COMBINATION OF FUSED DEPOSITION MODELLING WITH ABRASIVE MILLING FOR ATTAINING HIGHER DIMENSIONAL ACCURACY AND BETTER SURFACE FINISH

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ABSTRACT: Currently, two manufacturing methods, namely CNC (Computer Numerical Control) machining and rapid prototyping (RP), are widely used to produce final products and prototypes. Both the processes have their own advantages. CNC machining such as milling and grinding (subtractive method) can fabricate parts with higher precision and accuracy. On the other hand, RP (additive method), can manufacture parts with complicated 3-D (three dimensional) features, which ensures effective material usage. However, RP produced parts lack accuracy and smooth surface finish. In this research, we are aiming to achieve on-machine mechanical post-processing of 3-D printed (using Fused Deposition Modelling, a kind of RP process) parts to achieve higher dimensional accuracy and better surface roughness. To achieve the goal, we developed a new hybrid system to assimilate both of these processes. There are, however, two vital considerations needed to be taken into account for integrating the two processes. The first concern is the integration of dissimilar control systems for two processes and the second aspect is maintaining the tools' (milling spindle and the heat extruder) setup accuracy during the changeover step. The developed hybrid machine has been tested with experimentations and the result showed that the dimensional accuracy was improved by 71% to 99% when the FDM part was compared with the final part after abrasive milling operation. At the same time, average surface roughness (R_a) was improved up to 91.3%. Further, we found that low layer thickness improves the product quality. The proposed system could push the conventional FDM system to the next level to attain better quality of final products.

ABSTRAK: Dua kaedah terkini proses pembuatan, dinamakan mesin Kawalan Komputer Bernombor (CNC) dan prototaip langsung (RP) telah digunakan secara meluas bagi menghasilkan produk dan prototaip. Kedua-dua proses mempunyai keistimewaan tersendiri. Mesin CNC seperti mesin penghasil permukaan dan mesin penebuk lubang (melalui kaedah pengurangan) dapat menghasilkan sesuatu bahagian dengan ketepatan tinggi. Pada sudut lain, RP (melalui kaedah penambahan), dapat menghasilkan bahagian dengan kaedah 3D (tiga dimensi) yang rumit tetapi berkesan dalam memaksimakan penggunaan material. Walau bagaimanapun, penghasilan bahagian melalui kaedah RP mempunyai kekurangan pada ketepatan dan kekurangan pada kekemasan permukaan akhir. Kajian ini bertujuan meraih ketepatan dimensi yang lebih tinggi dan kekemasan permukaan yang lebih bagus pada proses terakhir pada bahagian cetakan mesin mekanikal

3D (menggunakan Model Deposit Fuse iaitu salah satu proses RP). Bagi mencapai tujuan ini, kami menghasilkan sistem hibrid terbaru untuk mengasimulasi kedua-dua proses. Walau bagaimanapun, terdapat dua perkara penting perlu diambil kira untuk diintegrasi bersama kedua-dua proses. Penilaian pertama adalah pada sistem kawalan tidak serupa, dan kedua pada aspek pengekalan alat (gelendung pemutar dan kepanasan pembentuk) ketepatan penyediaan semasa peringkat perubahan. Mesin hibrid yang dicipta telah diuji melalui eksperimentasi dan keputusan menunjukkan ketepatan dimensi telah bertambah daripada 71% kepada 99% semasa bahagian FDM dibandingkan dengan bahagian akhir selepas operasi putaran kasar. Pada masa sama, purata permukaan kasar (Ra) telah bertambah kepada 91.3%. Kami juga mendapati ketebalan lapisan bawah telah menambah baik kualiti produk. Sistem yang dicadangkan dapat mengubah sistem FDM konvensional kepada peringkat lebih tinggi bagi memperolehi kualiti terbaik pada produk akhir.

