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Vishal S. Sharma · Uday S. Dixit ·
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Manufacturing Engineering

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Lecture Notes on Multidisciplinary Industrial Engineering

Series Editor

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Chapter 1
Investigations on the Development of Heated Build Platform for Additive Manufacturing of Large-Size Parts

Sagar Kailas Gawali, Narendra Kumar, and Prashant K. Jain

Abstract Extrusion-based additive manufacturing (AM) is a process that fabricates the parts by extruding and depositing material through extruder in a layer-by-layer manner on a build platform. Build platform provides a foundation to fabricate parts and also provides an appropriate heat to bottom layer required for adequate adhesion. In extrusion-based AM, adhesion between the first deposited layer and the surface of build platform is crucial. Long and wide roads are deposited during the large-size part fabrication from a nozzle which leads to large temperature gradient between deposited roads. Therefore, a large-size platform having uniform temperature distribution is needed in order to fabricate large-size parts. This paper presents a study on the development of a heated build platform for enabling large-size part fabrication through a CNC-assisted extrusion-based AM system. The set-up consists of a screw-driven extrusion system and heated large-size build platform. Build platform consists of aluminium plate, silicon pad heater, levelling screw and PID temperature controller as the main components. The build platform is tested for temperature distribution using a Fluke IR camera. Results show that uniform temperature is distributed across the build platform, and it can be used for additive manufacturing of large-size parts.

Keywords Additive manufacturing · Build platform · Large-size parts · Pellet · ABS · Retrofitment · CNC-assisted extrusion-based AM system

1.1 Introduction

With the arrival of new technologies, designing products have become much easier. A large number of computer-aided design (CAD) software packages are available in the market, which has eased the design process as a whole, and the designers are experimenting much more with design and development of new products than

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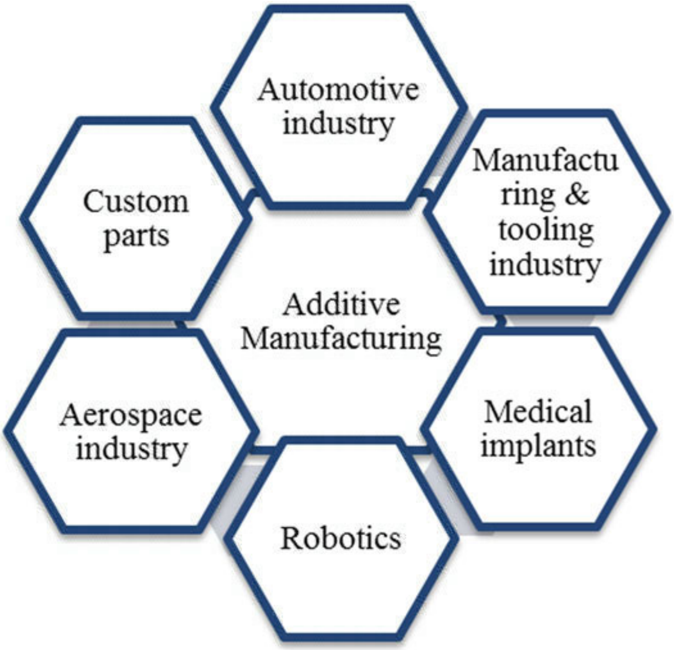


Fig. 1.1 Application domains of AM

ever before. In today's competitive world of manufacturing industries, competition has been increased rapidly for new product development as early as possible. Additive manufacturing (AM) process works as a flexible and quick manufacturing process that is used by manufacturers globally for product development due to various benefits.

In last decades, additive manufacturing (AM) emerges as the fastest growing technology, which is formerly known as rapid prototyping (RP), and it is also known as 3D printing. AM is the process that manufactures parts with resources efficiently in quick time. AM offering fabricated complex-shaped parts increases its popularity in application fields such as automotive, aerospace, biomedical, robotics, manufacturing industry and fashion and research. Figure 1.1 shows applications of AM in various industrial fields.

