Chapter 29
Additive Manufacturing of Large Size Parts Through Retrofitment of Three-Axes CNC Machining Centre

Sagar Kailas Gawali, Narendra Kumar, and Prashant Kumar Jain

Abstract The size of the additive manufactured parts limits their use in prototyping and small functional applications. Additive Manufacturing (AM) systems with large build volume are relatively costly as compared to small ones. However, the use of existing three-axis CNC machining centres could provide an alternative for large-size parts fabrication at a minimal cost. Therefore, the present paper investigates the possibilities for the additive manufacturing of large-size parts using retrofitted three-axis CNC machining centre. A CNC-assisted extrusion deposition based AM system has been used. The setup consists of a material processing tool (MPT) and large-size build platform. Initial experiments have been conducted to check the feasibility of the developed setup for large-size parts. Large parts with different cross-sections were fabricated by processing ABS material in pellet form. Moreover, characterization was carried out to analyse the quality of fabricated parts. The observed results show that developed setup has potential to fabricates large-size parts in future.

Keywords Additive manufacturing · Retrofitment · ABS pellets · 3D printing · Large-size parts · Hybrid process · Big area additive manufacturing · BAAM

29.1 Introduction

With the advent of modern technologies, designing the products have become much more convenient. A huge number of CAD tools are available in the market which makes a design process better all in all, and the designers are investigating much more with design and development of different products than ever before. This revolution in Information Technology (IT) enabled design-manufacturing has also been accompanied by a subsequent demand for flexible manufacturing processes. Additive

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Manufacturing (AM) is based on the concept of IT-enabled design-manufacturing technology which has been accepted by technologists and designers across the world.

Additive Manufacturing (AM) is a process that fabricates 3D objects by deposition of material in the layer-by-layer method, unlike subtractive manufacturing. The part fabrication capabilities of AM with any complexity offers the significant saving of cost and materials, unlike time-consuming conventional manufacturing processes like machining, casting, forming, etc. AM process works as a rapid and flexible manufacturing process. As per ASTM F42 standard, AM has been classified into seven classes based on different working principles as material extrusion, vat photo-polymerization, direct energy deposition, binder jetting, powder bed fusion, material jetting, sheet lamination, etc. (Fig. 29.1).

Among these working principles, material extrusion process has become most used due to its design simplicity and low cost. Fused Filament Fabrication (FFF) is one of the processes in which material in the form of filament is processed through extruder based on material extrusion principle to fabricate parts. The processed material in semi-molten state extrudes through nozzle and deposit on moving build platform in a layer-by-layer manner and built the part as shown in Fig. 29.2b. Nozzle extrudes material in a predefined toolpath in the X–Y plane and deposits the layer to

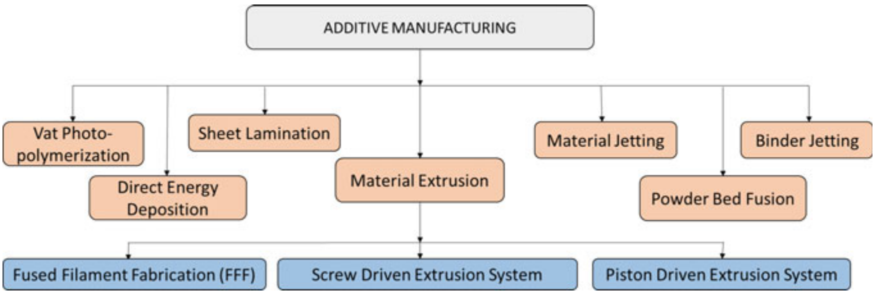

Fig. 29.1 Categorization of AM

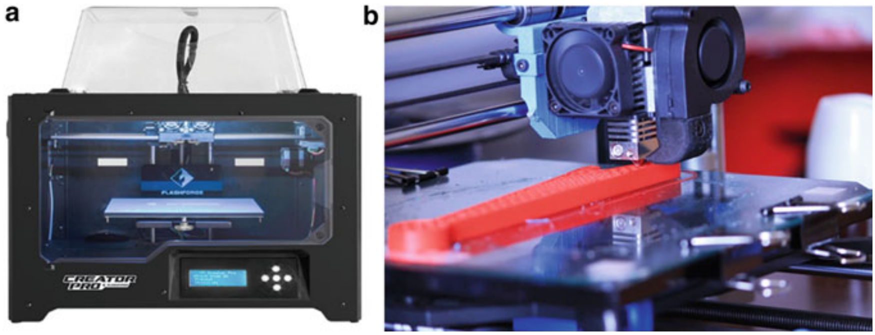

Fig. 29.2 **a** Flashgorge 3D printer (*Source* https://www.flashforge.com). **b** Small size part on FFF (*Source* https://www.sculpteo.com)

