Vol. 44, No. 4 (2022) 551-567, DOI: 10.24874/ti.1305.05.22.09

Tribology in Industry

www.tribology.rs

RESEARCH

Design and Development of Hot Vapour Polishing System and Optimization of It's Process Parameters for FDM Printed Parts

Sunish Ram Kishore[a], Amal Mathew[a], Anchil Tona Tomy[a], Manivannan Sugavaneswaran[a,b], A. John Rajan[a,*]

[a]*School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, 632 014, India,*
[b]*CSIR - NAL, Bengaluru, Karnataka, 560017, India.*

Keywords:

Hot chemical vapour smoothening
Fused deposition modelling (FDM)
Acyrlonitrile butadiene styrene (ABS)
Polylactic Acid (PLA)
Tetrahydrofuran (THF)
Surface roughness

Corresponding author:

A. John Rajan
E-mail: ajohnrajan@vit.ac.in

Received: 19 May 2022
Revised: 14 July 2022
Accepted: 12 September 2022

A B S T R A C T

Fused deposition modelling (FDM) is a process of layer-by-layer material deposition using a heated extruder. FDM printed parts have stair-stepped effect and ridge patterns that diminish surface quality. This research intends to develop a low-cost, high-efficiency experimental system for polishing a variety of materials using various chemicals, with a chemical vapour smoothening process. For evaluating the created set-up, tetrahydrofuran (THF) is used and acetone as solvents to polish polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). Taguchi multi-parameter optimization was used to optimize the input parameters (reagent volume, temperature, concentration, and time) in the vapour smoothening process. With the ideal input parameters, the roughness of the FDM printed parts was reduced by over 95%. The effectiveness of a vapour smoothening system is better when the system temperature is maintained at the boiling point of the reagent, the reagent is of its highest concentration, and when the specimens placed are placed directly over the ultrasonic mist-maker. The system discussed works best with FDM printed parts having minimum porosity and better quality. The hot chemical vapour smoothing approach reduced specimen flexural strength and increased top layer wear. The findings of this study will help develop a large-scale polishing system for FDM printed thermoplastics and enhance the use of FDM components in sectors that need highly polished parts.

1. INTRODUCTION

Fused deposition modelling (FDM), also known as fused filament fabrication (FFF), is a popular additive manufacturing technique that involves layer-by-layer deposition of material (filament) through a heated extruder to produce 3D printed models [1-6]. This method has revolutionized rapid prototyping by allowing highly complex geometries to be created without the use of dies or moulds. Even though FDM printing is a faster and less expensive method of rapid prototyping, its main flaw is its poor surface finish. The staircase effect and ridge patterns are the main causes of this poor surface finish. The staircase effect is due to the way FDM parts are made. That is, it is caused by a layer formed by filament deposition on an inclined surface. Ridge patterns are created when there is a gap between the beads [7,8]. As a result, improving the surface finish of FDM printed parts is critical because it improves the part's appearance, smooths out uneven surfaces, optimises specimen size and shape, and improves the part's overall aesthetics.

There are different ways to overcome this issue and can be classified mainly as pre- and post-processing. Pre-processing involves optimizing the layer thickness and part orientation, but the problem is that there is a limit on how much surface roughness can be obtained with this technique because of constraints like nozzle diameter, part shape, part orientation, rheological characteristics (melt flowability, shape stability, etc.) of melt filament [9] and print time, and also how feasible is the process, to be carried out in a controlled (closed) environment [10,11]. In some cases, pre-processing also involves changing the composition or micro-structure of the filament material to produce components with better surface finish, mechanical properties, and industrial application [12-15].

In the case of post-processing techniques [16-20] even though there are techniques like sanding and annealing [21], the most promising among the bunch is the chemical vapour polishing technique. chemical polishing can be done in three different ways. The first is immersion polishing, which involves dipping the part into the chemical, the second is cold vapour polishing, which involves enclosing the part in a closed chamber and exposing it to chemical vapours, and the third is hot vapour polishing, which involves exposing the specimen to a heated chemical.

Hot vapours produced during the hot vapour polishing improve the surface finish of the specimen by reacting with the surface and forming a chemical specimen material slurry that flows and fills the ridges between the beads and the gap between layers, eliminating the staircase effect.

The work [22] focuses on the experimental setup of an instrument for increasing the final model's surface polish to address the quality of the surface finish problem. A vapour smoothening method using hot chemical vapour combined with heated air produced a mint surface finish, according to the results of the trial. The paper also points out fundamental drawbacks of conventional finishing methods like sanding, painting, or any other smoothing procedure, coupled with additional issues, such as edge cutting and micro-cutting, which are all a concern.

The constituents of the experimental setup are an acetone storage tank that could be refilled even during operation, an acetone heating unit, a circulation fan to spread hot vapour, a cooling fan to minimise the temperature after the process, a PID temperature controller, an ultrasonic mist maker, and finally a glass chamber. The wooden chamber houses all of the electronic components. The observations made were that the greater the temperature, the better the surface quality, but the effect disappears beyond 80 degrees celsius (°C). One other thing to keep in mind: the completion time is exactly related to the weight increase experienced by the FDM component.

The goal of [23] research was to reduce the surface roughness of a 3D printed FDM object. The experiment focuses on the two most important elements that affect surface roughness: the frequency of smoothening cycles and the length of each cycle. Overall exposure duration to acetone vapour, was shown, to be by far the most important determinant of part surface roughness.

The purpose of [23]'s work was to recommend the optimum parameters for smoothening and to get a better surface roughness for every design variable. The usage of chemicals such as acetone vapour should greatly reduce the surface roughness without any modification in dimension as well as the reduction in smoothening time.

Acetone's cheap cost, low toxicity, and great diffusion are all advantages of employing it as a vapour. A slurry of acetone and ABS is generated when heated acetone reacts with ABS (acrylonitrile butadiene styrene) plastic. A smoother surface is created when acetone vapour leaves behind the strands of ABS polymer on the surface, which are left behind after the acetone evaporates. Finally, the use of an acetone vapour bath resulted in a 95% reduction in surface roughness.

The length of the vapour bath cycle had the greatest impact on surface roughness, as was discovered. When using ABS acetone slurry, it has been discovered that it solidifies at the bottom of the slope as a result of this process.

According to the experiment conducted by the researchers in [24], the orientation of the model's build has an important role in the final finish of the model, which is made of Poly acetic acid thermoplastic, and tetra hydro fluoride, the vapour used to finish the model. The tensile strength decreased by 63% and the elongation increased by 50% following the chemical treatment. Because it is made from maize, PLA (polylactic acid) is both biodegradable and environmentally benign. Tetra hydro furan (THF), an organic molecule that is colourless, non-toxic, and water-soluble, is the vapour utilised in the vapour smoothening process. An induction heater was used to evaporate the THF solution, and a thermometer was used to regulate the temperature such that the vapour stays between 64°C and 66°C. Containers for the THF solution and the prototype are put on steel stands.

