Significant improvement in surface finish of 3D printed parts using Pneumatically Configurable Polishing process

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Abstract

The need of nano range surface finish on industrial components is increasing especially in several niche domains where the product's functional capabilities are significantly influenced by its surface properties. Additive manufacturing which was originally developed as a rapid prototyping technique is now being used to fabricate end use products. However, additive manufactured parts which are produced using techniques such as fused deposition modelling often suffer from poor surface finish due to the intrinsic characteristics of the manufacturing process. The layer-by-layer material deposition leads to the development of a final surface which closely resembles a staircase texture.

This limitation of high surface roughness in FDM printed parts can be overcome using various post processing methods. The present study investigates the use of a novel post-processing compliant polishing technique called Pneumatically Configurable Polishing (PCP) to improve the surface finish of such components. To produce a nano range surface finish on substrate surfaces, the PCP process uses pneumatic pressure to optimally inflate a thin flexible polymeric membrane. The cup-shaped PC polishing tool's adaptive nature conforms to the workpiece's macro-features when it encounters the surface of the workpiece. The PCP technique offers the manipulation ease and determinism in polishing force control necessary to finish complicated surface profiles in a highly repeatable manner.

The present paper describes the experimental investigations carried out for finishing of a FDM printed polylactic acid (PLA) workpiece using the PCP process. The average surface roughness (R_a) of the component which initially ranged between 20 -25 µm was found to decrease to a final range of 30 - 50 nm thus indicating a significant improvement in surface finish using the PCP technique.

1 Introduction

The development of additive manufacturing has been an important milestone in the manufacturing industry because it paved way for rapid development of components and parts having complex features which were difficult to obtain using conventional machining methods. It was also revolutionary in the sense that it allowed creation of parts directly from a CAD model, thus allowing the realisation of an engineer's design into a part in a matter of few hours. The minimalistic requirement of specialised tooling and fixtures have allowed additive manufacturing to establish itself as a highly economical alternative to conventional machining. In the recent years, a multitude of additive manufacturing techniques have emerged out of which a few prominent ones are Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Stereolithography (SLA), Laminated Object Manufacturing (LOM) etc [1].

1.1 Fused Deposition Modelling

The Fused Deposition Modelling technique is one of the most inexpensive and versatile additive manufacturing techniques where the gradual heating and deposition of a thermoplastic polymer filament is used. The part fabrication involves the uncoiling of the solid filament from a spool and feeding it through a heating element which causes the filament's conversion into a semi molten state. [1] The incoming solid filament acts like a piston and forces the heated thermoplastic material through a nozzle and deposits it selectively as per the CAD model of the product in a layer-by-layer fashion. The freshly deposited filament material fuses with the previously fabricated part and thus a fresh layer is formed over the previous one. The platform is lowered by a fixed amount to allow the successive layer to deposit on the preceding layer. As a result, a complete part is gradually realised as per its CAD model. PLA and ABS are the two most commonly used build filaments used for FDM process.

The widespread acceptance of FDM as a 3D printing technique across industry is due to few major advantages: it's a neat process – no powders or liquid build materials are required and thus it can be kept in an office setup. Since no lasers are used and the build material are readily available the cost of fabrication is quite low [1]. Although FDM gives the benefit of flexibility in the production of complicated and intricate geometries and shapes, the surface quality of FDM-printed items is poor. This is due to the staircasing effect, which is a characteristic feature of the stacked layer deposition technique and restricts the commercial application of as-printed parts [2]. The average surface roughness of an FDM printed part ranges from 5 µm – 25 µm. As a result of this poor surface quality FDM parts need some pre & post processing to enhance their surface finish.

1.2 Surface enhancement techniques for FDM parts

1.2.1 Pre-Processing techniques

The commonly employed pre-processing techniques make use of optimization of fabrication parameters during the printing process such as bead width, layer thickness, extrusion temperature, build orientation and raster orientation etc.[2] Multiple researchers have employed techniques such as design of experiments for identifying optimum process parameters for achieving improved surface finish. Another approach for pre-processing techniques is the use of adaptive slicing where the different sections of the part are sliced into different values of thickness. However, in this approach the reduction of layer thickness leads to an increase in build time.

1.2.2 Classification of post processing techniques for 3D printed parts

The post processing techniques can be divided into two categories: chemical treatment processes and machining processes. The chemical treatment processes make use of techniques such as dipping the FDM part in a solution of dimethyl ketone (acetone) and water for a predefined time interval [4]. This chemical treatment causes removal of surface irregularities and improve the surface quality. Chemical processes also encompass techniques such as vapor smoothing [5] where the part is allowed to interact with a chemical vapor and then cooled. This allows the part surface to smoothen by reflowing the material inside the available gaps.