KEYWORDS: *fused deposition modelling; abrasive milling; hybrid system; FDM; rapid prototyping*

1. INTRODUCTION

In the 1980s, rapid prototyping (RP) technologies were introduced and were used to quickly create prototypes in an automated manner. RP is also known as 'Layered Manufacturing' (LM) and 'Additive Manufacturing' (AM). The additive mechanism that involves building the part by combining layers of material (solid sheet, powder or liquid) until the whole product is produced as stated by Wohler [1]. This technology has drawn significant interest due to its capability to overcome many drawbacks of traditional manufacturing techniques. Its ability to form almost any geometric feature or shape is a great advantage of AM as mentioned by Gebhardt [2]. This group of technologies was introduced to assist the development of new products, especially for evaluation processes and analysis. At early stages of product development, RP allows design changes and confirms products' validity before entering full-scale production. As time progresses, RP technologies have advanced, and their scope has been extended to create finished parts. Several techniques have been developed to establish RP technology as one of the most reliable manufacturing methods. More developments in RP have invented some advanced techniques that can process metallic materials as well produce polymeric products.

Various AM processes have been introduced to the commercial market by industrial companies as discussed by Goldsberry [3] including the Arcam in Sweden, Electro-Optical Systems (EOS) in Germany, Z Corporation and Optomec in the United States, Stratasys in the UK, and MCP Tooling Technologies, among others. AM processes are divided into the following three broad categories as noted by Kruth et al. [4] and Kruth [5]: (1) solid based, (2) powder based, and (3) liquid-based, as described. Fused Deposition Modelling also popularly known as 3-D Printing is a typical example of solid based Rapid Prototyping (RP Process). In the FDM process, a plastic material such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), investment casting wax, or elastomers is used by extruding it through a nozzle and depositing it layer-by-layer to build a part. Mostly, in the FDM method the material is supplied in the form of a filament. A resistive heater alongside the extruder is used to maintain the temperature of the filament just above its phase transitional point. This helps the raw filament to easily flow through the nozzle and deposit as a layer. As the deposited layer is exposed to the ambient it hardens instantly and bonds to the previous layer. This procedure of deposition of the layer continues until the final shape is obtained. The significant advantage of the FDM process is its ability to yield parts with complex features. However, due to the thermal shrinkages that occur during the RP process, the attainable surface quality and dimensional accuracy of the produced product are quite limited.

The surface quality of the parts produced by pure FDM method is significantly low because of the Staircase effect pointed out by Pandey et al. [6]. Anitha et al. [7] showed that the layer thickness of the FDM process plays the most vital role on the surface roughness of the finished product. In order to improve the surface quality of the FDM parts, there are several post-processing techniques (mechanical) available such as manual sanding, abrasive flow machining, abrasive milling, hot cutter machining, ball burnishing, etc. described by Chohan et al. [8]. Galantucci et al. [9] proposed abrasive milling using bulk lamellar abrasive paper to achieve 90% improvement in surface finish with reasonable dimensional accuracy. Pandey et al. [6] proposed a staircase machining approach for improving the surface roughness of the FDM parts. Other post-processing techniques for the products fabricated by rapid prototyping include Abrasive Flow Machining [10], Vibratory Bowl Finishing [11] and Barrel Finishing [12]. Ferreira et al. [13] retrofitted a large-format FDM printer to incorporate open source hardware and software, so that the printer can be used in a versatile way for the future research. Liu et al. [14] also developed a large-scale double screw 3-D printer to print large plastic product at a low cost. Boschetto et al. [15] proposed a process plan to carry out a finishing operation on the FDM parts using the CNC milling machine. Lee et al. [16] developed a machine where the FDM extruder and milling spindle were mounted on the same frame and could be positioned on the workpiece as necessary. This approach of the design made the overall structure of the machine bulky. In order to maintain the product accuracy by avoiding any setup error, it is necessary to carry out the post-processing of the FDM parts on the machine. Therefore, the main focus of this paper is to propose a modular design of a hybrid system combining Fused Deposition Modelling and CNC abrasive milling. The post-processing of the FDM parts was carried out by abrasive milling on-machine thus any error due to workpiece transfer was eliminated.

