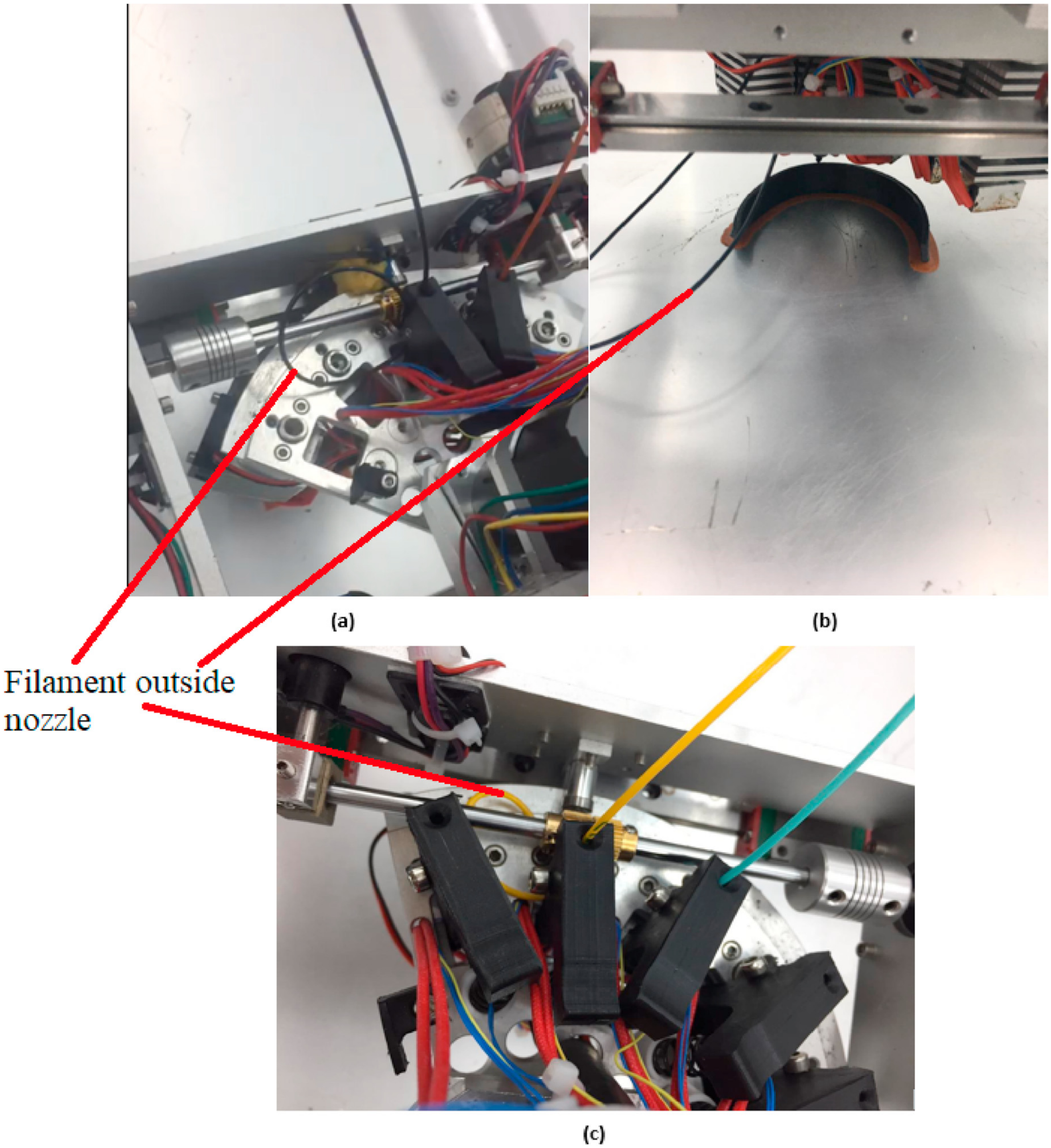


Fig. 12. Filament goes out of the extrusion due to stronger feed force (a–c).

right position, and it shifts from the original position giving the next layer a loose surface.