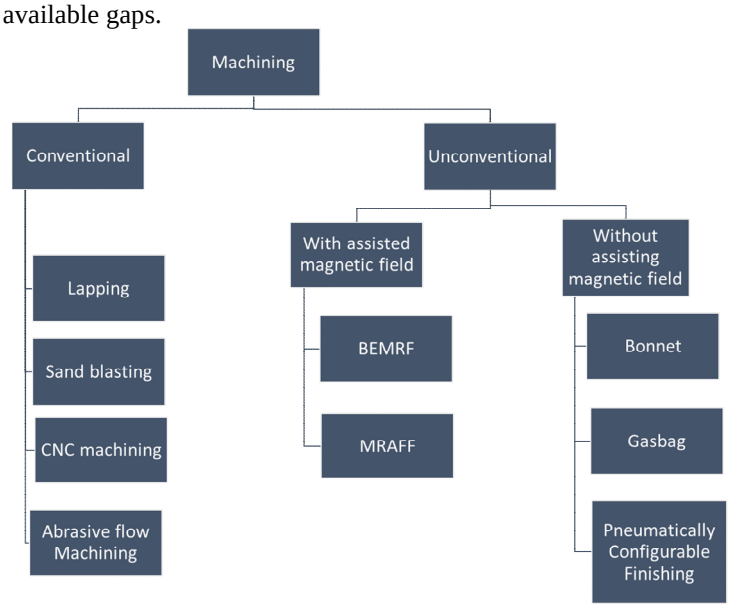


Figure 1: Classification of machining techniques used for post-process surface enhancement of FDM printed parts.

On the other hand, the machining techniques make use of a subtractive approach to selectively remove material and improve surface finish. The classification of machining processes is shown in Fig 1. The conventional machining techniques such as manual sanding, abrasive flow finishing, vibratory finishing, sand blasting etc. are age old finishing processes used for finishing different substrate surfaces. The unconventional finishing techniques can be classified on the basis of the fact that whether they utilise the assistance of a magnetic field or not during finishing. The magnetic techniques are those which utilise magnetic fields as a fundamental part of their finishing principle. Magnetic field assisted techniques such as the BEMRF [6] and MRAFF [7] have proven their efficacy in generating nano level surface finishes on substrates. However, the techniques such as bonnet polishing [8] and gasbag polishing [9] are techniques which do not utilise magnetic fields to obtain desired motion of abrasives during the finishing process.

A recent addition to the non-magnetically assisted finishing techniques is Pneumatically Configurable Polishing process [10]. It employs the use of pneumatic pressure to achieve precise control of finishing forces being transmitted to abrasives present in a carrier medium. Studies have shown that the PCP process is capable of producing nano level surface finish on metallic substrates. However, the use of the PCP technique for finishing of FDM printed parts has not been explored yet. Therefore, the present work investigates the finishing of FDM printed parts using Pneumatically Configurable Finishing technique. The improvement of surface roughness has been investigated using diamond abrasives and the contribution of important process variables on the resulting surface roughness has been examined.

2 Materials and methods

2.1 3D printed workpiece

The workpieces used for the investigation were printed using a Raise3D N2 FDM printer. Each workpiece has a cuboidal shape and its dimensions are 30 x 30 x10 mm^3. The process parameters used for 3D printing are presented in Table 1. The CAD model used for the generation of the STL file was used to obtain the CNC part program using the AutoDesk InventorCAM software.

Table 1: Process parameters used for FDM printing

Parameter	**Value**
Build density	100%
Filament material	PLA
Depostion layer thickness	0.1mm
Filament diameter	1.5 mm
Nozzle temperature	200^oC
Wall thickness	1 mm
Build orientation	90°
Nozzle diameter	0.4 mm

2.2 Experimental setup used

The experimental setup used for surface finishing of the FDM printed workpiece is a 5 axis (X-Y-Z -B-C) CNC finishing setup as shown in Fig 2. Each axis is operated by an independent servo motor while the polishing tool rotation is facilitated via a spindle servo motor. The tool tip position is controlled by the Z axis while its orientation is controlled by the B axis. On the other hand, the workpiece coordinates relative to the tool are controlled using the combined manipulation of X and Y axes while its orientation is controlled via the C axis. The CNC controller exercises its control on the finishing forces as per the part program using a digital pressure controller. A set of customized CNC H-codes were developed for real time manipulation of pneumatic pressure during finishing. The workpiece is firmly mounted in a precision vice and the tool is fastened to the polishing head spindle.