2. MATERIALS AND METHODS

To carry out the finishing operation on the FDM parts, a hybrid system was developed that integrates both the FDM and the finishing operation. In this project, abrasive milling was chosen as the finishing operation (commercially available abrasive Dremel {aluminum oxide} stone was chosen for this purpose). The material that was used to fabricate FDM parts was PLA (polylactic acid). As mentioned earlier it is preferred to unify the primary process (FDM in this case) and finishing process (abrasive milling in this case) into a single platform so that any form of setup error is avoided due to the transfer of the workpiece from one workstation to another. To achieve this unification, we chose a modular approach in our design. Fig. 1 (a) shows the CAD (computer aided design) model of the developed system. The system consists of three translation axes (X, Y, and Z) and one rotary stage. The rotary stage was mounted on the Z axis that holds the milling spindle or the FDM heat extruder as needed.

The heat extruder and the milling spindle were bought off the shelf as a standard product. However, the attachment was designed in such a way that these two components can be mounted on the rotary stage as necessary to ensure the modularity in the design. Furthermore, as shown in the Fig. 1, two infra-red sensors (IR) were placed on the vertical Z axis. The signal from these IR sensors ensures the parallelism of the heat extruder and the milling spindle with the Z axis. Figure 2 shows typical signal output from the two IR sensors received by the developed graphical user interface (GUI) for the hybrid system.

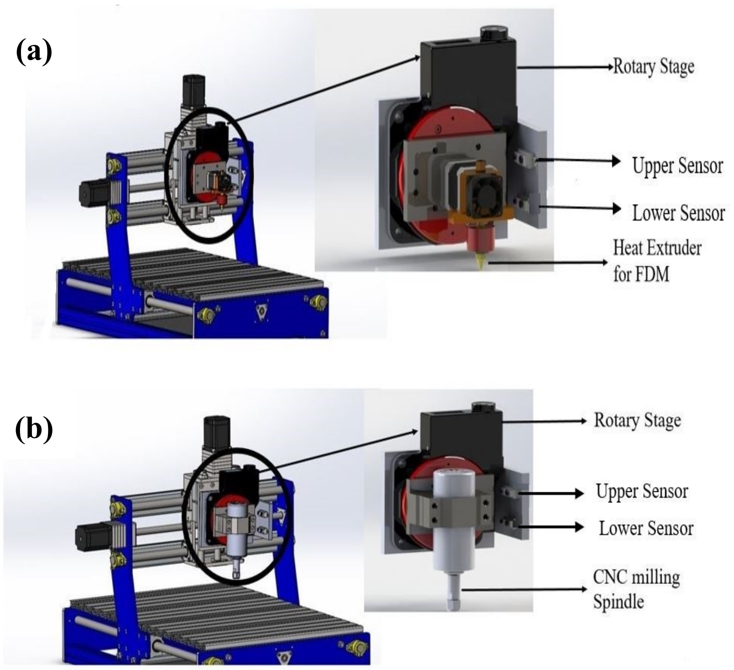

Fig. 1: CAD model of the developed hybrid system combining Fused Deposition Modelling and Abrasive Milling; (a) shows mounting of the heat extruder and (b) shows the mounting of the milling spindle.