build the base for the parts. After the deposition of first layer, build platform moves downward by the value of layer thickness for deposition of subsequent layer over the previously deposited layer and the process continues until the complete part was fabricated. In FFF process, most commonly used thermoplastic polymer material are ABS, Polyethylene (PE), and Polylactic acid (PLA), etc. FFF process mostly used for fabrication of parts among other AM processes because of simplicity in processing, minimum material wastage and easy material handling. Although, FFF process has various advantages but, there are certain limitations associated with this process which restrict its application domain [1–3]. Currently, part fabrication with small size is one of them which limits its use only for rapid prototyping (RP) and some end-use functional applications. The part size can be enlarged by adding large size build platform underneath of the extruder. Consequently, bigger gantry system would be required to build the parts with large-size on the large build platform.

Since the last five decades, manufacturing industries have used the CNC machining centre to fabricate the parts of metal with high precision. In these industries, large-size of CNC machining centre is used to serve the purpose which has larger gantry system as compare to existing FFF machines. In industries, the gantry system of the existing CNC machining centre could assist in the additive manufacturing of parts with large-size at a nominal cost. To achieve this goal, a material deposition tool could be developed compatible to CNC machining centre. This tool would be attached or detached with CNC machining centre similar to milling cutter. Moreover, a large build platform can also be designed and developed which can be kept on machining workspace.

Therefore, the present paper aims to perform additive manufacturing of large-size parts by developing a material deposition system compatible to CNC machining centre. The developed system is made up of three components: three-axis CNC machining centre, Material Processing Tool (MPT), heated large-size build platform. Three-axes CNC machining centre is used as a gantry system with a positional accuracy of 1 μm. MPT is attached to the spindle of machining centre for extruding material, while the heated build platform is placed on the machining workspace to utilize complete workspace. The method involves an approach of the material extrusion process and then building the 3D parts through the use of an MPT on the three-axes CNC machining centre. Thus, the development of the new system presents a major hope for the implementation of low-cost, large-size product development technique in manufacturing industries.

29.2 Literature Review

Many researchers have explored the fabrication of large-size parts through additive manufacturing by developing indigenous experimental setups. Wang et al. developed the Fused Pellet Modeling (FPM) system using a big size robotic arm for the fabrication of the large-size part. Different shapes of filament were investigated to minimize the formation of the voids in fabricated parts using multiphysics software.

Moreover, deformation was recorded within the part with an increase in size [4]. Liu et al. developed the double-stage-screw extruder to fabricate large-size part of composite material prepared using Acrylonitrile Butadiene Styrene (ABS) and 10 wt% of Glass Fibers (GF) (Fig. 29.3). The effect of screw speed and pressure were studied on the melt flow rate, print speed and layer thickness. Also, surface finish and bonding strength were examined under the variation in spacing between deposited roads [5].

Nieto et al. developed a pellet based AM process in which the functional prototypes with a volume of 2000 mm^3 were fabricated using PLA and ABS materials for the use in the naval industry. Thermomechanical deformation and behaviour were studied. Based on observations, weight was reduced by 64.4 and 55.5% for PLA and ABS prototypes respectively [6]. Felsch et al. have presented a study in which a combination of industrial robots was employed with additive manufacturing technologies for enabling the fabrication of complex and large parts [7]. Jun et al. developed a setup to fabricate large-size thin-walled parts using modified FDM process. An infrared laser was installed on the existing FDM machine to preheat the surface just before the deposition of material. Due to the preheating of surface, enhancement in the mechanical properties was observed [8]. Vijay et al. developed a direct ink writing based AM system using an industrial six-axis robot. Large-scale objects were fabricated using natural bio-composite materials. Improvement in tensile strength with minimum shrinkage was the main highlight of the study [9].

Apart from academia, the industries have also shown their interest in the additive manufacturing of large parts for the use in some functional applications. Cincinnati incorporation developed a Big Area Additive Manufacturing (BAAM) machine in collaboration with oak ridge national laboratory. It offers the material extrusion and deposition via screw extrusion principle. An open environment gantry system of unbounded size was utilized to fabricate large parts. In comparison to conventional FDM machine, part fabrication with large volume was offered by BAAM. The developed setup of BAAM had capabilities of fabricating ten times large volume parts than that of FDM [10]. Similarly, Thermwood company was collaborated with oak ridge national laboratory to develop a Large Size Additive Manufacturing (LSAM). A build platform of large size of $2540 \times 254 \times 508$ mm^3 was developed for fabricating parts like a boat hull, concrete mould etc.