4.7. *Requirement of post-processing*

The figure shows a very good printed part with additional materials on the surface. The materials are not a part of the printed object rather it falls on the body when the nozzle moved from one point to the next point. The problem is seen more in soft materials than hard materials. Examples of soft materials are Bflex, and rubber and hard materials are PLA, ABS, Nylon, and so on. After melting the soft materials, the viscosity increases, making it go out of the nozzle faster than the hard materials. But, this problem is not as severe as post-processing helps to remove those additional drops of materials from the printed objects. The external surface might slightly distort due to the additional materials on its surface but in most cases, it generates the expected results with a very smooth external surface. Fig. 14 highlights the need for the post-processing of FDM printed parts.

4.8. *Inefficient nozzle cooling*

Fig. 15(a) and (b) display the possible effect of inefficient cooling of the filament. It was observed that the materials were

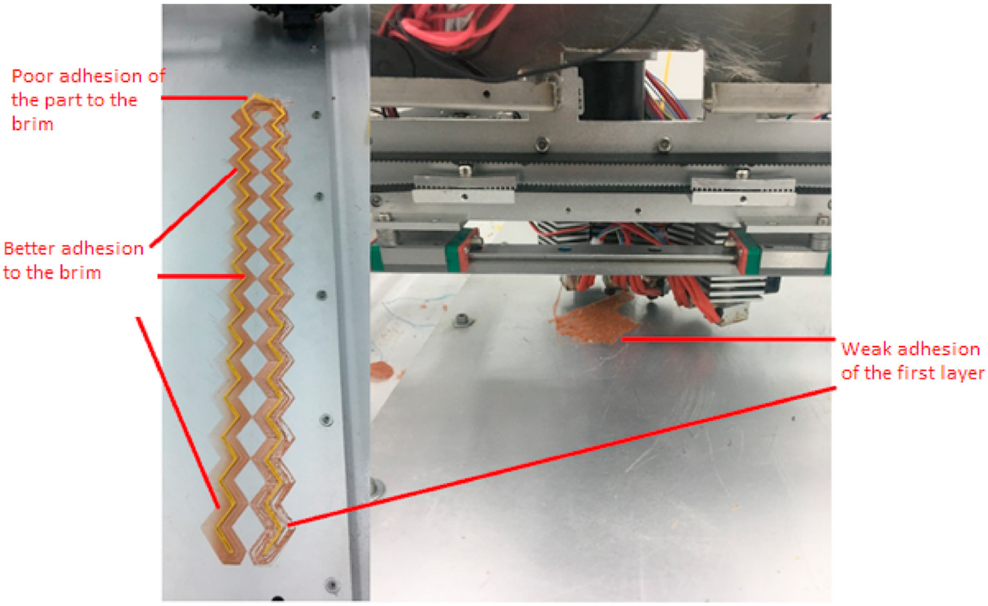


Fig. 13. Printing of support layers initial layers.