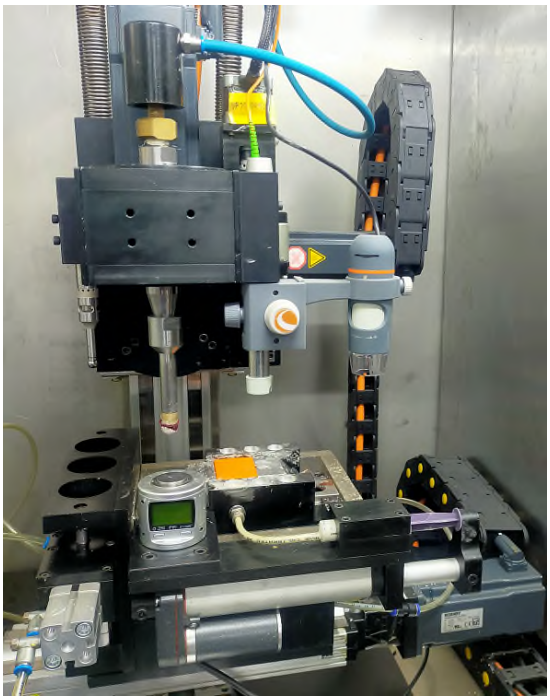


Figure 2: PCP setup used for finishing

2.3 Finishing principle

As shown in Fig. 3 the polishing tool used in Pneumatically Configurable Finishing has a hollow passage and allows the pneumatic pressure to inflate the membranous tool tip. The polishing slurry which contains the abrasives suspended in a viscous fluid is pre-placed at the tool tip. The abrasives are entrapped between the work – film interface zone under the effect of the applied

pneumatic pressure. The rotation of the polishing tool causes the shearing of the surface peaks, leading to the gradual generation of a finished surface.

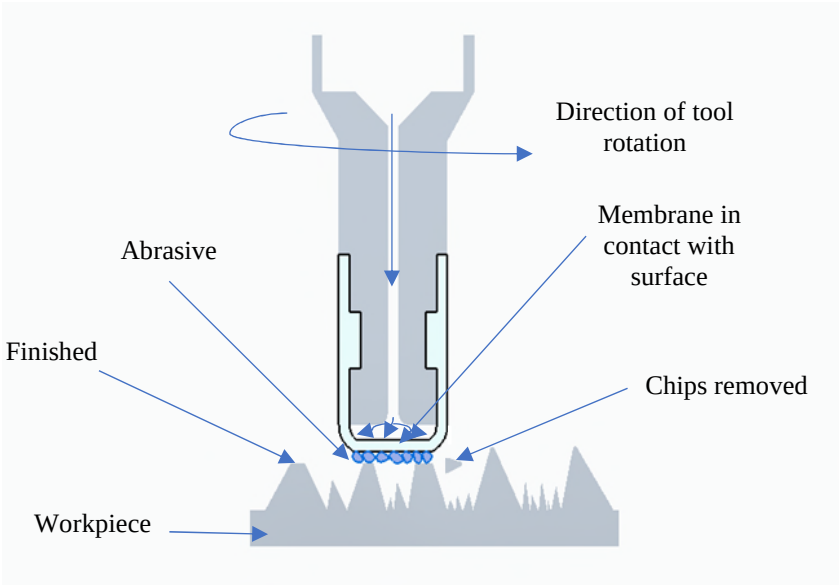


Figure 3: Working principle of Pneumatically Configurable Finishing process

2.4 Experimental methodology

The FDM printed workpieces were held in the precision vice of the PCP machine. The finishing of the workpiece was carried out using a reciprocatory finishing approach where the tool travels along a straight toolpath on the work surface and then retraces the same at a constant feed rate. The values of applied pneumatic pressure, tool rotation speed, feed rate and other process parameters used during experimentation are presented in Table 2. The range and values of the process parameters were determined through some preliminary studies.

The as printed part was finished directly using PCP without using any other secondary finishing process to bring the roughness in a sub-micron zone. The initial and final value of the profile surface roughness (Ra) was measured for the as-printed surface and the finished surface using a Mahr M310 surface roughness tester. The sampling length of 4 mm was evaluated while the cut-off length was kept at 0.8mm. The surface roughness values were obtained at 6 random locations before and after each polishing experiment and an average of the six values is recorded.