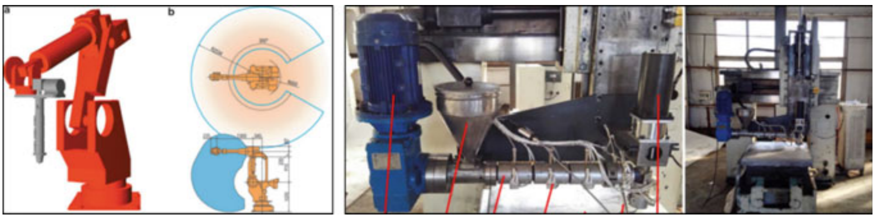

Fig. 29.3 **a** Big size robotic arm. **b** Double-stage-screw extruder

29.3 Methodology

Additive manufacturing of large-size parts requires not only the material processing unit but also require the large-size build platform. This has been achieved by developing a Material Processing Tool (MPT) and a large-size build platform for material processing and deposition respectively.

MPT works on the screw-driven material extrusion-based principle to process the pellet form of material. In this method, the material is processed through screw rotation. The required rotation to screw is provided by three-axis CNC machining centre. Apart from providing screw rotation, the CNC machining centre also offers the necessary movements to the tool for material deposition in X, Y and Z directions. Firstly, the CAD model of the part is prepared in 'Solidworks' software which is exported in Standard Tesselation Language (STL) file format. This STL file is further used for pre-processing purpose through toolpath generation software. Since current study explores the use of 3-axes CNC machining centre, the commercially available Computer-Aided Manufacturing (CAM) software can not generate a required toolpath for material deposition as they are intended to generate code for machining purpose only. Therefore, an in-house developed software has been used in the current study to fulfil above requirements related to toolpath generation. Full details about this software can be found elsewhere [11, 12]. The tasks such as slicing and toolpath generation are performed using the aforementioned software. The file containing generated toolpath is then fed into CNC machining centre (Fig. 29.4).

29.4 Fabrication of Additive Manufacturing Large-Size Parts (AMLSP)

29.4.1 Material Processing Tool (MPT)

Material Processing Tool (MPT) is used for extruding material in continuous and uniform manner. Part quality may be affected greatly by the performance of MPT. In the current study, the modified version of a deposition tool is used as MPT which was earlier developed by Kumar et al. to fabricate flexible parts of EVA (Ethylene Vinyl Acetate) material. More details about MPT can be found elsewhere [13]. In this version, assembly of hopper, barrel, and nozzle was modified to fabricate large-size parts comparatively at a faster rate. The different diameter of nozzles were taken to perform the current study. 2.5 and 3 mm diameter nozzles were considered initially for performing preliminary experiments. Material in the viscous/semi-molten form was extruded from these nozzles in the form of continuous extrudates which is deposited on the developed build platform to fabricate large-size parts.