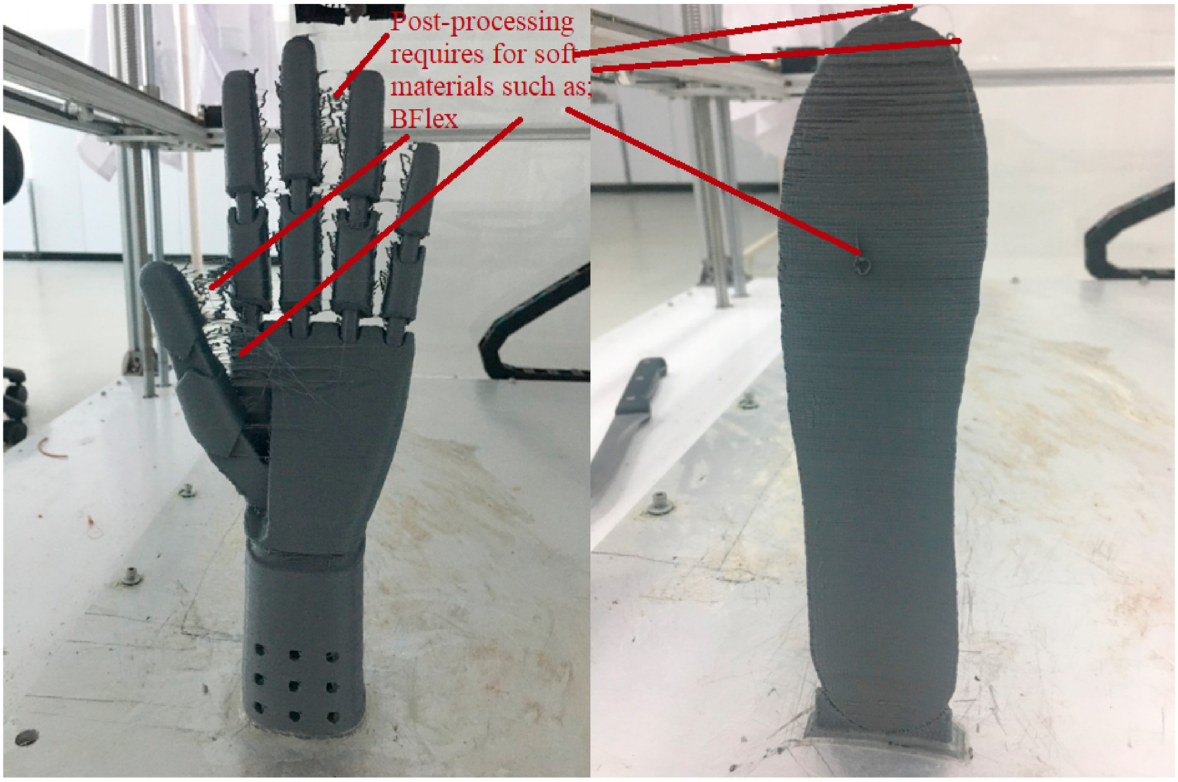


Fig. 14. Requirement of post-processing.