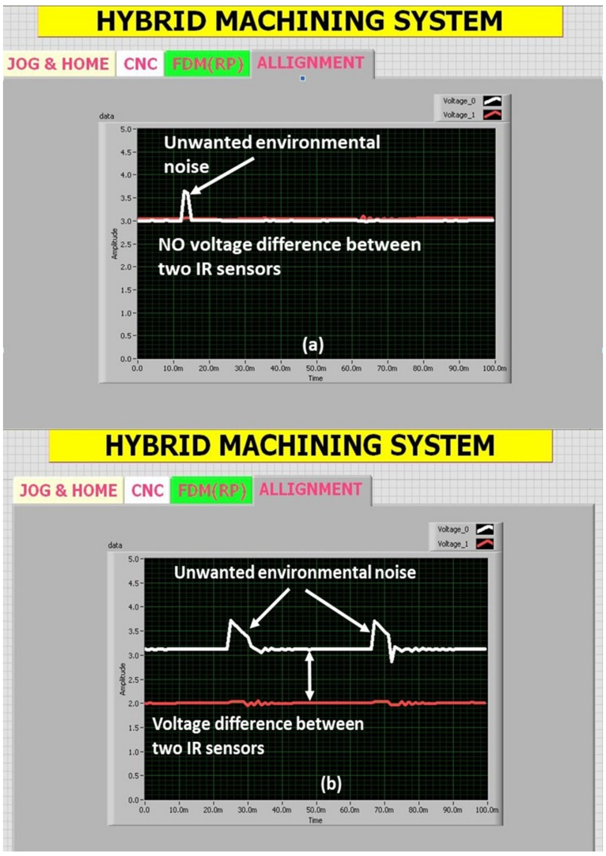

Fig. 2: IR sensor feedback to align the FDM extruder and the milling spindle:
(a) aligned condition (b) non-aligned condition.

It can be understood from Fig. 2, that when both the IR sensors generate the same voltage level (i.e., the difference is zero as shown in Fig. 2 (a)) the heat extruder or the spindle mounted on the rotary stage can be assumed to be parallel to the Z axis. However, if the voltage output of the two sensors is not zero, as shown in (Fig. 2 (b)), then the rotary axis is rotated accordingly to achieve the desired level of alignment of the heat extruder/ milling spindle. A graphical user interface (GUI) was developed using the Labview integrated development environment (IDE) to integrate the operation of the two processes.

The operational sequence of the whole process can be explained by Fig. 3. Initially, the CAD model of the desired object was created and saved in the .stl format using SolidWorks [17]. Next, Slic3R [18] software was used to slice the CAD model into layers according to the given layer thickness. After that, the G code of the CAD model was also generated from the same software to be used for the rapid prototyping purpose. Before starting the rapid prototyping operation, the heat bed needs to be levelled with the base of the machine so that the layer of the raw material is deposited properly on it. To level the heat bed a digital calliper was used. Several measurements were taken from the base to the upper surface of the heat bed in its four corners. Next, the RP process was carried out. Several products were produced with layer thickness ranges from 0.1 mm to 0.2 mm. Finally, to do the final finishing of the produced FDM parts, the heat extruder was replaced with a CNC spindle and the abrasive milling operation was carried out.

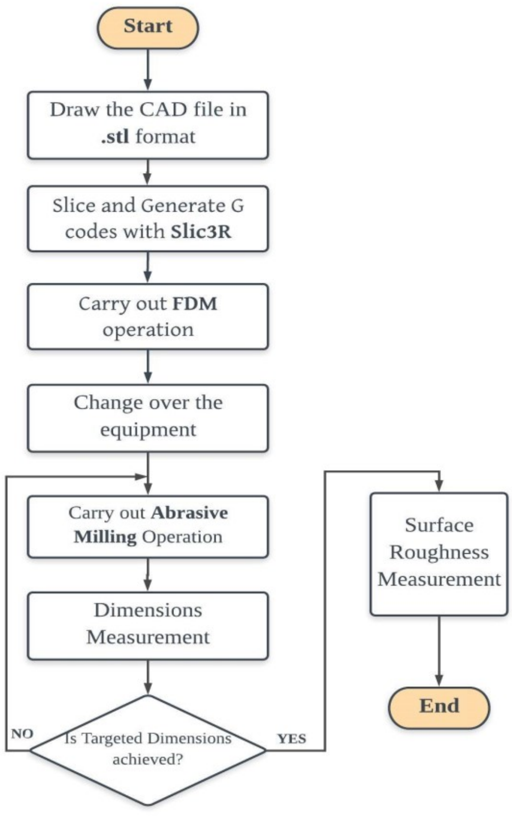

Fig. 3: Flow chart of the whole working process.

3. RESULTS AND DISCUSSION

To evaluate the performance of the FDM-Abrasive Milling-based hybrid system, a test specimen was printed and machined with the following targeted dimension 15 mm x 15 mm x 10 mm. FDM operation was conducted with three layer thicknesses (0.1 mm, 0.15 mm, and 0.2 mm). Several studies were carried out for both the FDM parts and FDM followed by abrasive milling parts. The scope of the study is limited to evaluate the performance in regards to dimension accuracy and the surface roughness of the final product as they are the two most important aspects in manufacturing.