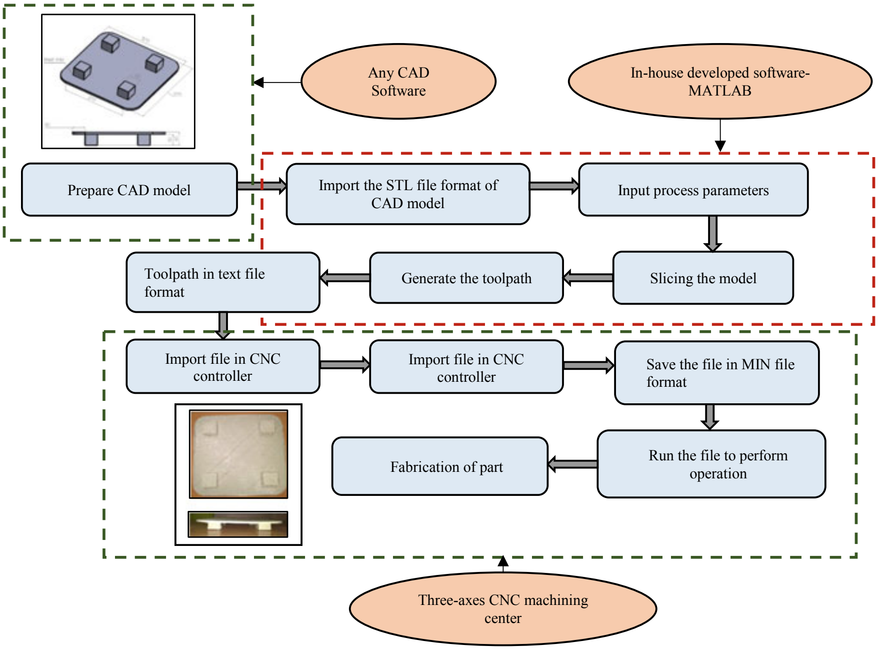

Fig. 29.4 Process flowchart of CNC-assisted extrusion deposition based AM system

29.4.2 Large-Size Build Platform

The build platform plays an important role during part fabrication as the material is deposited onto it in prespecified manner. It is eminent that warpage may occur within the fabricated part as a result of induced thermal stresses. When the surface area of part increases with an increase in the size of part, may lead to rapid transfer of heat which results in warpage. As a result of warpage, the part may be failed as lowermost layers of the part may get curled and peeled off from the build platform. Build platform provides the required temperature to the part during the fabrication process to avoid failure because of warpage. Build platform allows the fabricated part to stay warm during the fabrication and may prevent any damage to part tempted due to uneven heat transfer. Moreover, the build platform is helpful to stick the first layer of part strongly on its surface [14–17].

In the current study, large-size build platform has been developed. Heating elements are provided to preheat the build platform surface at the appropriate temperature for avoiding any possible warpage problem. The developed platform consists of a 5 mm thick aluminium plate, a 230 W AC operated silicon pad heater (AC supply), PID (Proportional-Integral-Derivative) temperature controller as the main elements. Moreover, the type-k thermocouple is also attached to monitor and maintain the given temperature value. Similar to the commercial 3D printer build plate, threaded bolts with adjustable nuts has been provided to fix the developed platform

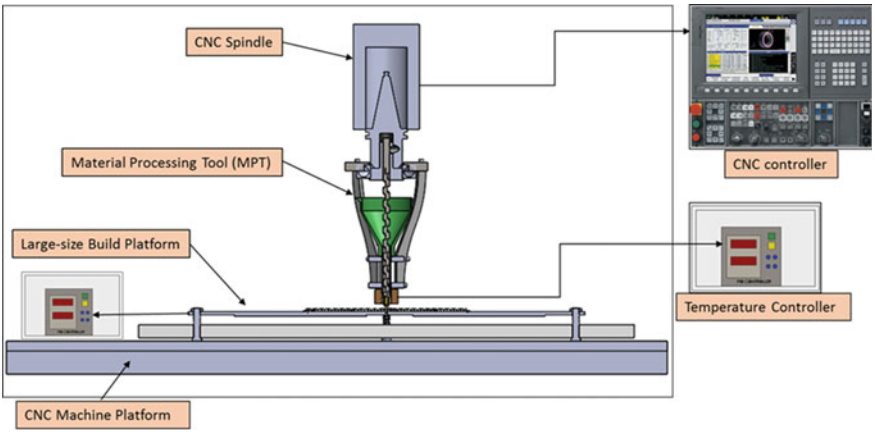

Fig. 29.5 Proposed experimental setup

on CNC machining centre bed to adjust the gap between the nozzle and build platform [18]. The developed build platform has been placed on the CNC machining centre bed with the help of jigs and fixtures. The CNC machining centre used in the current study has a maximum travel range of 750, 450 and 400 mm in X-, Y- and Z-axis respectively. Because of design constraints of developed platform, part of size 600 mm × 450 mm × 400 mm can be fabricated. Schematic diagram of the proposed experimental setup consists of a material processing unit and build platform is shown in Fig. 29.5.

29.5 Feasibility Testing, Part Fabrication and Characterization

Acrylonitrile Butadiene Styrene (ABS-M204) is used as a raw material in form of pellets because of ease in availability at a cheap rate. The robust rheological behaviour of ABS material provides extrusion at a continuous rate which may help in fabricating robust parts. Moreover, ABS material has been recognized as the standard material in additive manufacturing, that's why the ABS material is selected in the current study. The properties of ABS considered in current research work is shown in Table 29.1 (Fig. 29.6).

Figure 29.7 shown in-below is a developed experimental set-up on a three-axis CNC machining centre that consists of MPT and build platform.

For fabrication of the large-size parts, the nozzle of diameter 2.5 mm was used in the present study. To fabricate the part in the initial studies, process parameters is been chosen based on the literature study as MPT temperature (220 °C), material deposition speed (700 mm/min), screw speed (60 RPM), build platform temperature

Table 29.1 Properties of ABS material

Properties	ASTM test method	Test conditions	Units	Value
Melt flow index	ISO 1133	220 °C/10 kg	gms/10 min	35
Vicat softening temperature	D 1525	Cond. B-50 N	°C	97
Co-efficient of linear thermal expansion	D 696	23–55 °C	10E-4/°C	0.7–1.0
Rockwell hardness	D 785	23 °C	R-scale	103
Tensile strength at yield	D 638	50 mm/min	kg/cm^2	500
Tensile modulus	D 638	50 mm/min	kg/cm^2	27,000
Flexural strength	D 790	5 mm/min	kg/cm^2	750

Fig. 29.6 ABS material pellet form

(110 °C). Preliminary experiments have been conducted using these process parameters and carried out a feasibility study of the developed system by fabricating some primitive shapes of large-size. Some primitive shapes is been presented along with their dimensions in Fig. 29.8.