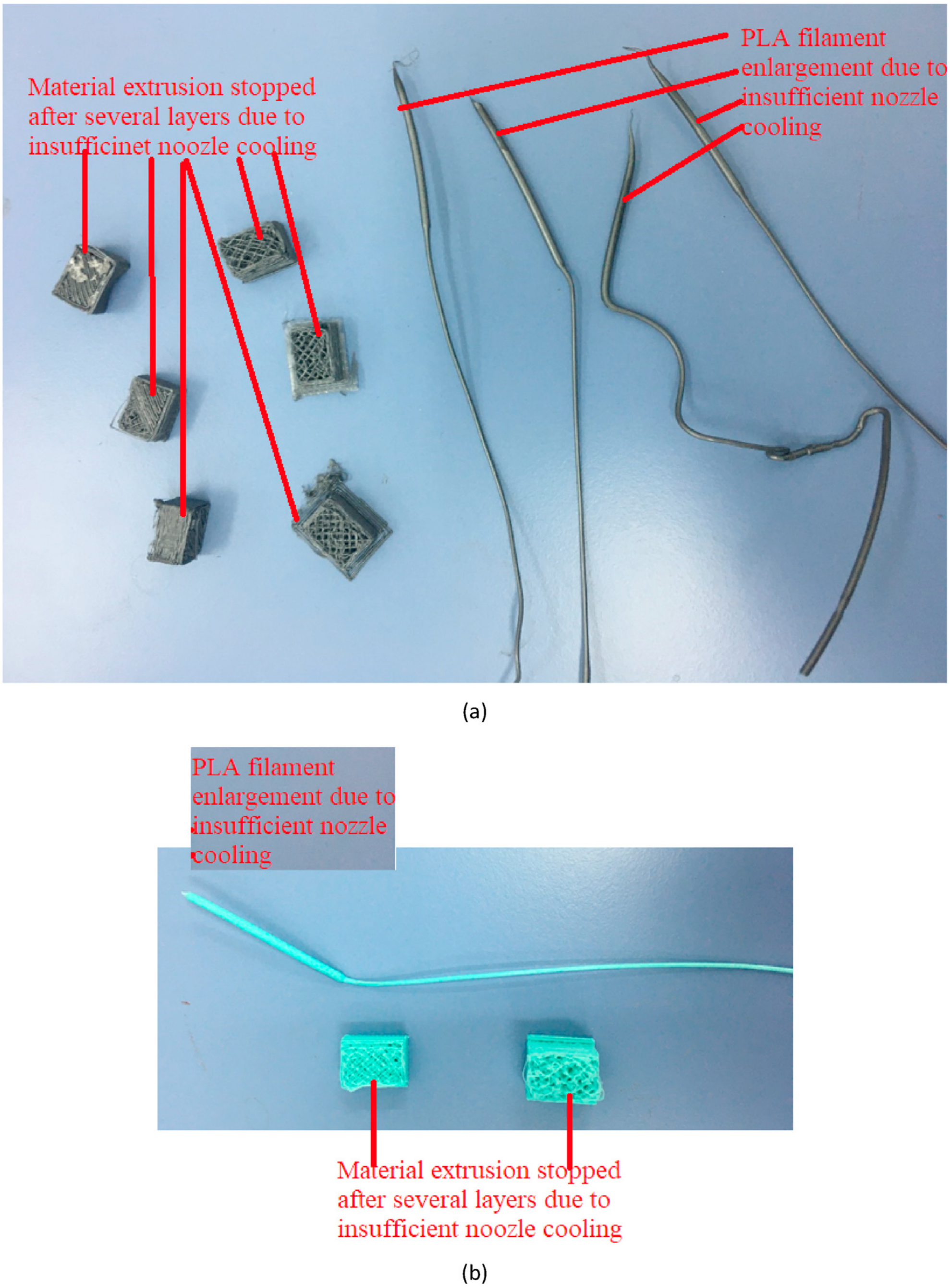


Fig. 15. The results of inefficient nozzle cooling (a–b).

not extruding properly due to the cooling fan's low performance. A 24 DVC with a 0.06 A cooling fan was used for the heat block. It was noticed that the material stopped extruding through the nozzle head due to creating a bold head in the Teflon tube which stopped the material flow to the nozzle head. After printing several layers, it was found that the material did not come out of the nozzle, and upon removing the filament from the nozzle head, the swallowed shapes were observed several times. A new efficient cooling fan may help to solve this problem.

5. Successful printing of large-dimensional products

Fig. 16(a–g) show various successful printed parts using the developed large-scale customized FDM printer. The parts were printed in both the vertical and horizontal directions to verify the machines working performance. The parts were not printed in the first place, after trying and tuning the printing parameters, the optimal printing conditions were achieved. Printing parameters also depend on the material used to print the object.