It can be concluded that 90° orientation using 10mL THF solution decreased surface roughness by 78% in five minutes, demonstrating that the coating solution volume has a considerable influence on the surface quality.

Vapour smoothening using acetone on polylactic acid (PLA) specimens is the subject of [25] report's experimental setting. The setup includes a device that moderates the amount of acetone used at varied concentrations under variable operating parameters, such as temperature and control time. FDM components post-treatment was explored in [25] experiment with great depth. In which, the setup had a pyrex cylindrical chamber, two electrical furnaces, stainless steel hook for hanging the model and gas injection unit for injecting vapour from the bottom, and a condensation unit for feeding acetone vapour back to the metering pump for re-injection into the heating element. There are also flowmeters and t-connectors in the arrangement. So, to summarise, results in [25] demonstrate that adding acetone PLA slurry significantly improved the surface quality, but also reduced the model's overall thermal conductivity.

The study in [26] investigated a polishing method for ABS 3D printed objects that may be used to remove surface imperfections. It's cheap cost and lack of chemical voltage, as well as its great efficiency and excellent dimensional precision, are the design's defining features. There are many parts to the experiment, including a temperature sensor, a device for controlling the ambient air temperature, a timer and even a circulation fan with a rotary motor and an electric heating element with a microcontroller. The most significant benefit of this configuration is that it removes the requirement for expert labour [27] when polishing a 3D printed object. This polishing may also be used for sophisticated models that need a relatively minimal amount of computational power. To further shorten processing time, this experiment's vapour polishing model has dipped in an acetone solution before the vapour smoothening procedure.

In the [28] study, they've examined the effects of vapour bath polishing on FDM parts and have recommended the optimum method for smoothening them. The experiment, that yielded the greatest surface finish was the one that employed three rounds with 15 seconds on each round. A shorter cycle time had a greater influence on surface finishing than a higher number of cycles; layer thickness was also shown to be the primary design component determining surface roughness, with a thinner layer yielding a smoother surface.

Post-processing of FDM models utilising cold acetone vapour for 3D printed ABS components was examined in [29]'s research. Surface finish and treatment time for two alternative process configurations were the key topics of investigation. The most stable arrangement was found to have a 98% decrease in surface roughness after post-process treatment. To experiment, the team used an acetone liquid container housed within a steel container held at ambient temperature. It is put in two separate positions within the steel container, one towards the acetone solution and the other looking rearward. The experiment's most significant result is that orientation has a crucial effect on the quantity of surface finishing. While the backward configuration produces superior outcomes in the case of absolute final roughness and uniformity, the facing configuration is more progressive in the decrease of roughness during the treatment duration, particularly when beginning from a rough surface.

The thermal characteristics of a model were examined in [30] research, concerning the impact of vapour smoothening. The prototype was made of ABS plastic, and acetone vapour was utilised to smooth it out. Temperatures over 50 degrees Celsius revealed no substantial change in thermal characteristics, while at lower temperatures, thermal stability was shown to be considerably compromised. Vapour smoothening has a noticeable effect on model attributes, compared to the model that didn't have this treatment. The temperature-dependent tan delta maximized between 65°C and 75°C in the sample with vapour smoothening, and the storage modulus drops fast as the temperature rises. Following the acetone vapour smoothing process, the thermal stability of ABS 3D printed objects was found to be greatly diminished.

Chemical vapour smoothening (CVS) was used to enhance the surface smoothness of FDM-based ABS models in [31]. During the analysis in various research works, it was discovered that the model's build orientation, raster orientation [32] temperature [33], road width, air gap, and layer thickness were all key contributors to surface roughness and various mechanical properties (fatigue life [32], residual stress [34]). The parameters derived out from modal analysis and the vibration response are most significantly impacted by the type of adhesion [35]. Layer thickness and component orientation are two of the most common reasons for poor surface quality in these. Pre- and post-processing procedures are discussed in [31]'s study to enhance the surface finish. The experiment showed that the best CVS surface polish was achieved when the orientation value was 90 degrees and three cycles of 10 seconds each were performed. The CVS method produced a smoother surface with less dimensional variance than the conventional techniques at a faster phase.

The focus of the study [36] was on the mechanical characteristics of 3D-printed FDM components that have undergone post-processing by vaporisation. The specimen's tensile strength, flexural strength, and surface finish were examined in a series of tests, and a comparative study was done between the sample that was not exposed to acetone vapour and the sample that was. To verify that the sample after vapour smoothing can bear stress and does not indicate a decline in quality, mechanical qualities must be studied. After conducting the study, they found that the tensile strength of the original part was 25.661 MPa, while the specimen that experienced vapour smoothening for 45 minutes produced a better value of 27.89 MPa, and the specimen that underwent vapour smoothening for 15 minutes showed 26.083 MPa. This indicates that the tensile strength of the specimen was improved compared to that of the model that is not treated with vapour smoothening.

The flexural strength tests are contrary to the findings of the tensile tests, which reveal a different conclusion. The original specimen has a flexural strength of 52.4621 MPa. As one can notice, the flexural strength of a specimen that was exposed to the vapourised environment for 45 minutes, 30 minutes, and 15 minutes decreased from 51.0768 MPa, 50.3549 MPa, and 50.28407 MPa respectively. As a result, it was determined that this specimen's true strength would be reduced during vapour smoothing. [36] discovered that the surface quality of the vapour smoothened specimen increased significantly from the initial model in the third investigation. In the end, it was determined that a cycle time of 45 minutes was best for maximising mechanical attributes.

The study in [37] focuses on the development of an acetone vapour polishing mechanism for FDM produced ABS components. Dimensional precision and excellent polishing efficiency may both be achieved at a reasonable cost and with no waste of chemicals thanks to this technology. In addition to the microcontroller, the vapour polishing system includes a temperature controller and a circulatory fan to circulate the vapour. After the acetone had completely evaporated, the heating element was adjusted to 57 degrees celsius to speed up the cooling process. With a fan speed of 70 and a processing period of 5 minutes, this system was able to reduce the surface finish from 91 μm to 2 μm. The researchers in [37] are also focussing on predicting the polishing time and studying the linear trend by using a curve fitting equation. Among the system's advantages is the ability to polish even the most complexly shaped pieces with great precision.

From the literature survey for a chemical vapour polishing system for improving the surface finish of FDM printed parts, several gaps were found in this study.

One of the most significant research gaps discovered is that very little study has been undertaken for multi-parameter optimization for hot vapour smoothening. Even though chemical vapour polishing produces a high surface quality, investigations on the parameters required to achieve a certain degree of surface finish are lacking. To obtain a consistent finish from the hot vapour polishing technique, along with a proper experimental setup, it is important to provide the specimen with constrained parameters to get the desired surface finish without damaging the specimen. These parameters include the volume of reagent, run time, cooling time, volume of the chamber, distance between specimen and reagent, and orientation of the specimen.

No adequate information about the comparative study of mechanical properties and material properties before and after the hot vapour polishing is available. These properties include flexural strength, wear resistance, etc.