Table 2: Process parameters used during finishing

Parameter	**Value**
Applied pneumatic pressure (bar)	0.5 , 1, 1.5, 2, 2.5, 3
Tool rotation speed (RPM)	400, 800, 1200
Working gap (mm)	0.5, 1.5, 2.5
Slurry fluid	Parafin oil
Feed rate (mm/min)	50 , 100 , 150
(% wt) concentration	0.5
Abrasives used	Diamond
Abrasive size	5-7 µm
Tool diameter	12 mm

3 Results and Discussion

3.1 Effect of working gap on the final surface roughness

The working gap represents the normal spacing between workpiece and the polishing tool in its non inflated state. The inflation of the polishing tool is dependent on the physical properties of the elastomeric membrane and the extensible polishing film. At low values of pressure, if the maximum inflation of the tool is less than the working gap, the tool will not touch the workpiece. In such a case no finishing is observed unless a cutoff pressure is applied as evident from Fig 4. However, at lower values of working gaps, polishing is observed even at lower values of pressure. It can also be observed from Fig. 4 that as pressure is increased beyond a certain value (limiting pressure) the final surface roughness increases and surface quality starts depleting as the substrate tends to turn into semi molten state due to the heat generated by the tool.

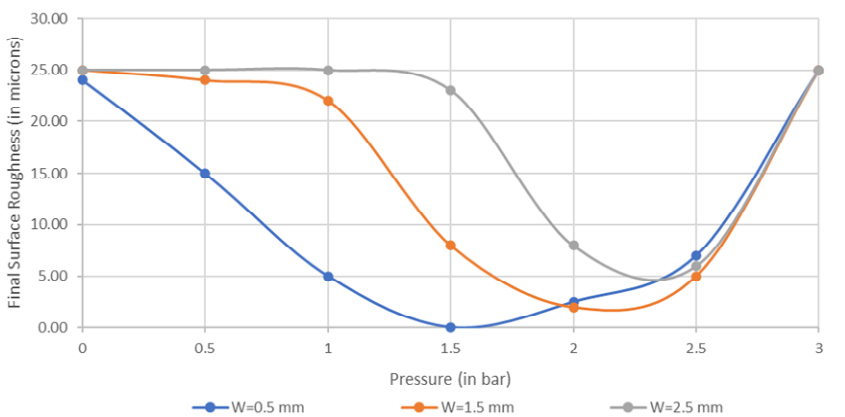


Figure 4: Variation of the final surface roughness w.r.t pressure at different working gaps

As evident from Fig. 4, the value of this limiting pressure increases with the working gap as the total normal force transmitted to the workpiece will decrease at higher working gaps. If the input pressure is increased even further (>3.0 bar), the final surface roughness becomes greater than the initial Ra value and this is considered as the zone of invalid finishing.

3.2 Effect of tool rotation speed on the final surface roughness

The tool rotational speed provides a measure of the relative velocity of the active abrasives w.r.t to the workpiece. The active abrasives entrapped in the polishing film are forced to abarade against the workpiece surface thus removing microscopically small fragments of work material in the form of debris. The forces transmitted normally to the abrasives is proportional to the applied pneumatic pressure. Hence, as the pneumatic pressure increases the value of the final surface roughness declines gradually. However, as shown in Fig. 5, this reduction in surface roughness continues till a optimum value of the pneumatic pressure. After this optimum pressure value the surface quality decreases due to the heating effect as discussed in the previous section. As evident from Fig. 5 this optimum pressure is inversely proportional to the tool rotation speed. Therefore, at lower tool rotational speed (400 RPM) the optimum value of pressure is around 1.5 bar while at higher rotational speeds this value is around 0.5 bar. The fundamental reason that can be cited is that higher values of tool rotational speeds lead to an increased heat generation during finishing.

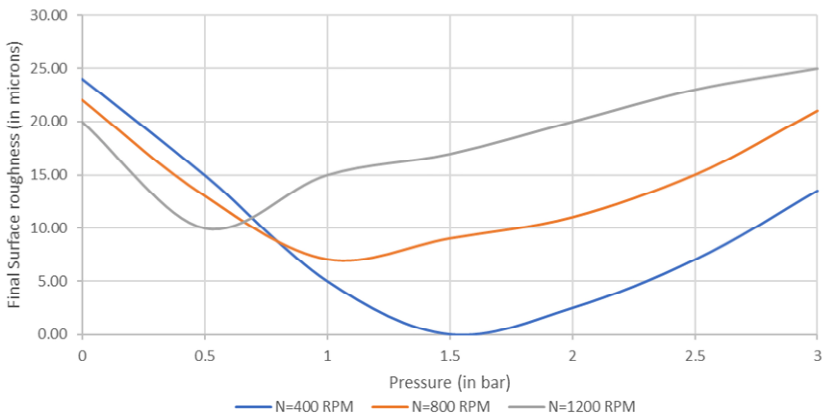


Figure 5: Variation of the final surface roughness w.r.t tool rotational speed

3.3 Effect of feed rate on the final surface roughness

The feed rate defines the speed at which the tool moves along the tool path over the work surface. At higher values of feed rate, the dwell time of the tool at any polishing spot will be lower. As a result, at a given pneumatic pressure more material removal will be observed and better surface finish is obtained. As