1.1.1 Additive Manufacturing

Additive manufacturing (AM) is a process of fabricating 3D parts from CAD model directly. It simply built the parts by adding material in a layer-by-layer manner. On comparing with traditional manufacturing processes, there is no requirement of specific tools and fixtures to fabricate parts. According to 'ASTM F42–Additive

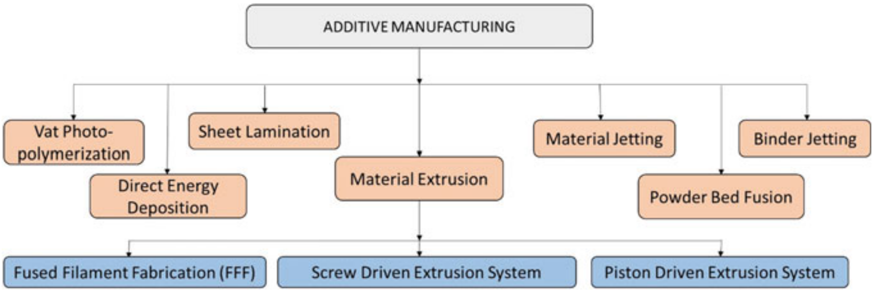


Fig. 1.2 Categorization of AM processes

Manufacturing' standard, AM processes can be classified into seven categories based on different working principles, i.e., material extrusion, direct energy deposition, powder bed fusion, binder jetting, vat photo-polymerization, material jetting, sheet lamination, etc. [1] (Fig. 1.2).

Among these processes, material extrusion-based AM process has grown as viable and economical manufacturing technology. Material extrusion is a process that consists of mainly a material extrusion tool and build platform. Either of the material extrusion tool or build platform is moved in usually *z*-direction that helps to deposit material on top of layer previously deposited on build platform. After fabrication, parts have to perform some post-processing, that is essential for functional use. The AM system manufactures parts at reasonable cost with good quality in the shortest time, which helps to compete with others in the current manufacturing world. Manufacturing world witnessed evolution of new process since last three decades, and earlier, AM process is only used for prototyping purpose, popularly known as rapid prototyping (RP). Nowadays, many industries adopted AM to make functional products of parts to minimize the product development cycle time [2–5].

1.1.2 Fused Filament Fabrication (FFF)

Fused filament fabrication (FFF) is a one of the most popular material extrusion-based AM processes which is used to fabricate prototypes and small end-use functional products [6–8]. FFF is a process in which material in the filament form is processed through extrusion principle to fabricate plastic parts, as shown in Fig. 1.3. FFF is the most commonly used process for fabrication of parts among other AM processes with ease, minimum wastage of material and easy material change. FFF is a typical RP process that fabricates prototypes for visualization and validation of designs. FFF process need not require a tooling for fabrication of parts and has design freedom with no geometrical restriction [9–11].

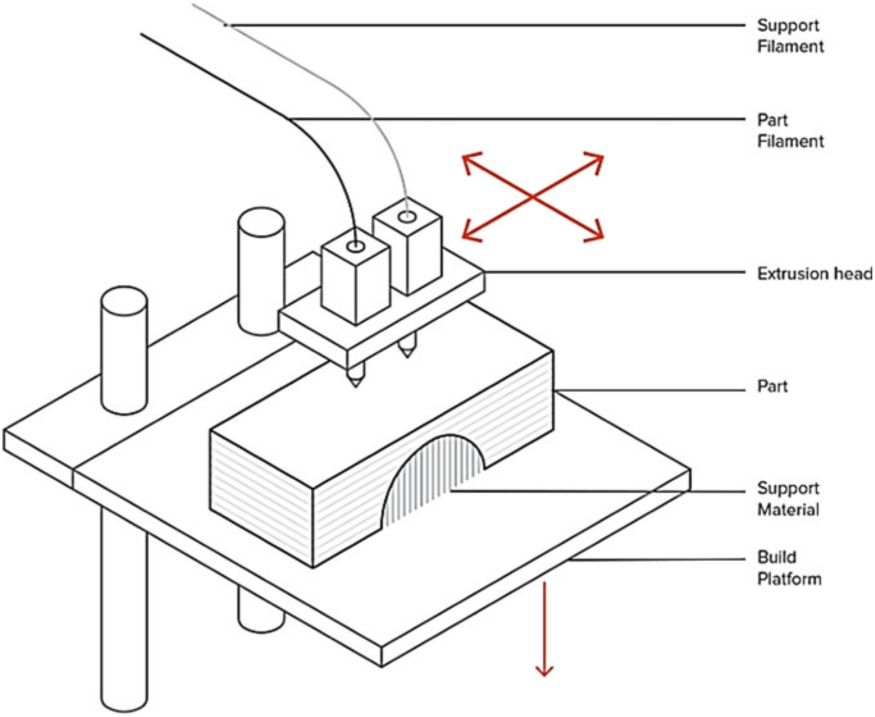


Fig. 1.3 Schematic diagram of the FFF system. *Source* 3D Hubs

1.1.3 Need of Build Platform and Issues with FFF

There are various parameters in extrusion-based AM process which affect the quality of fabricated parts, as shown in Fig. 1.4.