A comparative study of mechanical, material and surface roughness properties between ABS (polished with acetone) vs ABS (polished with THF) is not available.

Looking over the gaps and understanding the problem definition, the following objectives are considered for this research work: a) To create an experimental set-up and system where chemical vapour smoothening can be carried out for both ABS and PLA plastics so that under constant parameters, the outcome of the specimen is consistent; b) To study the comparison of mechanical, material and surface properties of the FDM printed specimen before and after vapour smoothening polishing technique; c) To conduct a comparative study of mechanical, material and surface properties of ABS plastic vapour polished with acetone and THF and PLA plastic vapour polished with acetone.

This paper deals with developing a low-cost highly efficient experimental setup flexible enough to polish using different chemicals and on parts made of a different material. Here acrylonitrile butadiene styrene (ABS) and poly latic acid (PLA) are selected along with acetone and tetrahydrofuran (THF) as the chemicals respectively. The system parameters are further optimized using the Taguchi method of multiparameter optimization [38] and various surface test like wear tests, scratch tests and flexural tests were conducted on the most polished part to figure out the amount of variation from the specimen which did not undergo this treatment. This system produces a product suitable for end-user applications in the field of patterns for casting [39], automotive [40] and aerospace prototyping [41,42], complex consumer goods which require a high surface finish, and prototypes used for research and learning application [43-45].

2. MATERIALS AND METHODS

The test specimens for both ABS and PLA were designed in fusion 360 software and were printed using duplicator 4S 2.5D FDM printing machine. The CAD model prior to printing was further adjusted in FlashPrint 4.6.4 software. Then the part was sliced using the same FlashPrint 4.6.4 (machine type: FlashForge Creator Pro) into thin sections with a layer thickness of 0.20mm and first layer thickness as 0.30mm, and with other printing properties as shown below in the table 1.

Table 1. Printing properties of the specimens to be used for analysis and testing.

Properties	For ABS material	For PLA material
Adhesive used on build platform	No	Yes, Glue
Shells		
Perimeter shells	3	
Top solid layers	3	
Bottom solid layer	3	
Infill		
Fill Density	20%	
Fill pattern	Line	
Combine fill	Every 2 layers	Disable
Speed		
Print speed	30mm/s	
Travel speed	80mm/s	
Temperature		
Right extruder	230°C	200°C
Platform	90°C	50°C

ABS and PLA along with acetone and tetrahydrofuran respectively are selected as the specimen material and the chemicals because these two are the most common materials and chemicals used for FDM 3D printing for better surface roughness results.

2.1 Experimental setup

The printed part's surface finish was improved using post-processing with hot vapour polishing. The prototyping and modelling of the hot vapour polishing system were done in Fusion 360 CAD software and the final prototype was manufactured. The system for polishing ABS parts is composed of an ultrasonic mist maker and its adaptors, a Temperature controller, an induction heating coil, an Induction coil control panel, and LED driver. The vapour chamber is made of transparent acrylic and accommodates compressed polyurethane foams that are used to further change the volume of the vapour chamber, heating plate, chemical container and housing made up of plywood, laminated with mica and sealed using M-seal. The induction coil components like the transformer and the heat sink were attached at the bottom of the main body which prevents this component from overheating.

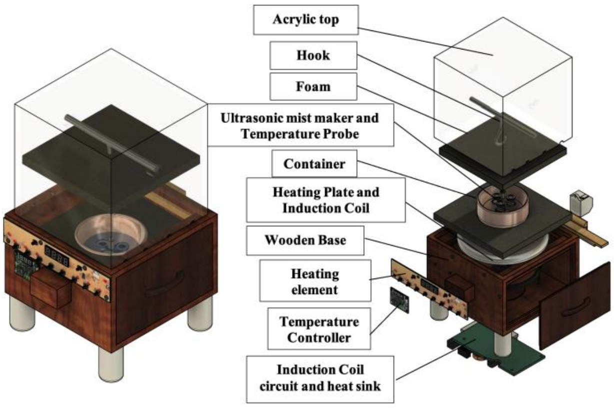
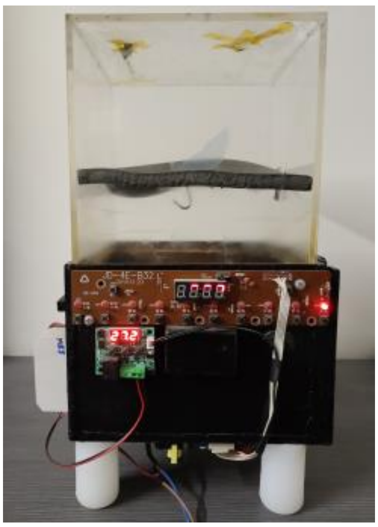
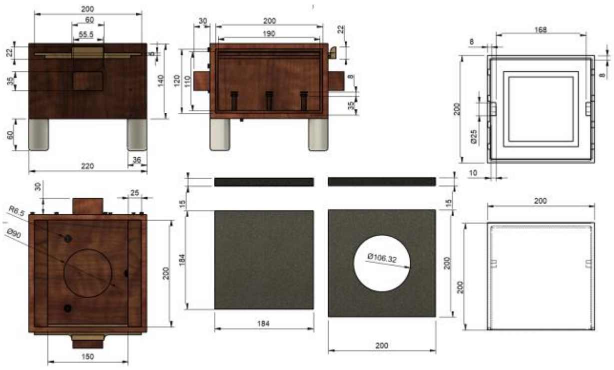


Fig. 1. Final CAD model, left side – orthographic view; right side- exploded view.

The polishing system for PLA uses the same setup, except for an absence of the mist maker as the operating temperature of the mist maker, though specified as 70 degrees, with the boiling point of tetrahydrofuran being 66°C itself, the soldering in the sensor got disconnected due to high heat.



(a)



(b)

Fig. 2. (a) Manufactured experimental setup; (b) actual dimensions of the experimental setup (all dimensions in mm).

2.2 Process

The polishing temperature of acetone vapour polishing is 56°C and tetrahydrofuran 66°C based upon their boiling temperatures.

The process starts by first placing the specimen inside the vapour chamber. After pouring the required amount of the chemical into the chemical container temperature probe of the temperature controller and the ultrasonic mist maker (only for acetone) are fixed inside the container. The next step is to set the time in the stopwatch and the temperature in the temperature controller as per the chemical used. Then the machine is turned on the temperature controller controls the temperature by turning off the induction coil if the temperature exceeds the set temperature and turning the coil off if the temperature goes below the temperature range. The smoothening of the specimen takes place inside the vapour chamber and after the set time the parts are taken out of the chamber.