Figure 29.9 shows that parts with smooth and curvy edges successfully fabricated using developed setup. Also, internal contour features in the fabricated parts were shows the capability of setup. The fabricated parts have been characterized to analyze the structure and quality of parts visually. Various issues were encountered in fabricated parts which are to be discussed in the next section.

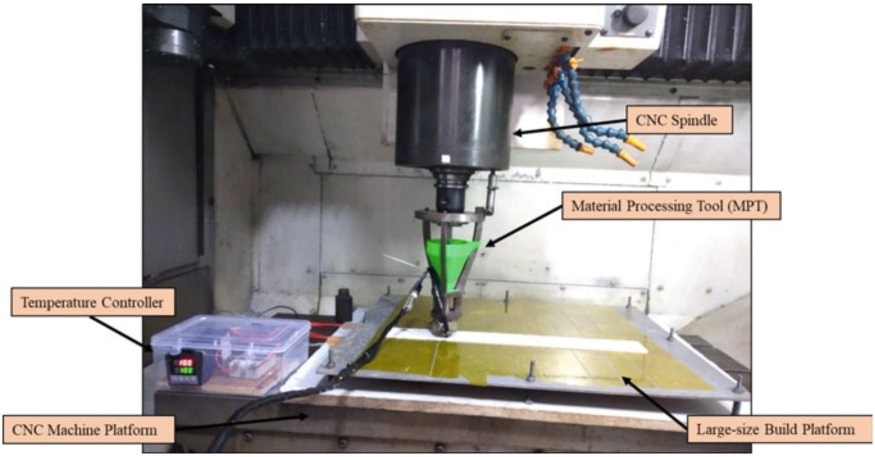

Fig. 29.7 Developed experimental setup

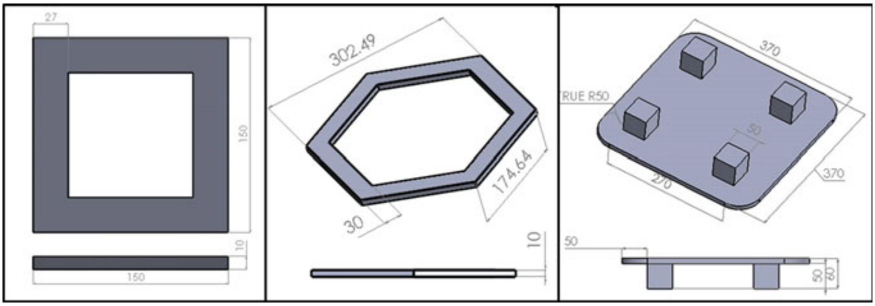

Fig. 29.8 Different primitive shapes

29.6 Characterization Results and Discussion

In the developed system, parts are fabricated similar to the commercial extrusion-based AM systems, using different material processing technique. In AM, the quality of the parts fabricated through extrusion-based AM depends on various factors. The changes in processing method, nozzle diameter and build platform may cause a change in the quality of parts. In order to observe and study the effect of these changes, characterization is done by taking the images of parts structure. The characterization study includes an effect of modified system and values of process parameters on dimensional accuracy, surface quality and structure of fabricated parts. There were various issues found during and after the fabrication process, which are compiled and enlisted.