In these processes, the material is heated until it reaches to semi-molten state and then extruded through a nozzle on the build platform. During the material deposition, heat is transferred from the part to the environment due to temperature difference which leads to the formation of defects, i.e., warpage, deformation [12, 13]. In commercial material extrusion system, two discrete methods are used to prevent or limit warpage, one is the incorporation of the heated build platform and another one is closed build chamber [14].

Despite the wide use, FFF can make parts with limited dimensions due to the small size workspace of build platform. As dimension of workspace increases, capital cost of machine increases for large-size parts and due to slow rate of material supply effects on build rate which is very slow for high volume manufacturing [15, 16]. The size of the part can be increased by enhancing the dimensions of the build platform. The modifications in the size of build platform would lead to change in the dimensions of gantry system of machine. Machines with large build platform are costly as compared to small ones as large gantry system is added. Large-size parts

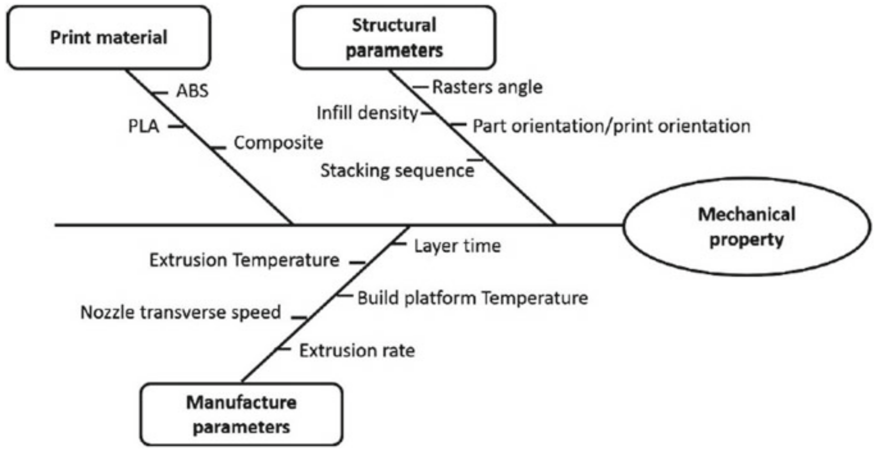


Fig. 1.4 Cause and effect diagram of extrusion-based AM process

fabrication can be accomplished with a large gantry system and large-size heated build platform. Therefore, the present paper aims to develop a heated build platform for additive manufacturing of large-size parts. However, available CNC machining centre has been used as a gantry system which helps in material deposition at required coordinates. Development of build platform depends greatly on the material being processed, nature of the build platform surface and heating mechanism.

1.2 Development of Heated Build Platform

Heated build platform is vital element of system which plays a major role during part fabrication. It is well-known that warpage may occur within the fabricated parts due to induced thermal stresses. When surface area increases with an increase in part size, it may lead to rapid heat transfer which results into warpage. Due to this warpage, part fabrication may be failed as bottom layers of the part may get curled and peeled off from the build platform as shown in Fig. 1.5.

Build platform provides the essential temperature to the part during fabrication in order to avoid any possible warpage by keeping your part warm during the whole process which keeps the material at or above the glass transition temperature to prevent any possible damage to part induced due to uneven heat transfer. Moreover, build platform helps in the increase adhesion with the surface and to improve part quality [17].

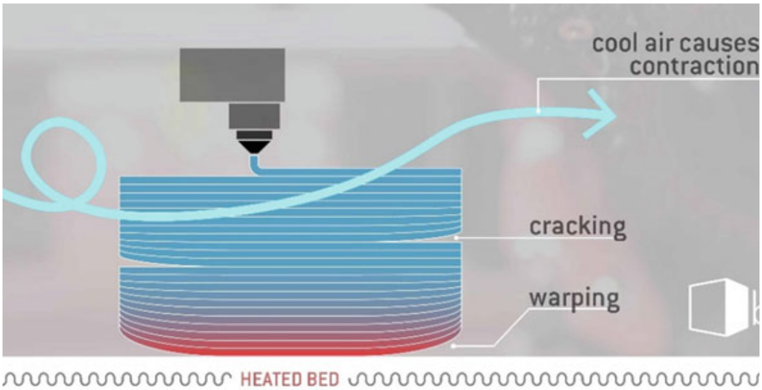


Fig. 1.5 Issues due to build platform. *Source* https://box3d.eu

1.2.1 Design Methodology

The purpose to develop the build platform is to improve the adhesion of base layer with heated surface and to help in bonding of successive layers. Deposition of the first layer on the build platform is most vital to the successful fabrication of the part, and it acts as a base to other layers. Improper build platform may cause warpage or separation of the deposited layer from the platform during processing. It may lead to part failure and process interruption. Purpose of build platform is to provide heat to fabricated parts during the process to raise the temperature of part up to or more than the glass transition temperature of a material, and efficient heat transfer is vital.