To optimize the control parameters of the setup so that parts printed in this can give a high surface finish, the Taguchi method of multiparameter optimization was used. Specimens made of optimized parameters were studied using various tests like flexural and wear tests to measure the extent of property change from the part without vapour polishing and the part with polishing. So, to ensure that surface finish is happening without sacrificing mechanical properties

The ultrasonic piezo electric transducer, which comprises a DC 5V ultrasonic humidifiers power circuit board atomizing chip (ultrasonic mist maker disc) and an adapter, is the essential component of a mist maker. The primary idea underlying the mist maker's operation is cavitation. 1.70 Mhz is the resonance frequency of the atomization chip. The liquid above the sensor is atomized when the chip is triggered with this high frequency. The liquid above the ultrasonic transducer cannot vibrate at the same frequency as the transducer's high-frequency oscillation. When the transducer is in negative amplitude, a vacuum is formed above it, causing air bubbles to develop. This is known as cavitation. When the transducer's amplitude shifts to positive, these air bubbles, together with liquid particles, are pushed out, causing the liquid to atomize. The atomized particles are between 1 and 5 microns in size. The density of the mist created by the mist maker is proportional to the frequency; as the frequency falls, so does the density.

The mist maker is an essential part of the hot vapour polishing machine since it was discovered in the early trials that by employing a heated liquid vapour combination, the polishing speed could be enhanced. As a result, the liquid is heated and then atomized, which interacts with the surface and reduces surface roughness. The mist producer also aids in the application of the chemical to the desired surface. It also significantly decreases the total polishing time. In comparison to a hot vapour polished component without a mist producer, it also increases the product's surface quality.

The power circuit board on the mist maker tends to heat up with frequent usage, which was the primary issue. The sensor was not employed for tetrahydrofuran since the mist maker's working temperature was lower than tetrahydrofuran's boiling point.

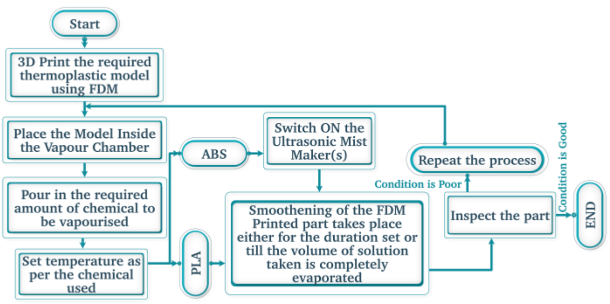


Fig. 3. Process flow of the chemical vapour polishing system developed in this research.

2.3 Surface roughness measurement

The surface roughness measurement was conducted using a surface profilometer and digital surface roughness tester. The surface profilometer was used for having a better view of the surface imperfections via graph for the specimens that didn't undergo many variations in their shape (flatness) due to their exposure to a higher temperature in the closed chamber. So, majorly digital surface roughness tester was used to cater to all polished and unpolished specimens of varied shapes.

The surface profilometer used was a MAHR profilometer with MFW 250 probe and GD 120 CNC (computer aided numerical control) drive unit. 3 sample lengths were taken for each specimen. The main objective is to find out the surface roughness parameter Ra. The specimen was placed on the platform and the probe was adjusted accordingly. The test was conducted with the transverse length kept at 5.60 mm, Low-pass at 2.50 µm, with a measuring range of ± 250 µm and a traversing speed of 0.50 mm/s.

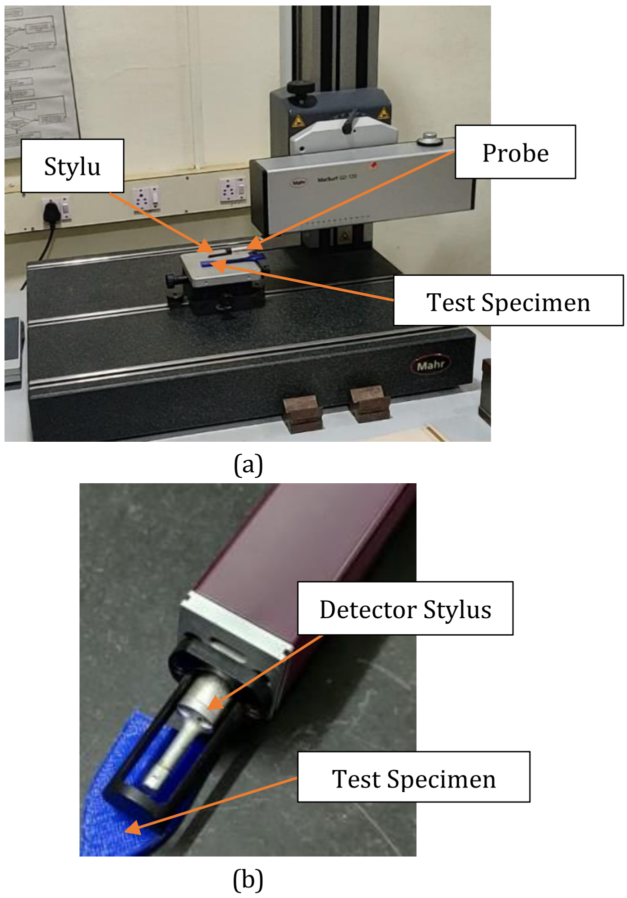


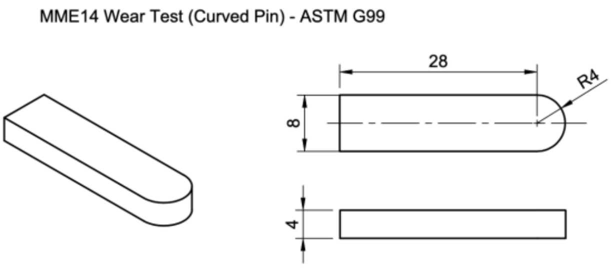
Fig. 4. Surface roughness measurement using (a) surface profilometer; (b) digital surface roughness tester.

The digital surface roughness tester used was a surftest Mitutoyo surface roughness tester SJ210. 3 sample lengths were taken for each specimen. The main objective is to find out the surface roughness parameter Ra. The specimen was placed on a platform and the probe was adjusted accordingly on the surface of the specimen. The test was conducted with a tracing speed of 0.50 mm/s and a measuring range of 17.50 mm. The tip of the stylus has a radius of 5 μm.

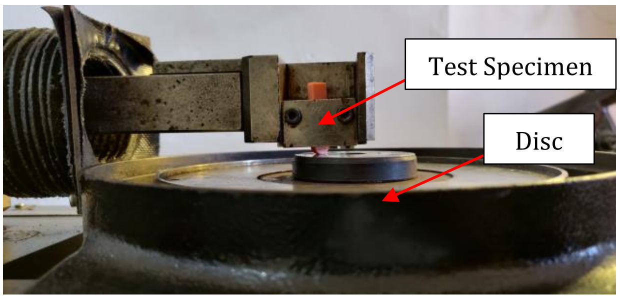
The specimen used for measuring surface roughness before and after the CVS process was a 10mm*10mm cross-section of ASTM D638 standard (determination of tensile properties of plastics) with 3 different locations since it was easy to mount in the CVS machine.