3.1 Study of the Dimensional Accuracy

In order to compare the dimensional accuracy, a cuboid was printed using the FDM process with the programmed dimension of 15 mm x 15 mm x 10 mm. For comparison, FDM parts were further machined (finishing) using a commercially available grinding stone. During the finishing operation, the heat extruder was removed from the machine, and the milling spindle was mounted with proper alignment. The dimensions were measured using a digital calliper with a resolution of 0.01 mm. The findings of our study are plotted in the Fig. 4. The measurements were taken for all the three dimensions (length, width, and height). Both types of samples (FDM and FDM-Milled) were compared with the programmed dimensions. Dimensional accuracy was measured as the deviation of the actual dimension from the programmed dimension. It can be seen from Fig. 4 that as the layer thickness increases, the dimension deviates positively from the targeted one for the pure FDM samples (without abrasive milling). The reason for this deviation could be explained as follows. The layer thickness of the FDM process is controlled by the vertical step movement (upward) of the Z axis, the coarser the upward movement of the extruder the larger the layer thickness. Larger layer thickness caused non-uniform overlapped deposition of the melted PLA material on the previous layer hence, caused dimensional inaccuracy.

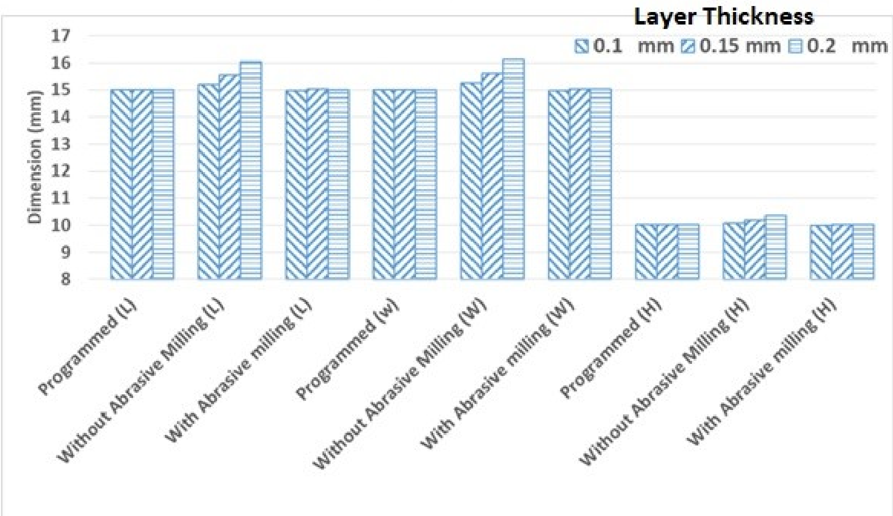

Fig. 4: Shows comparative study of the dimensional accuracy between FDM parts and FDM parts with post finishing process (abrasive milling).

As for 0.2 mm of the layer thickness the measured dimension of the FDM part (in length) was 16.05 mm. Therefore, the deviation from the programmed dimension was obtained as 16.05-15 = 1.05 mm. However, as the part was milled with the abrasive stone the deviation was reduced to 0.01mm. Hence, we can conclude that the abrasive milling process improved the product accuracy (for this particular case) by (1.05-0.01)* 100/1.05 = 99%. The measured dimensions of the FDM parts and FDM parts that underwent abrasive milling are shown in Table 1.

Table 1: Measured dimensions of FDM parts and FDM parts that underwent Abrasive Milling

Layer Thickness	Programmed Dimension (mm)		FDM parts (mm)	Deviation (mm)	FDM parts with Abrasive Milling (mm)	Deviation (mm)	Improvement (%)
0.1 mm	Length	15	15.2	0.2	14.96	-0.04	80
	Width	15	15.25	0.25	14.98	-0.02	92
	Height	10	10.07	0.07	9.98	-0.02	71
0.15 mm	Length	15	15.55	0.55	15.05	0.05	91
	Width	15	15.62	0.62	15.03	0.03	95
	Height	10	10.2	0.2	10.03	0.03	85
0.2 mm	Length	15	16.05	1.05	15.01	0.01	99
	Width	15	16.13	1.13	15.03	0.03	97
	Height	10	10.35	0.35	10.04	0.04	89