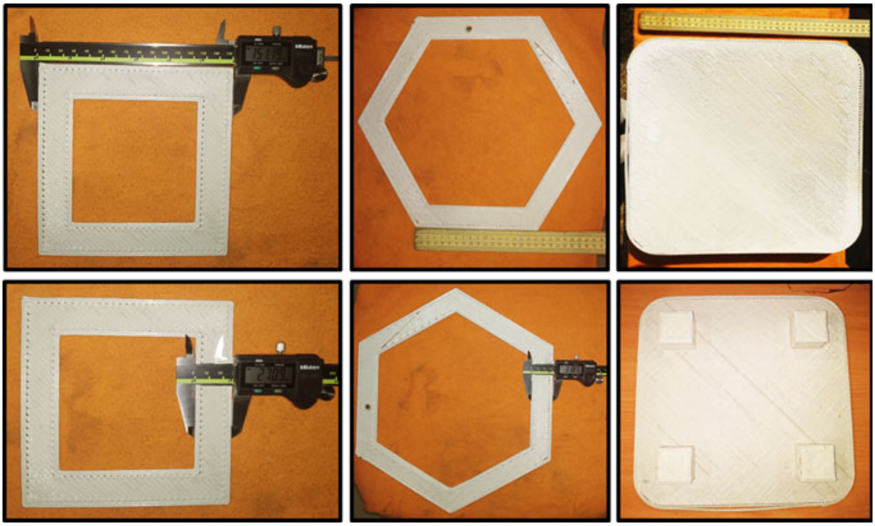

Fig. 29.9 Fabricated parts of the different primitive shapes

29.6.1 Dimensional Accuracy

In AM, dimensional accuracy always been a major concern, in the pre-processing stage maybe some CAD information lose during slicing and toolpath generation. In the fabrication of large-size parts issue of dimensional accuracy mainly observed, because of factors such as thermal contraction, under or over-extrusion, pellets quality, and even the standoff distance of first layer nozzle. In the present study, the fabricated parts were equated with CAD model dimensions to estimate deviations from actual dimensions. The results showed significant changes between dimensions of the fabricated parts and CAD model in all three directions. Results are reported in Table 29.2. The reason behind the obtained deviation can be related to thermal shrinkage during the cooling period. The filament extruded through MPT is varying its uniformity with time while depositing onto the build platform. Because of this reason, more change in deposited filament road width was observed than the filament thickness.

29.6.2 Surface Texture

Surface texture, also known as surface roughness is measuring the unevenness of the surface. The quality of surface of fabricated parts in AM become a more vital being used for end-use applications. The surface finish of parts is important not only to improve functionality and appearance but also for cost-effective processing and reduction of processing time. Surface roughness can be characterized in two different

Table 29.2 Dimensions of different cross sectional shapes

S. No.	Part	Dimensions	Actual (mm)	Measured (mm)	% Difference
1		Length	150.00	151.19	0.79
		Width	150.00	151.19	0.79
		Thickness	10.00	9.85	1.50
2		Length	302.49	300.00	0.82
		Width	174.64	172.00	1.51
		Thickness	10.00	8.90	0.11
3		Length	370.00	350.00	5.40
		Width	370.00	350.00	5.40
		Thickness	42.00	41.80	0.47

planes one is along with the build orientation and another one is perpendicular to build orientation.

In the present study, the surface roughness of the fabricated parts was measured using contact-type Mitutoyo Surftest SJ-500 surface roughness tester. In order to study surface roughness of fabricated part cutoff length considered 1 mm. The obtained surface roughness profiles of parts shown in Fig. 29.10. The profiles signify that in third cross-section (Table 29.2, Sr. No. 3) measured the height of roughness in both along and perpendicular to build orientation deviates more from its mean position. The parameters affect behind deviation of height mainly initial selected values of a parameter such as layer thickness and deposition speed. In order to enhanced surface roughness ultimately the quality of parts have to optimize the parameters accordingly.

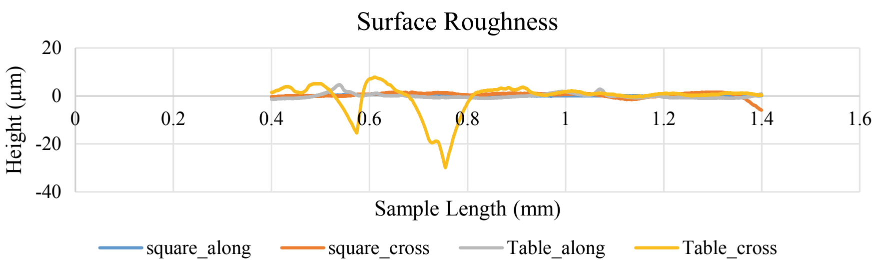

Fig. 29.10 Surface roughness measurement of different cross-sections

29.6.3 *Structural Analysis*

The mechanical properties and surface quality of any part largely depend on its microstructure. These qualities and properties of fabricated parts can be predicted with the help of microstructure or internal structure and bonding between the layers. In the present study, ABS pellet is processed using CNC-assisted extrusion deposition based AM system. Therefore, it is necessary to analyse the structural changes within the part. The issues related to analysis is been discussed in the section.