2.4 Wear test

The wear test measurement was conducted using a wear and friction test rig. The test was conducted on a DUCOM pin on disc tribometer model TR-20LE-PHM-250. The specimen standard used here is ASTM G99 [46]. The specimen is loaded on the device and the test is conducted. The initial and final weight of the specimen is measured, and the wear loss is calculated from the reduction of the weight of the specimen.



(a)



(b)

Fig. 5. (a) Wear test specimen's specification used in this research; (b) PLA ASTM G99 specimen undergoing wear test in the wear & friction test rig.

2.5 Flexural test

The flexural strength of the specimen depicted in Figure 6 was evaluated using an ASTM D790 flexural test. The Static 3 point flexure fixture holds the specimen in place while applying stress to the specimen's centre until it fractures. The supports are separated by 60 mm. The tool is spherical with a 5-mm diameter loading nose. The testing was carried out at room temperature with a constant crosshead speed of 2 mm/min and a deformation or strain rate of 5%.

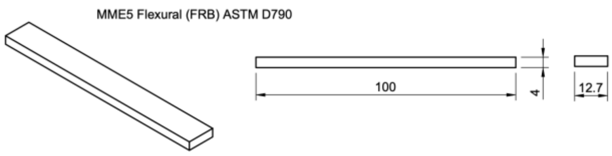


Fig. 6. Flexural test specimen used in this research.

3. RESULTS AND DISCUSSION

Before the real experiment, trial runs were carried out to determine the boundary conditions and fixed or variable constraints. The first observation made was that the volume of the reaction chamber plays a key role in surface finishing; homogeneity of surface finish may be achieved by managing the volume of the chamber. Polyurethane foam was used to limit the volume and maximise the concentration surrounding the product as much as feasible.

The time it took to complete vaporisation was first utilised as a constraint for tetrahydrofuran, but during testing, it was discovered that this required a long time, especially when a high volume was involved. As a consequence, the constraint was changed to concentration, which resulted in a faster polishing time and consistent outcomes.

3.1 Hot chemical vapour treatment of ABS parts with acetone

In this study, Taguchi multi-parameter optimisation approach is used to create a three-level design orthogonal matrix with three factors and nine experiments, referred to as L9 runs. Initially, input parameters such as volume (70 mL, 80 mL and 90 mL), temperature (45°c, 50°c and 55°c), and concentration (80%, 90% and 99.9% concentration (concentration here refers to the volume-by-volume concentration of the liquid medium used. Amount of water and acetone were calculated accordingly for 100 mL of solution to be used. For example, for 80% concentration – 90.09 mL of Acetone and 9.91 mL of distilled water was mixed.)) were used to optimise the smoothening of ABS parts.

After measuring the Ra values, the surface roughness improvement percentage was computed using the % increase formula = ((New Value - Original Value)/Original Value) * 100.

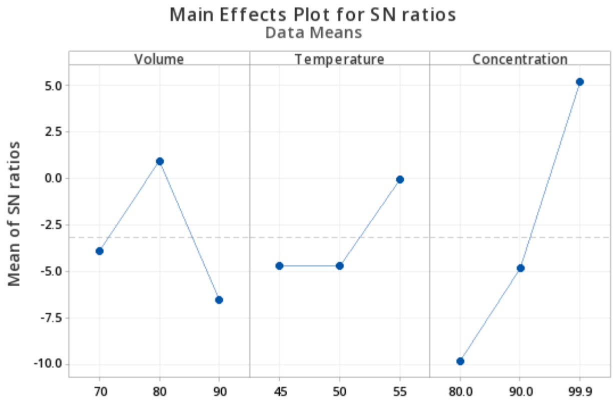
The initial roughness for ABS was determined to be 22.068µm, and trial 3 (70mL of acetone, 55°C system temperature, and 99.9% concentration) had the greatest improvement in surface roughness, with a 98.40 per cent improvement in the surface finish (images for which are shown in figure 7).

Figure 7 depicts the most important MiniTAB results for optimising these input values. These are the results of the Taguchi analysis, which used volume, temperature, and concentration as input parameters, Ra as response data, and a signal-to-noise ratio of "smaller is better." Changing the concentration has the biggest influence, according to the findings. Furthermore, reducing the concentration reduced the per cent improvement in surface roughness by a significant amount.

The ideal combination for the chemical vapour polishing process of ABS with acetone is 80mL of Acetone with 99.9% concentration heated at 55°C until the liquid is completely evaporated, according to the results of the optimization procedure.

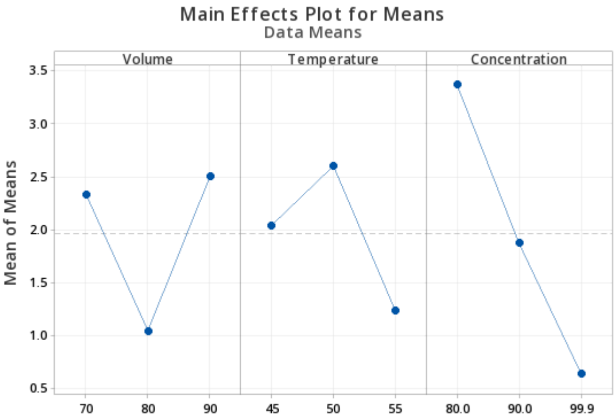
Following that, the experiment was carried out using the best possible combination. The ABS part was smoothed to a surface roughness of 0.299µm from an initial roughness of 22.068µm, resulting in a 98.65 per cent reduction in surface roughness.

Response table for signal to noise ratios			
Smaller is better			
Level	**Volume**	**Temperature**	**Concentration**
1	-3.89065	-4.68501	-9.80555
2	0.96645	-4.71239	-4.82883
3	-6.49971	-0.02650	5.21048
Delta	7.46616	4.68590	15.01603
Rank	2	3	1



(a)

Response table for means			
Level	**Volume**	**Temperature**	**Concentration**
1	2.3413	2.0473	3.3747
2	1.0517	2.6060	1.8770
3	2.5053	1.2450	0.6467
Delta	1.4537	1.3610	2.7280
Rank	2	3	1



(b)

Fig. 7. Results of ABS with acetone experiment's taguchi optimisation in MiniTAB, (a) SN ratio response table and main effects plot; (b) means response table and main effects plot.

(a) Before (b) After

Fig. 8. ABS with acetone optimised result.

Table 2. Trail experiments conducted for smoothening of ABS parts using acetone.

Trail No.	Input parameters			Time taken (H-hours, M-minutes, S-seconds)	Results		
	Volume (mL)	Temperature (°C)	Concentration (%)		Ra (μm) – average of 3 trails	Standard Deviation of 3 trails of Ra	Percentage improvement (%)
1	70	45	80	42M 23s	3.851	0.0021	82.55
2	70	50	90	1H 09M 32S	2.82	0.0104	87.22
3	70	55	99.9	23M 21S	0.353	0.0025	98.40
4	80	45	80	1H 39S	1.096	0.0099	95.03
5	80	50	90	53M 15S	0.392	0.0021	98.22
6	80	55	99.9	32M 25S	1.667	0.0153	92.45
7	90	45	80	1H 22M 3S	1.195	0.0026	94.58
8	90	50	90	39M 35S	4.606	0.0051	79.17
9	90	55	99.9	37M 24S	1.715	0.0020	92.23
Overall standard deviation (Ra)					**1.493**		
Average improvement achieved							**91.09**

Table 3. Trail experiments conducted for smoothening of PLA parts using THF solution.