illustrated in Fig 6, beyond the optimum of pressure the surface finish obtained diminishes. The optimum pressure is found to vary proportionally to the feed rate employed.

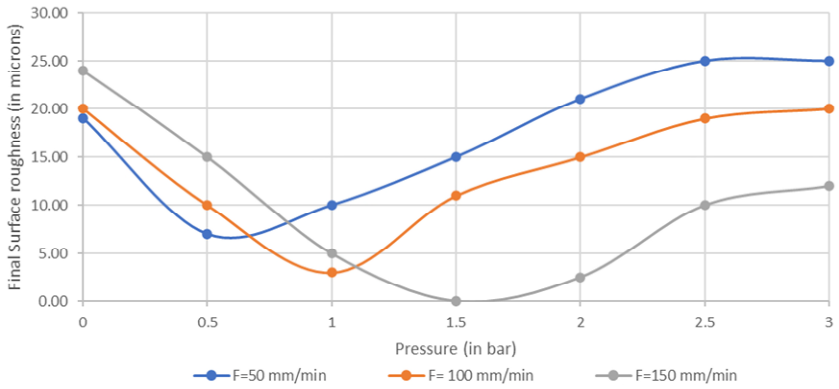
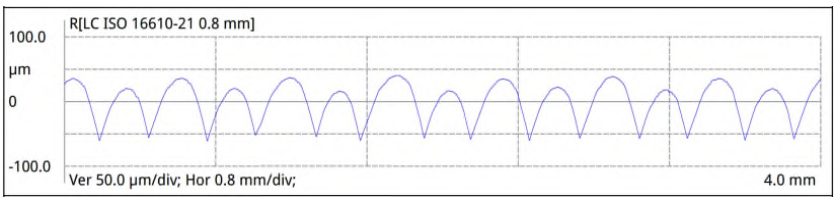


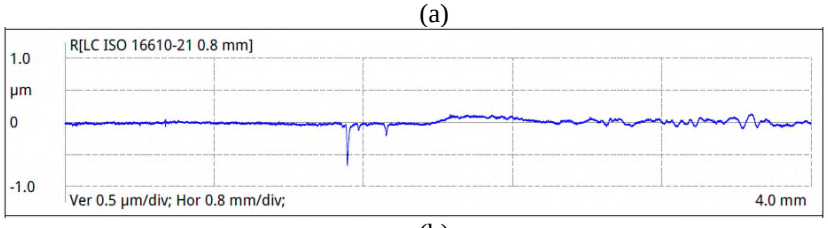
Figure 6: Variation of the final surface roughness w.r.t tool rotational speed

3.4 Surface finish enhancement achieved

The optimum value of surface roughness is achieved at a tool rotational speed of 400 RPM , applied pressure of 1.5 bar and working gap of 1.5 mm. The initial surface roughness of approx 22µm is reduced to a final value of approx 30 -50 nm after finishing. The surface roughness profiles for the initial and final surfaces are shown in Fig. 7(a) and Fig. 7(b) respectively. The peaks and valleys of the order of few microns, which are prominently visible in the unpolished surface are entirely eliminated.



(a)



(b)

Figure 7: Surface roughness profiles of the work surface (a) initial (b) final

4 Conclusions

The finishing of FDM printed parts using the PCP technique is investigated. Following conclusions have been drawn from this study

1. A significant improvement in the surface roughness of FDM printed PLA parts is achieved using the PCP process. Using the optimum process parameters, the initial Ra value of ~22µm has been reduced to a final value of ~30 – 50 nm.

2. The process parameters such as pneumatic pressure, tool rotation speed and feed rate are found to have a profound effect on the final surface roughness.

3. The value of optimum input pressure is identified, beyond which surface finish starts deteriorating due to the heating effect caused by the tool. The optimum value of input pressure is directly proportional to the feed rate while it is inversely proportional to the working gap and tool rotational speed.

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