Selection of platform material is important to adhere the layers, especially for large-size and complex parts and high-shrinkage materials. In the current research, aluminium material has also been selected as a build platform surface for developing uniform heating in a simple and cost-effective manner. Aluminium was selected due to high thermal conductivity which provides uniform heating and high durability. Also, ease in removal of fabricated part with aluminium builds up over time after each fabrication. Also to maintain uniform heating of build platform, there should be different heating systems that have been used to avoid cold spots on the surface. For the large surface area of platform capacity of the heating build platform, the controlled silicon heating pad may be a good choice of preference. Silicone heater under an aluminium build platform will heat evenly. Also, it is easy to choose heater power with a silicone heater. Silicon pad heaters are selected as a heating element because of its advantages such as light in weight, fast heating and reliable. Silicon pad heaters are easy to install with aluminium plate due to good adhesion quality (Fig. 1.6). These heaters are relatively inexpensive and long life span as compared to other types of heaters. The need of AC supply to operate these heaters is the biggest limitation as circuit needs ground connection with AC.

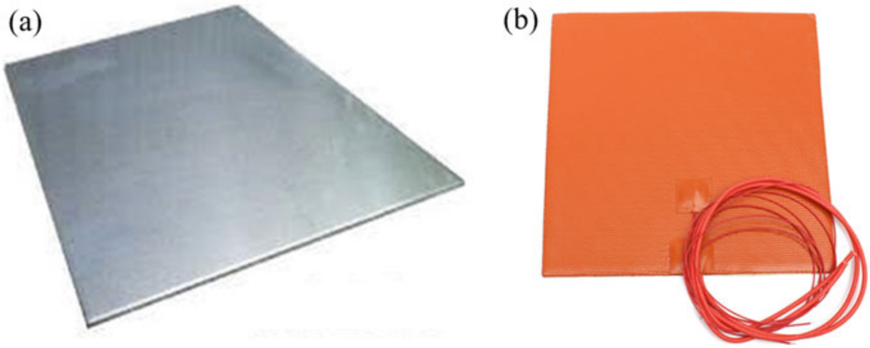


Fig. 1.6 **a** Aluminium plate, **b** silicon pad heater

1.2.2 Development of Build Platform

Build platform has been developed using components, namely (a) aluminium plate (5 mm thick), (b) silicon pad heater (AC supply 230 W), (c) wooden board, (d) PID temperature controller, type-K thermocouple and (e) levelling screw. Aluminium plate of dimension $600 \times 450\,\text{mm}^2$ is used (Fig. 1.7). Aluminium plate is kept fixed over the wooden board using levelling screw, and four silicon pad heaters are attached to the bottom side of plate in order to provide uniform heating. A type-K thermocouple is attached to the centre of the plate to measure the temperature and to provide feedback to the controller.

1.2.2.1 Proposed Circuit of Build Plate Design

A circuit has been proposed to connect all the heating mechanism components together. Figure 1.8 shows a proposed circuit diagram prepared to provide heat to the