Trail No.	Input parameters			Results		
	Volume (mL)	Time (minutes)	Temperature (°C)	Ra (μm) – average of 3 trails	Standard deviation of 3 trails of Ra	Percentage improvement (%)
1	20	5	65	0.994	0.0121	93.45%
2	20	10	70	4.604	0.0051	69.67%
3	20	15	75	11.095	0.0050	26.92%
4	30	5	70	4.473	0.0112	70.54%
5	30	10	75	2.432	0.0104	83.98%
6	30	15	65	1.011	0.0081	93,34%
7	40	5	75	1.136	0.0051	92.52%
8	40	10	65	1.485	0.0150	90.22%
9	40	15	70	4.083	0.0057	73.10%
Overall standard deviation (Ra)				**3.229**		
Average improvement achieved						**77.08%**

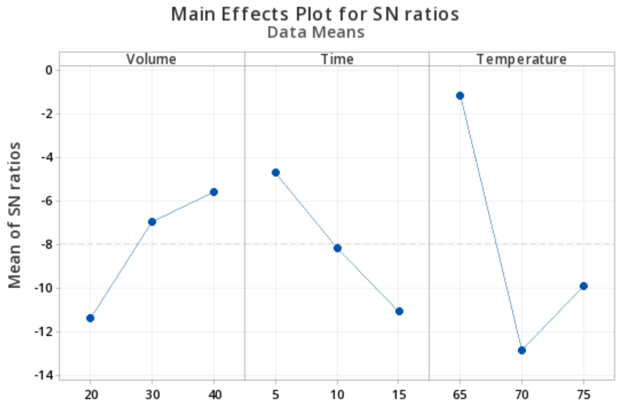
3.2 Hot chemical vapour treatment of PLA parts with THF solution

For the optimisation of PLA's chemical vapour polishing using THF solution, a Taguchi design similar to the one utilised for improving the chemical vapour polishing of ABS with acetone was examined. Volume (20mL, 30mL, and 40mL), time (5 minutes, 10 minutes, and 15 minutes), and temperature (65°C, 70°C, and 75°C) were the input parameters.

It can be noted that time was considered for experimentation of the PLA smoothing using THF solution mainly because THF is highly toxic and hence, concentration couldn't be varied easily, and external exposure of THF vapours after a certain time duration is highly dangerous. Also, since the boiling point of the THF solution is higher (65°C), the PLA part tends to lose its shape (bend) and the formation of heat bubbles on the surface was observed when exposed to the system for a longer time (more than 20 mins).

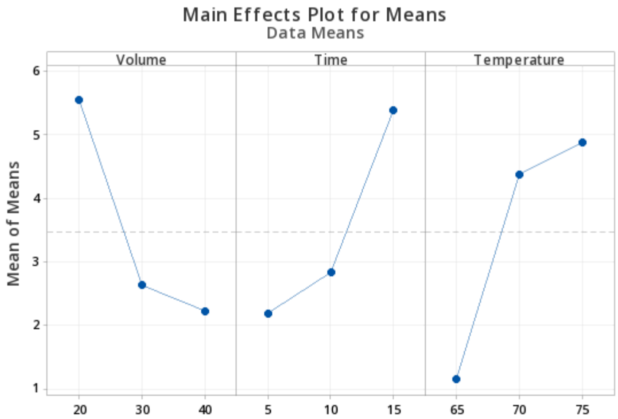
When examined, the PLA specimen had an initial surface roughness of 15.181μm and the maximum improvement in surface finish was measured with trail 1 (20mL of acetone, 65°C system temperature, and 5 minutes) which had a surface finish improvement of 93.45 per cent.

Response table for signal to noise ratios			
Smaller is better			
Level	**Volume**	**Time**	**Temperature**
1	-11.371	-4.689	-1.159
2	-6.942	-8.139	-12.831
3	-5.587	-11.072	-9.910
Delta	5.784	6.383	11.672
Rank	3	2	1



(a)

Response table for means			
Level	**Volume**	**Time**	**Temperature**
1	5.564	2.201	1.163
2	2.639	2.840	4.387
3	2.235	5.396	4.888
Delta	3.330	3.195	3.724
Rank	2	3	1



(b)

Fig. 9. Results of PLA with THF Solutions Experiment's Taguchi optimisation in MiniTAB, (a) SN ratio response table and main effects plot; (b) means response table and main effects plot.

The results of the DOE analysis for the process of chemical vapour polishing of PLA using THF solution show that temperature variation is the most important factor, with an increase in temperature above the boiling point decreasing the improvement percentage with each additional degree of temperature increase. The importance of the time and volume parameters is then discussed.

For PLA smoothening the optimal combination is to use 40mL of THF solution of 99.9% concentration heated at 65°C for 5 minutes duration. With this ideal combination, the experiment was performed, showing an improvement of 94.20% of surface finish from its initial surface roughness of 15.181 µm to a surface roughness of 0.881 µm

(a) Before (b) After

Fig. 10. PLA with THF solution optimised result.

Following the completion of all optimization procedures and analysis of the findings produced through the DOE of hot chemical vapour polishing of ABS and PLA components using acetone and THF solutions, it was discovered that:

- The ideal vaporisation temperature for ABS and PLA vapour smoothing is to keep the system temperature at the boiling points of acetone and THF, respectively. In general, keeping the system temperature at the boiling point of the reagent used for vapour smoothing is optimal.
- The concentration of the reagent used should always stay at the maximum.

Finally, while conducting experiments with the hot chemical vapour polishing system devised in this research for ABS and PLA parts to be polished using acetone and THF solutions, the following major observations were made:

- The parts when placed closer to the liquid will tend to produce a higher surface finish with the lowest of the time.
- With both the trial-and-error method and through Taguchi method, it is conclusive that for a regular sample in the experimental setup (4,800 cm^3 of reaction chamber area – adjusted to this using the foams), the volume of Acetone required is 80mL. This is true in most cases and might vary if the part size is quite large.

- (20cm * 20cm * 12cm) 4800 cm^3 of reaction area (4.8 L) -> 80 mL of acetone
- Significance of the acrylic top is to have a clear view of the process happening inside the chamber, but with several amounts of experiments being performed, scale-formation is a possibility.
- Small porosity in the printed part will cause bubble formation when vapour treated. Also, improper printing will lead to penetration of vapours inside part and would cause damage to the structure.

Fig. 11. Bubble formation due to a small porosity in the printed part .