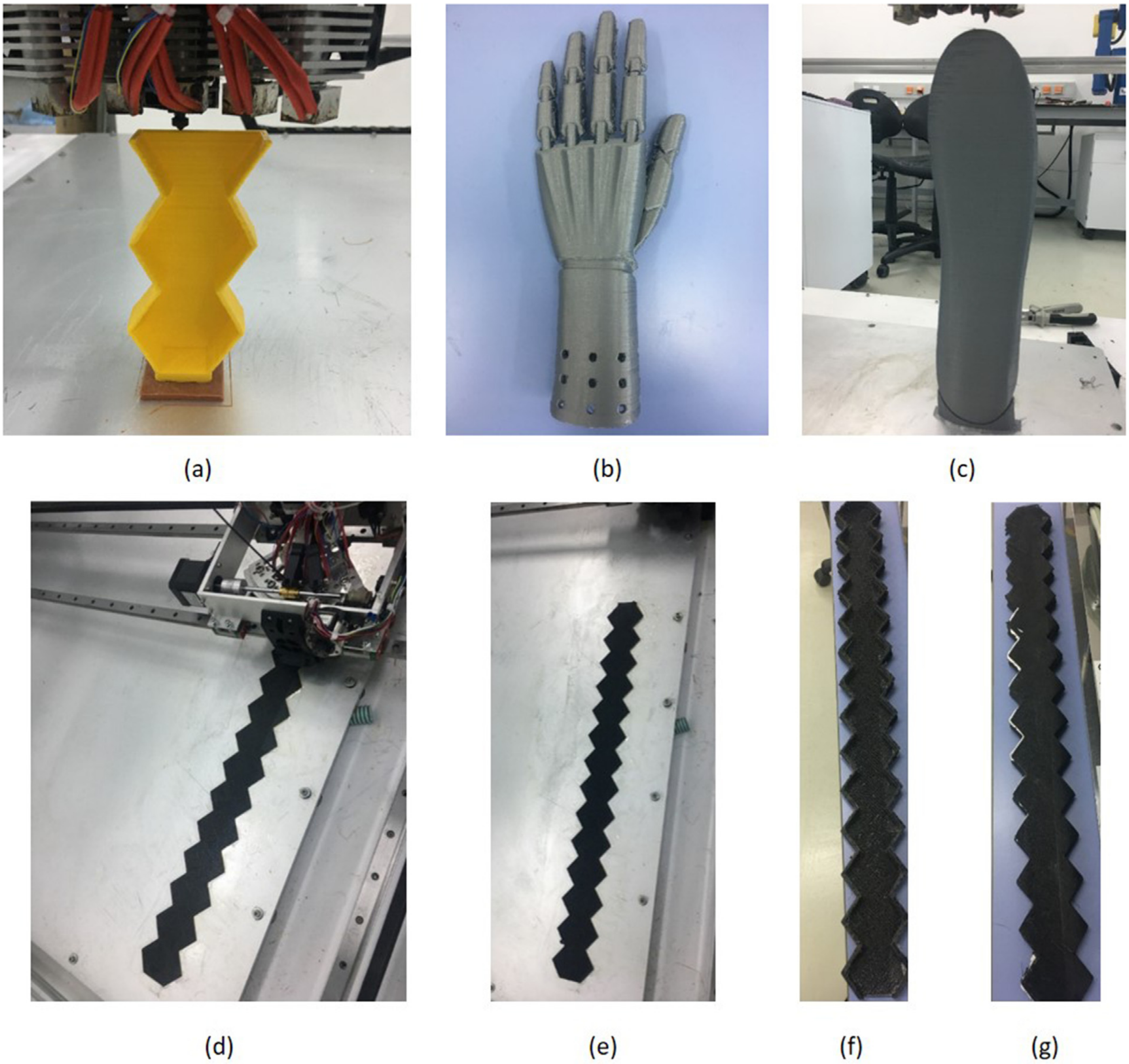


Fig. 16. Samples of successfully printed objects with a large-scale FDM printer (a–g).

The materials used for the below parts are Flex and Bflex materials.

6. Conclusions and future works

The paper presented some samples of large objects printed by the customized large-scale multi-extrusion 3D printer. It also discussed the challenges of printing such as large objects. Many important parameters need to be optimized to get successful results. Finding the optimal print bed is a key challenge in the large-scale printer. The bed surface deviation irregularities were observed during the experiments. To print a large object, longer hours are necessary. Both the vertical and horizontal print directions can be used to print large-scale products but the main condition is to set the optimal support structure for each object. Adhesion glue or tape can be used to increase the adhesion of the support structure or selecting a larger base than the original product may help to stabilize the first layer.

In the next stage, the optimal bed temperature, feed rate, printing speed, nozzle temperatures, surrounding environment temperature support structures, and print directions could be investigated for large-dimensional product development. In addition, a large diameter nozzle with a long extruder heater could reduce the build time which is crucial in analyzing product development costs.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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