The minimum deviation was attained for the lowest layer thickness of 0.1 mm which is 0.2 mm, 0.25 mm and 0.07 mm for the length (L), the width (W) and the height (H) respectively as shown in table 1 (FDM part). As for the samples with abrasive milling, the inaccuracy was reduced to 0.04 mm, 0.02 mm and 0.02 mm for the length (L), the width (W) and the height (H) respectively as shown in Table 1. The standard deviation of the dimensions of the samples (Length, width, and height) for different layer thicknesses was in a range of 10's of micrometres in the case of samples that underwent abrasive milling operation. For the samples without the finishing operation, the value easily rose to 100's of micrometres. Therefore, it can be further concluded that similar levels of dimensional accuracy can be achieved irrespective of the layer thickness (during the FDM operation) if abrasive milling operation is carried out on the samples.

3.2 Study of the Average Surface Roughness and Morphology

Average surface roughness and morphology are two important aspects of studying for the fabricated prototypes. The surface roughness of the produced parts was measured with Mitutoyo SV-C4500 Surface roughness/contour measuring system. The measurement length was kept to be 5 mm to ensure that the stylus does not overshoot and touch the edge of the produced structure. Multiple measurements were taken to ensure the integrity of the results. Figure 5 shows the surface profile of FDM parts with the abrasive milling operation and without the abrasive milling operation for different layer thicknesses.

It can be easily inferred from Fig. 5 that the post machining process (abrasive milling in this case) significantly improves the surface profile by reducing the staircase effect of the FDM part. Moreover, it can be further concluded that layer thickness plays a significant role in the surface roughness on the FDM parts and the best profile was achieved at 0.1 mm layer thickness for this research. The reason for achieving better surface roughness at lower layer thickness is due to the uniform deposition of the melted PLA on the preceding layer. Figure 6 shows the plot of average surface roughness (Ra) and the total height of the profile (Rt). In both cases, it was observed that post finishing process helps to improve the surface roughness parameters.