- Vapour is not the reacting medium; it is rather the hot vapour droplets that react with the top layer of the FDM printed part and form the smoothened layer.
- When a trial run for the Immersion Technique of ABS part was performed with Acetone, it showed a key demerit of colour-fading of the outer contacting surface

3.3 Wear and flexural test results

For the wear test, the sliding disc diameter of the device is 40 mm. The applied load on the specimen is 10 N. The sliding velocity is 1 m/s and the sliding distance is 300 m. Based on this the disc was made to rotate at 478 rpm (rpm = (Sliding Velocity*60000)/ (Pi*Sliding dia)) for 300 seconds or 5 minutes (time = (Sliding distance*60000/(Pi*Sliding Dia*r.p.m)) secs) period.

Table 4 shows that the percentage reduction in weight (or wear loss in g) of the unpolished PLA and ABS specimens is lower than the percentage reduction in weight of the polished PLA and ABS specimens. The coefficient of friction was first calculated using the data acquired from the wear test (time, wear, frictional force, and temperature) using the formula: Coefficient friction = Frictional force/Applied force. The graphs time versus (vs) wear, time versus frictional force, and time versus frictional coefficient were then constructed.

Table 4. Tabulation for conducting the wear test for the polished and un-polished specimens and to calculate the wear loss.

Test parameters				Machine setting						
Sample name	Applied load (N)	Sliding velocity (m/sec)	Sliding distance (m)	Sliding dia in mm	r.p.m	Time in secs	Initial weight in g	Final weight g	Wear loss in g	Percentage reduction
PLA un-polished	10	1	300	40	478	300	0.857	0.842	0.015	1.75 %
PLA polished	10	1	300	40	478	300	0.845	0.821	0.024	2.84%
ABS un-polished	10	1	300	40	478	300	0.722	0.707	0.015	2.08%
ABS polished	10	1	300	40	478	300	0.735	0.712	0.023	3.13%

From the data collected during the wear test, the average coefficient of friction (see table 5) was calculated. When comparing polished PLA and ABS specimens to unpolished specimens, figure 12 (a) and 13 (a) – time versus wear graphs shows that polished specimens wear at a faster rate. It can also be concluded from table 5 and figure 12 (b) and 13 (b) that following hot chemical vapour polishing, the specimen's coefficient of friction decreases, resulting in rapid specimen wear.

The flexural test results of polished and unpolished ABS and PLA specimens are shown in figure 14 and table 6. It can be observed that the break load of polished ABS and PLA specimens is lower than that of unpolished specimens.

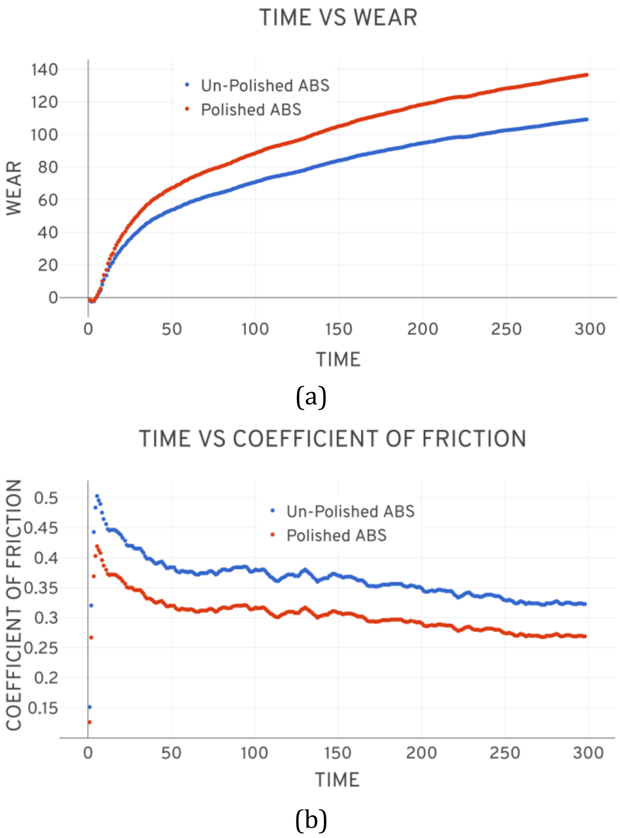


Fig. 12. Wear test graphs for ABS Specimens, (a) time vs wear; (b) time vs coefficient of friction.

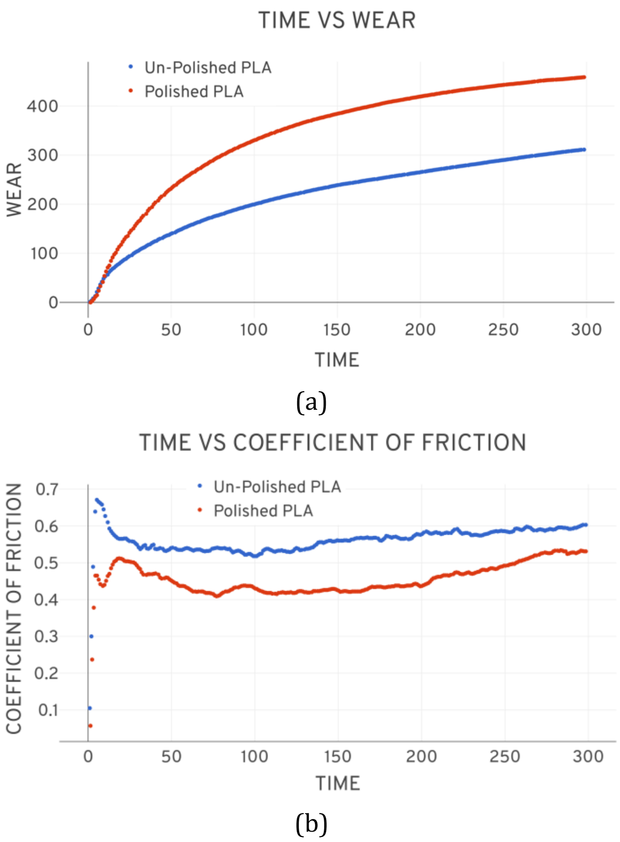


Fig. 13. Wear test graphs for PLA Specimens, (a) time vs wear; (b) time vs coefficient of friction.

Table 5. Average coefficient of friction of the specimens obtained through wear test.

Specimen	Average coefficient of friction
PLA un-polished	0.56
PLA polished	0.45
ABS un-polished	0.36
ABS polished	0.30

For both ABS and PLA material specimens, however, displacement at FMAX is seen to be increased when it undergoes hot chemical vapour polishing. Finally, after the vapour smoothening process, the flexural-ness of the ABS and PLA specimens decreases marginally. This phenomenon is due to the new top layer formed with vapours, which is more rigid and brittle, resulting in a reduced flexural-ness.