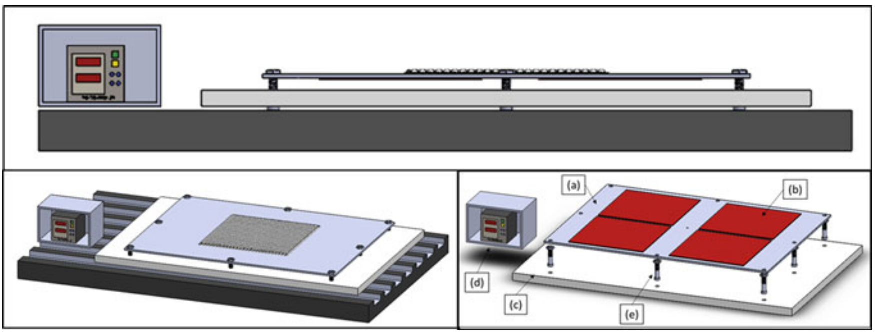


Fig. 1.7 Proposed CAD design of build platform

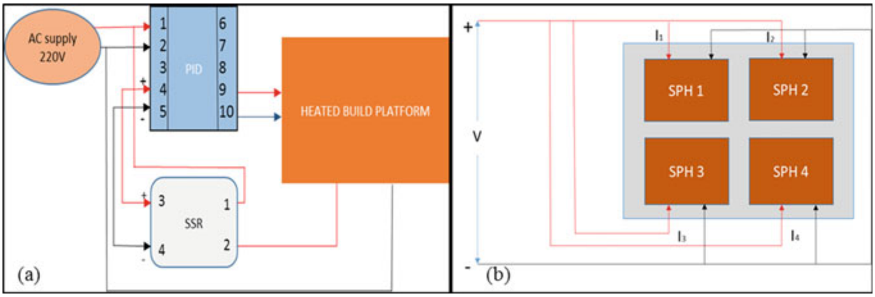


Fig. 1.8 **a** Proposed circuit diagram, **b** parallel connection of four SPH

developed build platform. The proposed circuit is an assembly of components such as silicon pad heaters, proportional–integral–derivative (PID) temperature controller, solid-state relay (SSR), type-K thermocouple (Table 1.1).

The temperature controller takes an input from the thermocouple and has output of PID temperature controller maintained the temperature of system at set value temperature. PID controller accurately control process temperature without the involvement of operator, a control system relies upon a PID controller feedback data, and it compares the actual temperature to the desired control temperature, or set value

Table 1.1 Build platform components

PID temperature controller		• Control unit that easier to implement • Act as feedback unit • More robust to tuning mismatches • Easier to tune by simple trial and error • Better response to unmeasured disturbances
Solid-state relay (SSR)		• Electronic switching device • Very fast response usually about 1 μs ON and 0.5 μs OFF • Life span is much higher • Low power consumption, highly durable

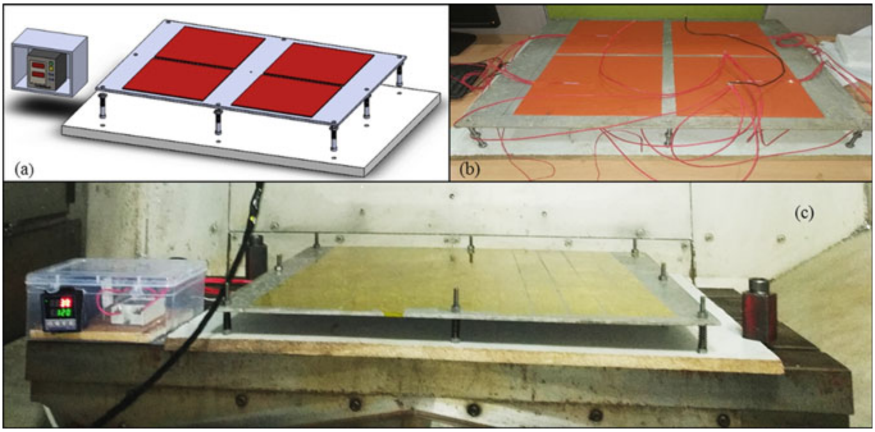


Fig. 1.9 **a** CAD model of a proposed design, **b** assembly of SPH on the plate, **c** developed set-up of build platform

temperature. Solid-state relay (SSR) plays the role of a switching device which maintained the actual value of temperature to set value temperature. SSR is a device that responds to correct input, and it acts as an electronic switching device which enabled and disabled the power supply to load circuitry. This circuit assembly shown in Fig. 1.9 is attached bottom side of the aluminium plate to develop a build platform.

1.2.2.2 Time Taken to Heat Build Plate-Calculation

• SPH—Silicon pad heater	• Heat required to plate
Specifications: Voltage 220 V Current 1A • Plate material: Aluminium Thickness: 5 mm Dimension: 600 × 450 mm Weight: 4.5 kg Specific heat capacity: 900 J/kg K • Bed temperature: 110 °C • Room temperature: 25 °C	$Q = m \times Cp \times (T_1 - T_0)$ $= 4.5 \times 900 \times (110 - 25)$ $= 344.25\ \text{KJ}$ • Power supplied to circuit $P = V \times I_T$ $= 220 \times 4 = 880\ \text{W}$ • Time taken to heat 5 mm plate $t = Q \div P$ $= 344{,}250/880$ $= 391.1931\ \text{s} = 6.51\text{min}$

Similar to commercial AM machines, threaded bolts with spring and adjustable nuts are provided to fix and level the platform on CNC machining centre. The gap between nozzle and build platform can also be adjusted. This developed build platform is placed over the CNC machine workspace and fixed with jigs and fixtures. The maximum travel range of CNC machine workspace was $750 \times 450 \times 400\,\text{mm}^3$. In order to utilize the space for additive manufacturing purpose, a build platform with the size of $600 \times 450 \times 400\,\text{mm}^3$ was developed.