29.6.3.1 Gaps Between Infill and Internal–External Contours

In additive manufacturing, each layer is formed when the material is deposited within and along the contours. Contours represent the boundary of a part that guides material deposition tools in the filling of area inside the boundary. In the fabricated parts through the system, there were some gaps between infill and contours observed. Since the current study was the initial investigation in which part fabrication has been done initially with randomly chosen process parameters based on user experience. It is well-known that process parameters such as infill percentage, deposition speed and raster angle play a vital role during part fabrication. In this way, the observed gaps between infill and contours can be attributed to the fabrication with unoptimized process parameters. As compared to the other two parameters, deposition speed may affect the deposition rate of material within contour which may lead to the formation of irregular shape voids. As a result of higher deposition speed, the road does not get sufficient time to bond with contours. In the present study, material is deposited at a raster angle of 45° which is different than the orientation of the contour. This may also generate voids between infill and contours. To eliminate or minimize the gaps between infill and contours decreases or optimizes deposition speed (Fig. 29.11).

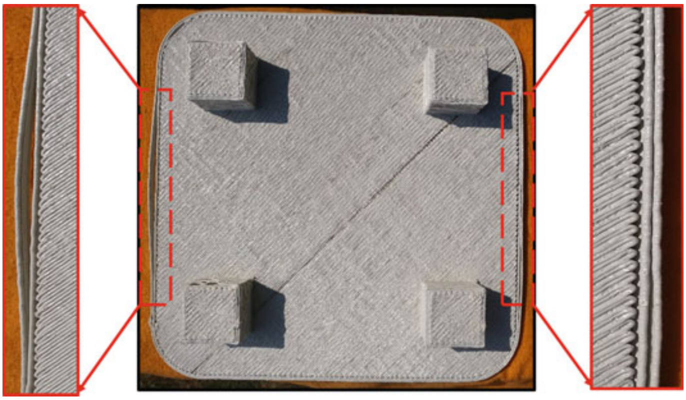

Fig. 29.11 Gaps between infill roads and contours

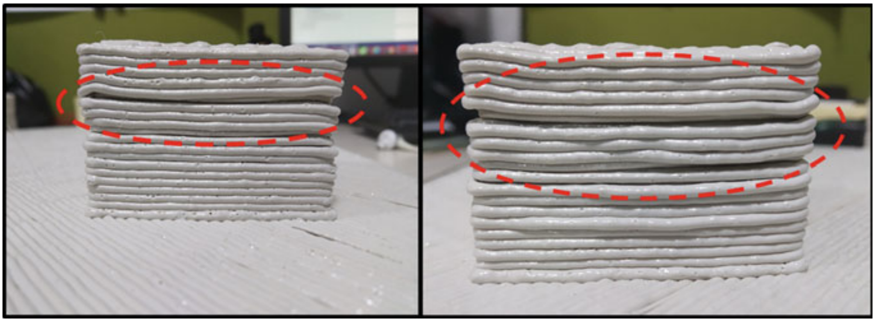

Fig. 29.12 Delamination

29.6.3.2 Layer Separation/ Delamination

AM is the process that builds the parts by layer-by-layer manner to create a desired 3D shape. However, for the build parts to be strong and reliable, need to assure that the deposited layer adequately bond with the previous layer. If bonding between the layers is not enough, then the part may split or layer gets separate. Parameters such as layer thickness, barrel temperature and deposition speed affect mainly bonding of layer. In the present study, these parameters values are considered as follows, layer height is been selected same as the diameter of nozzle, barrel temperature set nearer to the value of melting point of the material. After selecting the value of parameters fabricate part using system, during fabriaction issues like layer separation occurred, as shown in Fig. 29.12. This issue may be minimized with the selection of layer thickness lesser than the diameter of the nozzle. In this manner, a new layer would press the layer below it so that the two layers may bond strongly. Moreover, other process parameters related to temperature and speed could also be controlled to avoid layer separation.

29.6.3.3 Warpage

It is found that the heat transfer rate is increased with the increase in surface area of the part. Due to this, deposited roads cool and solidify fastly as a result, first few deposited layers of build part solidify quickly and lead to curl and deform edges of parts, that is known as warpage. Its effect can be severe which can separate out the part from the build platform. In the present study, the same issue was observed due to the large surface area of the parts (Fig. 29.13).

Warpage may be eliminated by incorporating a closed heated chamber across the build parts which is not the easy task as a developed system uses a CNC machining centre a gantry system. This constraint does not allow to build a closed chamber. Therefore, only the heated build platform was incorporated instead of the closed build chamber which may help to avoid the warpage issue through gradual increase