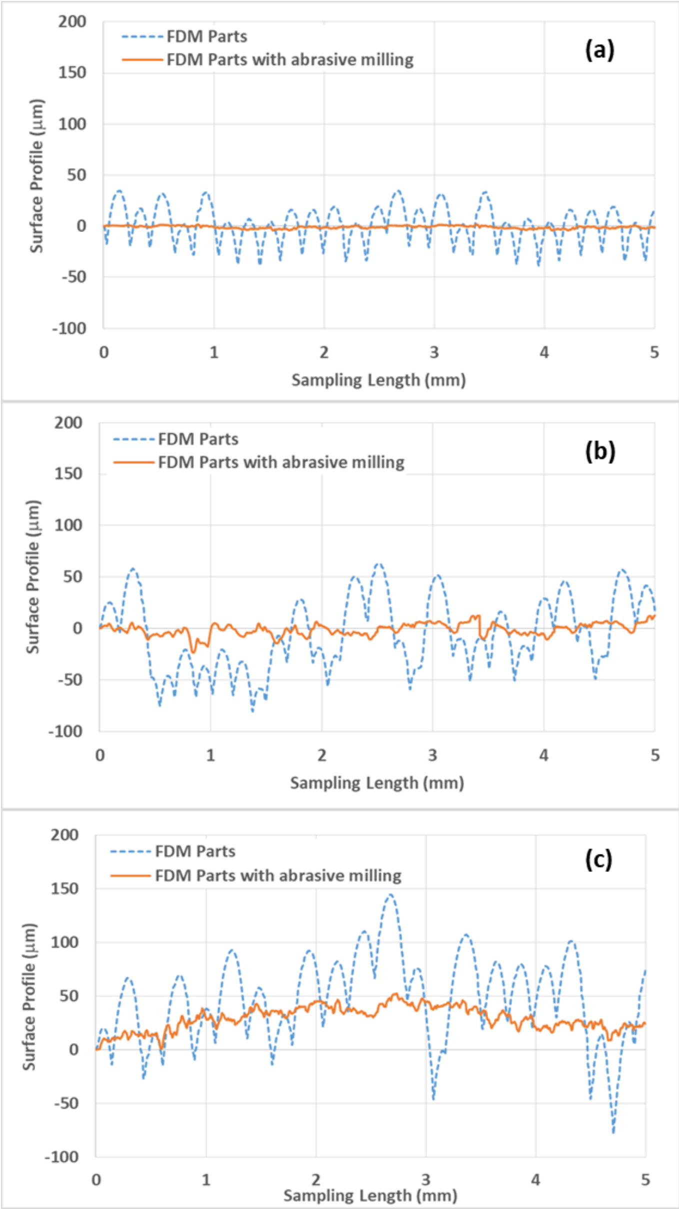

Fig. 5: Raw surface profile of parts produced by FDM and FDM parts that underwent abrasive milling finishing operation, with parts produced (a) at 0.1 mm layer thickness (b) at 0.15 mm layer thickness and (c) at 0.2 mm layer thickness.

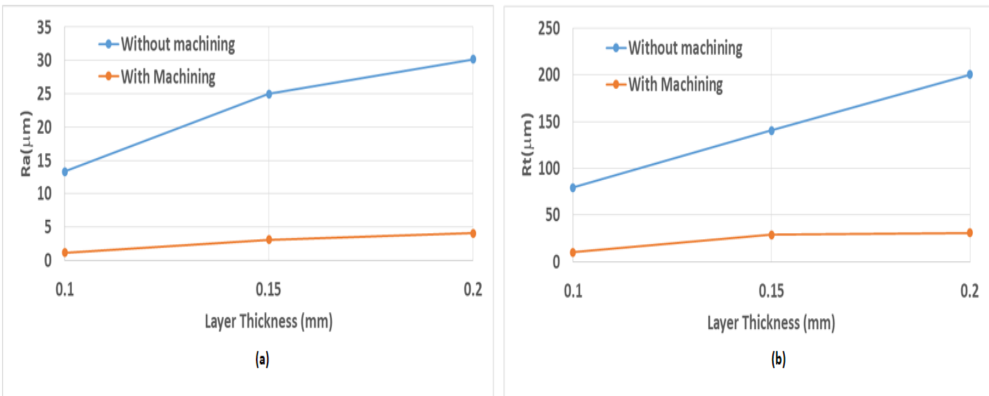

Fig. 6: Shows the comparison of Ra (a) and Rt (b) between pure FDM parts and FDM parts with post finishing operation for different layer thickness.

The best Ra value was achieved at 0.1 mm layer thickness with an abrasive milling finishing process, which was 1.16 µm. The improvement was almost 91.3% as compared with the FDM part without the finishing operation. For the same sample, the Rt value was improved by 87.2% from the FDM part without the post-processing. The morphological study by scanning electron microscopy (SEM) was conducted after coating the sample with a thin layer of gold because of its' nonconductive characteristics. Figure 7 shows the SEM images of the samples which further validate the study of dimensional accuracy and surface roughness. The SEM images of FDM parts without post-finishing operation shows typical staircase effects (Fig. 7 (a), (b) and (c)). However, for the parts with the finishing operation, SEM images (Fig. 7 (d), (e) and (f)) confirm that the staircase effect was reduced by a significant margin and the surface becomes smoother. The phenomenon was the same for all layer thicknesses, i.e. 0.1 mm, 0.15 mm and 0.2 mm. Furthermore, Fig.7 confirms that FDM parts have voids between their layers due to non-uniform overlapping of the layers, as shown in Fig. 7 (b) and (c) (white circles). The void remains in the produced parts even after the abrasive milling operation, as shown in the Fig. 7(e) and (f) (white circles). The voids created between the layers are the main reason for worsening dimensional accuracy and surface roughness of the FDM parts with greater layer thickness.