1.3 Characterization of Developed Build Platform

Developed build platform was characterized in order to assess its temperature and heat distribution capability.

1.3.1 Temperature Distribution Testing

Thermal IR camera was used to check temperature distribution across the build platform surface. Captured thermal images show the uniform distribution of heat across the surface of the build platform. It also shows that developed build platform can attain appropriate temperature within a short time of span. Build platform heated using four silicon pad heaters that stick to the bottom side provides a uniform heat distribution on the total surface of platform. It helps to reduce warpage during and after process. The heated build platform has been developed based on the parameters required for the printing of ABS material. It is known that 110 °C build platform temperature is need to build parts of ABS material [18]. Figure 1.10 shows temperature distribution from the initial time (t_0) to time (t_{10}) at an interval of 1 min till platform reaches a temperature 110 °C. It can be seen that temperature has been attained within 10 min.

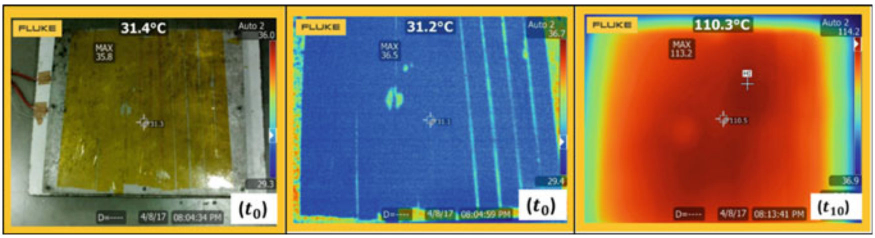


Fig. 1.10 Temperature distribution on build platform

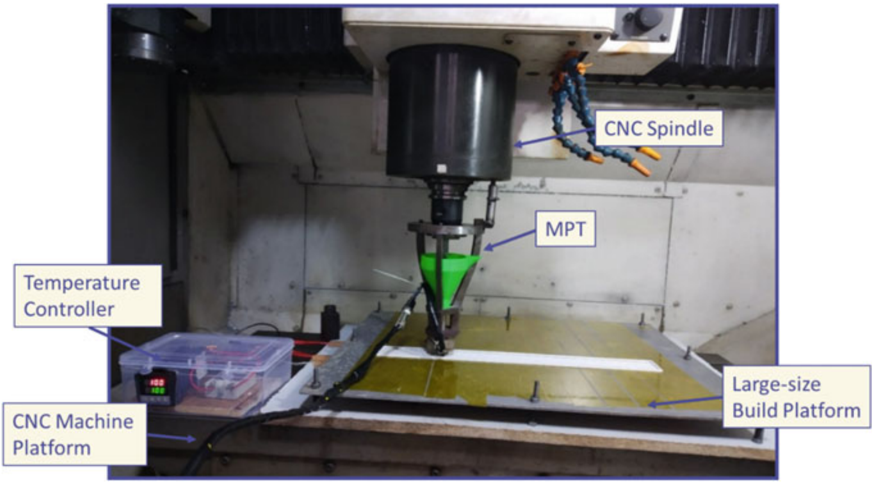


Fig. 1.11 Developed experimental set-up

1.3.2 Experimental Testing

The developed build platform was tested experimentally in order to see its feasibility for additive manufacturing of large-size parts. Therefore, it was tested with the already available CNC-assisted extrusion-based AM system developed Kumar et al. [19]. The available AM system uses CNC machining centre as a gantry system along with a material processing tool (MPT). Material processing tool (MPT) is a vital element which is accountable for continuous and uniform extrusion of the material. MPT works on screw-driven extrusion principle to process the material in pellet form. In the current study, processing tool was modified which was developed by Kumar et al. In this version, hopper, barrel and nozzle assembly is modified to fabricate large-size parts relatively faster rate. The developed experimental set-up of the MPT and build platform on three-axes CNC machining centre is depicted in Fig. 1.11 [20–23].

1.3.2.1 Material

Acrylonitrile butadiene styrene (ABS) grade M204 was taken as a raw material in pellet form due to easy availability at low cost (Fig. 1.12). The robust rheological behaviour of ABS provides material extrusion at constant rate which may help in robust part fabrication. Moreover, ABS has established itself as the standard material in commercial additive manufacturing. This is the reason why the ABS is selected in the current study.