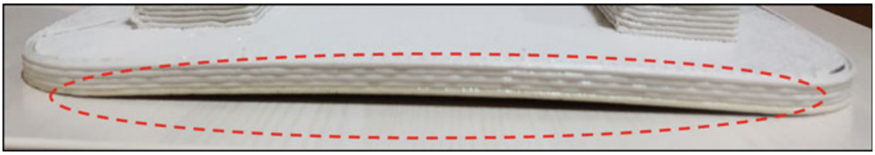

Fig. 29.13 Warpage

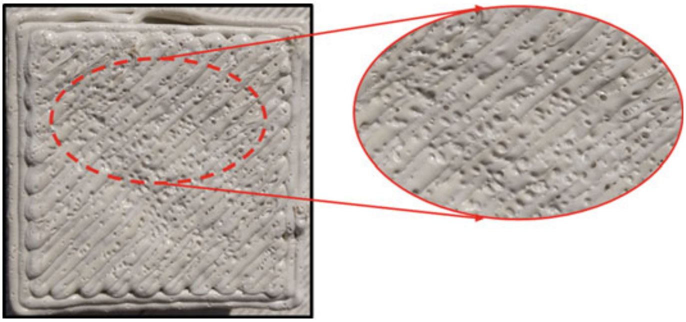

Fig. 29.14 Holes on top layers

or decrease in build platform temperature. Heated build platform helps to keep the bottom layers of part warm throughout the fabrication process. The heated build platform temperature was kept at 110 °C, which significantly reduced the amount of warpage in these layers. Problem with a thermoplastic material such as ABS is that it tends warpage during cooling. To avoid this, the fabricated parts were cooled down slowly at a gradual temperature interval.

29.6.3.4 Holes in the Top Layers

Blowholes were observed within deposited layers due to the hygroscopic nature of ABS and air entrapment during material processing in the barrel of MPT as shown in Fig. 29.14. Preheating of ABS and proper feeding of pellets into the barrel can be useful to overcome these issues.

29.6.3.5 Under-Extrusion/ Over-Extrusion

The material extrusion process does not provide any feedback about how much material extrude through the nozzle. Due to this, sometimes less or more amount of material (under-extrusion or over-extrusion) is extruded through nozzle than that of expectation. The developed system consists of Material Processing Tool (MPT) that does not have any response unit to control the flow of extruded material through the

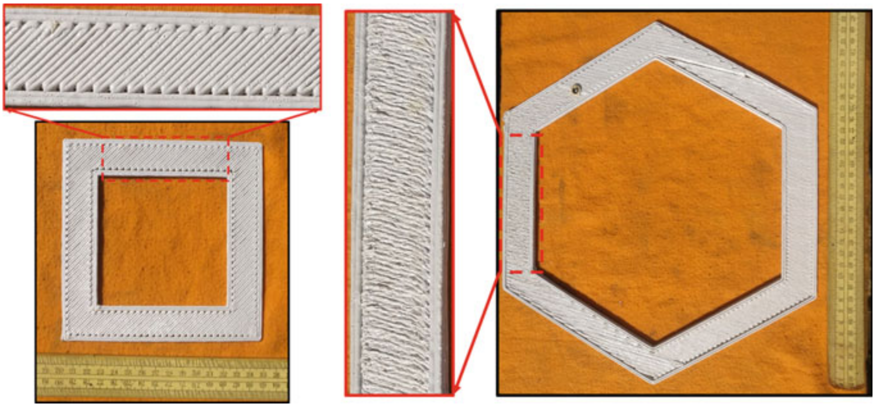

Fig. 29.15 Under-extrusion/over-extrusion

nozzle. Therefore, some issues are noticed such as gaps between the contours and layers due to under-extrusion, overlapping of layers due to over-extrusion as shown in Fig. 29.15. In order to overcome these issues, further experimentation is required to determine the optimum value of screw speed, deposition speed.

29.7 Conclusion

The purpose of large part fabrication was achieved by successful retrofitment of existing three-axis CNC machining centre. The detailed study of the Materail Processing Tool (MPT) was presented in this research work. The feasibility of experimental setup has been validated through the fabrication of large-size parts of the different cross-sections. The characterization study of fabricated parts and fabrication related issues have also been presented. The effect of process parameters, such as layer thickness, screw speed, deposition speed on the surface quality, dimensional accuracy and structural analysis of fabricated parts has also been discussed. The results revealed that layer thickness and deposition speed had a great influence on the structure of fabricated parts. Also, the surface quality was highly affected with larger layer thickness and higher deposition speed. Apart from these parameters, the influence of build platform temperature during and after the fabrication of parts was more significant for the quality of parts. The observations showed that the fabricated part gets warped or deformed due to inappropriate build temperature, thermal contraction, and environmental conditions. Overall characterization results suggest that further improvements are required in order to get large parts with desired dimensional and surface quality. Optimized values of different process parameters need to be determined. It can also be concluded that the developed setup has potential and could be used to fabricate large-size parts in forthcoming after incorporating some improvements in the existing setup.

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