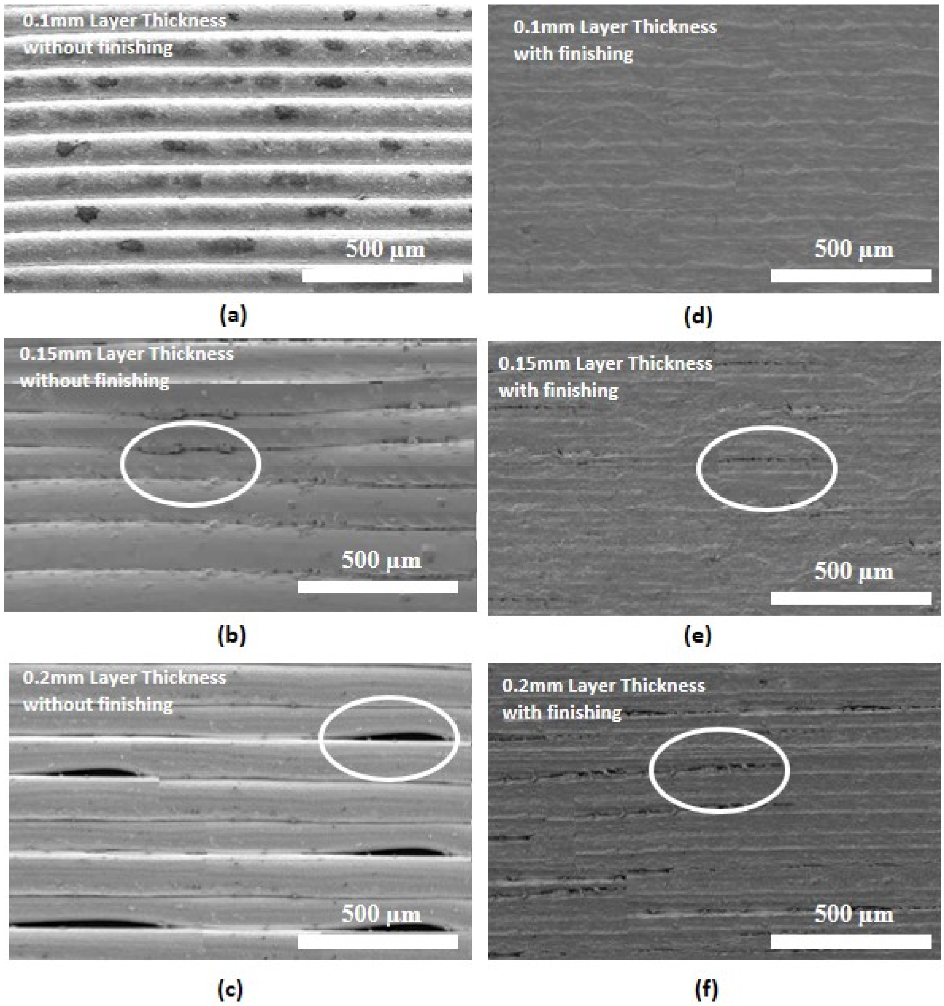

Fig. 7: SEM images of the produced samples with different layer thickness. (a), (b) and (c) are FDM parts without the finishing operation; (d), (e) and (f) are FDM parts with the abrasive milling operation. The circle marks shows voids due to non-uniform overlap of the layers for thicker layers.

4. CONCLUSION

This paper proposes a modular design to integrate FDM and post-finishing (abrasive milling) processes into a single platform. Conventionally, the finishing operation of the FDM process is carried out off the machine, which increases the chances of product damage due to mishandling and product inaccuracy because of the changeover process from one machine to another. The proposed hybrid system eliminates such possibilities. A rotary axis was integrated with the vertical axis (Z axis) to hold the FDM heat extruder or the milling spindle. To maintain the parallelism of the FDM heat extruder or the milling spindle with the Z-axis, the rotary axis was adjusted from sensor feedback. Experimental studies were conducted to evaluate the performance of the newly built FDM-Abrasive Milling-based hybrid system. The dimensional accuracy was enhanced substantially for FDM parts after abrasive milling, as compared to pure FDM parts (improved by a margin of ~5 x (L), ~13 x (W) and ~35 x (H)). Similarly, surface roughness was also lowered considerably for FDM parts after the finishing operation (R_a reduced by ~11.5 x). Moreover, the new system is also capable of carrying out the pure milling operation separately, which helps to achieve the user's dual manufacturing processes in a single system. In future, the software of the developed system would be further improved so that the system can be fully autonomous.

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