Fig. 1.12 ABS material used in the current study

1.3.2.2 Feasibility Study

For feasibility analysis of set-up, nozzle of 2.5 mm diameter was used in the current study. For part fabrication at initial level, process parameters were chosen based on the literature as build platform temperature (100 °C), screw speed (60 RPM), extrusion temperature (220 °C) and deposition speed (700 mm/min). Using these process parameters, experiments were conducted and fabrication of different primitive shapes of large-size was attempted in order to analyse the feasibility of developed system. The considered geometries are presented along with their dimensions in Fig. 1.13.

Figure 1.14 illustrates the successful fabrication of parts with straight and curvy edges through developed set-up, Furthermore, internal contour features in the parts were combined which shows the capability of system.

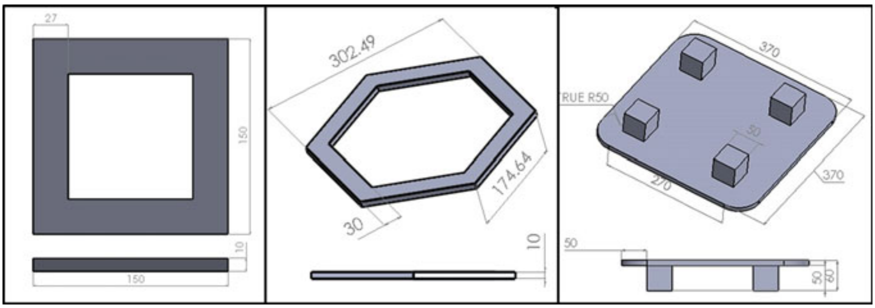


Fig. 1.13 Primitive shapes

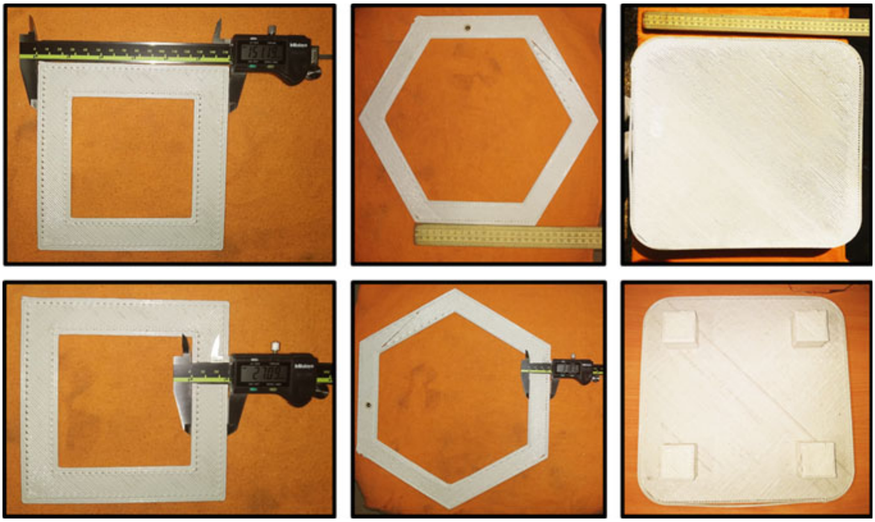


Fig. 1.14 Fabricated parts

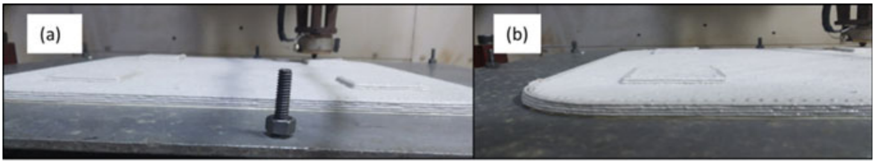


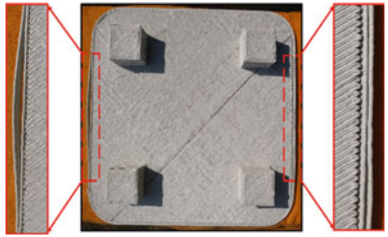
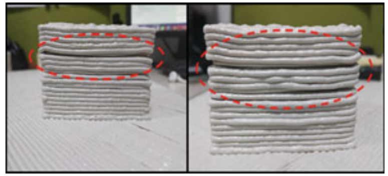
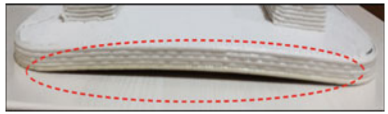
Fig. 1.15 **a** Adequate adhesion, **b** no warpage

Also, obtained results show that build platform is capable to generate heat uniformly across the surface during part fabrication. There was no warpage and deformation induced within the fabricated parts. Moreover, adequate adhesion between the roads and layers was found which indicates the capability of developed heated build platform (Fig. 1.15). The fabricated parts were characterized in order to see the structure and quality.

1.3.2.3 Parts Characterization

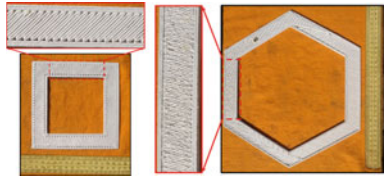
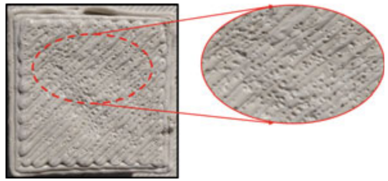
The fabricated parts were characterized to analyze their quality as the presented approach is different in comparison with commercial extrusion-based AM process. The differences are in the material processing technique, size of nozzle and build platform. In additive manufacturing, the quality of the fabricated parts depends on various factors. The changes in processing technique, size of nozzle and build platform may lead to change in the quality of fabricated parts. Therefore, it was important to assess the quality of parts for validating the process and presented approach. In

Table 1.2 Observations during characterization of parts

Gaps between infill and internal–external contours	• Infill percentage, deposition speed and raster angle • Due to higher deposition speed, road does not get enough time to bond with contour, which leads to creation of voids of irregular shapes	
Layer separation/delamination	• Layer thickness, barrel temperature and deposition speed • Variation in deposition speed leads layer separate	
Warpage	• High heat transfer rate • Deposited roads cool and solidify fast • ABS has tendency of warpage during cooling	

(continued)

Table 1.2 (continued)

Under-extrusion/over-extrusion	• MPT which do not have feedback unit to control the flow through nozzle • Screw speed, deposition speed • Under-extrusion gaps between the contours and layers • Over-extrusion creates overlapping of layers	
Holes on the top layers	• Pellet form ABS material contains an some moisture and entrapped air • Intra-bead porosity manifests as small circular voids in beads	

order to observe part quality, characterization was done by capturing the images of fabricated parts structure. The characterization results are enlisted in Table 1.2.

1.4 Conclusions

Commercial additive manufacturing (AM) systems with large build volume are relatively costly as compared to small AM machines. However, the use of existing CNC machining centres could provide alternate solution for large-size parts fabrication at a nominal cost. Therefore, a detailed study on the development of cost-effective build platform was presented. A large build platform was developed that was retrofitted on three-axis CNC machining centre for the fabrication of large-size parts. The characterization of the developed build platform was done in order to see its capability for additive manufacturing of large-size parts. Results showed the satisfactory performance of developed build platform. It can be concluded that the developed build platform set-up has potential and could be utilized to fabricate large-size parts in future under the industrial environment.

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Chapter 2
On the Numerical Investigation of Material Deposition in Fused Filament Fabrication

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Abstract Fused filament fabrication (FFF) is a widely used additive manufacturing process in which part is fabricated by depositing material in the form of strand through a nozzle. Material deposition with different processing conditions may influence the part quality, namely surface finish, mechanical strength and dimensional accuracy. The part quality largely depends on the cross-sectional shape of deposited strand which gets affected by the stand-off gap between nozzle tip and bed surface and moving velocity of bed. Thus, it would be important to study the effect of these parameters on the cross-sectional shape of deposited strand numerically prior to actual part fabrication. It may provide optimum process conditions for part fabrication without any material wastage. In this paper, a numerical investigation has been carried out to study the effect of stand-off gap between the nozzle tip and bed surface with moving velocity of bed on the cross-sectional shape of deposited strand. ANSYS Fluent along with computational fluid dynamics (CFD) has been used in order to carry out the investigation. Material has been deposited at different process conditions, and then, the cross-sectional shape of deposited strand is obtained using extraction of point cloud data in MATLAB. Results show the variation in cross section of the deposited strand. In most of the cases, elliptical and rectangular with rounded corners shapes have been observed.

Keywords Additive manufacturing · Fused deposition modeling · Fused filament fabrication · 3D printing · Numerical simulation · Strand deposition

2.1 Introduction

Additive manufacturing (AM) is an advanced manufacturing process, which comprises processing of digital data of geometrical model for fabricating part by adding material in layers. There are various types of AM processes available which work on

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