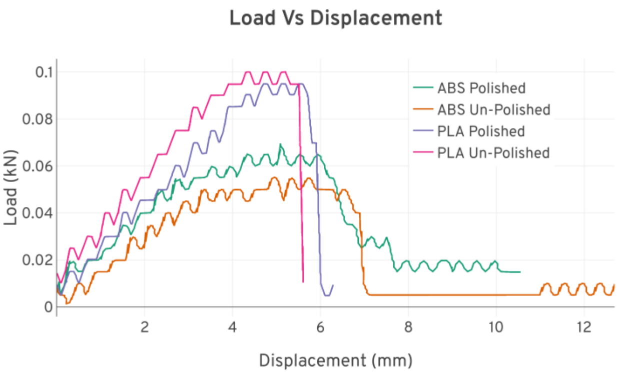


Fig. 14. Load vs displacement graphs obtained as result from flexural test for polished and unpolished ABS and PLA specimens.

Table 6. Flexural test results.

Specimen	Ultimate / Break Load (N)	Disp. at FMAX (mm)	Max. Disp. (mm)	Area (mm²)	Ultimate Stress (N/mm²)
PLA Un-Polished	1000	4.30	5.60	49.501	2.3
PLA Polished	95	4.70	6.30	49.509	2.0
ABS Un-Polished	55	4.90	12.70	51.040	1.3
ABS Polished	15	10.60	10.60	51.054	0.2

During the process of experimentation and while developing the CVS system, one major limitation of the system was the use of toxic chemicals as reagents. Heated chemical vapours may escape the system through the small gaps provided in the system to maintain the pressure developed through evaporated hot vapours. So, while performing a polishing activity with chemicals, necessary precautions need to be made. In future, a system capable of containing such toxic vapours within the system or a system with safe exhaust methodology or a system that avoids the usage of such chemicals as reagents by identifying chemicals that are safe to use need to be developed. Also, for some complex parts, multiple number of cycles was required to uniformly polish the entire geometrical surface of the part.

As stated in [29], it was observed that prolonged exposure of the specimen to the CVS system led to improved surface finish outcomes. As mentioned in [33], it was observed that part density plays a major role in the hot vapour polishing process for getting better surface finish results. It was noticed that higher density specimens can be kept inside the vapour chamber for a prolonged time without undergoing part deformation. With the variation of input parameters considered in this research (volume, temperature, and time or concentration) there is significant variability in surface finish compared to the parameters taken into consideration in [33]. But, both the processes with the optimised configuration parameters produced similar levels of surface finish for all specimens after the CVS process.

4. CONCLUSION AND FUTURE DIRECTIONS

In this study, a system is designed that can be used to polish various FDM printed thermoplastic components using hot chemical vapour deposition, and it is tested using acetone and THF solutions for ABS and PLA components, respectively. Process parameters of the experimental set-up such as volume of reagent, temperature, concentration, and time were optimised for the ideal combination of factors to generate a higher surface finish in the experimental set-up, through which the following observations were made - a vapour smoothing system's best performance is achieved by keeping the system temperature at or near its boiling point; always use the highest possible concentration of the reagent being employed.

With the ideal combination formed, the set-up achieved a surface finish improvement % of 98.65% for hot chemical vapour polishing of ABS with acetone and 94.20% for hot chemical vapour polishing of PLA with THF solution. Finally, the system makes the product suitable for end user applications like patterns for casting, automotive and aerospace prototyping, complex consumer goods which require high surface finish, prototype used for research and learning application

In addition, it is discovered that the smoothed layer is generated by an interaction between the top layer of the FDM printed part and heated vapour droplets, rather than by the vapour itself, after several attempts with the experiment. Then, after the tests, it was clear that after the hot chemical vapour smoothening procedure, the specimen's top layer wear accelerated, and its flexural-ness decreased to some level.

The following are the advancements in this system, which could be worked on in the future to enhance the surface finish by hot vapour polishing:

- Although the system is now portable, it may be made compact enough to polish small prototype components anywhere, at any time.
- Currently, the system can only polish one part at a time; however, a system that can polish many parts of different materials at the same time can be developed.
- This approach might also be progressed to the point where a closed conveyor system, such as a powder coating system, could be employed on a big scale. The system and atomiser outlet would be kept at the reagent's boiling point, and the part would be polished by entering and exiting the container via a rig.

Acknowledgement

The authors would like to extend their sincere thanks to the School mechanical of mechanical engineering, Vellore institute of technology, Vellore for their support in completing this research work by providing us with various laboratory facilities to 3D print the required components and conduct our surface roughness testing.

The authors also like to express their gratitude to METMECH analytical engineers for their assistance and guidance in conducting the critical tests - flexural and wear tests - that were essential for this study.

REFERENCES

[1] U. Chadha, A. Abrol, N.P. Vora, A. Tiwari, S.K. Shanker, S.K. Selvaraj, *Performance evaluation of 3D printing technologies: a review, recent advances, current challenges, and future directions*, Progress in Additive Manufacturing, vol. 7, iss. 5, pp. 853–886, 2022, doi: 10.1007/s40964-021-00257-4

[2] N. Shahrubudin, T.C. Lee, R. Ramlan, *An overview on 3D printing technology: Technological, materials, and applications*, Procedia Manufacturing vol. 35, pp. 1286–1296, 2019, doi: 10.1016/j.promfg.2019.06.089

[3] E. Sachs, M. Cima, J. Cornie, *Three-Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model*, CIRP Annals, vol. 39, iss. 1, pp. 201–204, 1990, doi: 10.1016/S0007-8506(07)61035-X

[4] H.D. Vora, S. Sanyal, *A comprehensive review: metrology in additive manufacturing and 3D printing technology*, Progress in Additive Manufacturing, vol. 5, iss. 4, pp. 319–353, 2020, doi: 10.1007/s40964-020-00142-6

[5] Z. Liu, Y. Wang, B. Wu, C. Cui, Y. Guo, C. Yan, *A critical review of fused deposition modeling 3D printing technology in manufacturing polylactic acid parts*, The International Journal of Advanced Manufacturing Technology, vol. 102, iss. 9-8, pp. 2877–2889, 2019, doi: 10.1007/s00170-019-03332-x

[6] M. Quanjin, M.R.M. Rejab, M.S. Idris, N.M. Kumar, M.H. Abdullah, G.R. Reddy, *Recent 3D and 4D intelligent printing technologies: a comparative review and future perspective*, Procedia Computer Science, vol. 167, pp. 1210–1219, 2020, doi: 10.1016/j.procs.2020.03.434

[7] R. Anitha, S. Arunachalam, P. Radhakrishnan, *Critical parameters influencing the quality of prototype in fused deposition modeling*, Journal of Processing Technology, vol. 118, pp. 385–388, 2001, doi: 10.1016/S0924-0136(01)00980-3

[8] S. Palekar, P.K. Nukala, S.M. Mishra, T. Kipping, K. Patel, *Application of 3D printing technology and quality by design approach for development of age-appropriate pediatric formulation of baclofen*, International Journal of Pharmaceutics, vol. 556, pp. 106–116, 2019, doi: 10.1016/j.ijpharm.2018.11.062

[9] R. Arrigo, A. Frache, *FDM Printability of PLA Based-Materials: The Key Role of the Rheological Behavior*, Polymers, vol. 14, iss. 9, pp. 1–15, 2022, doi: 10.3390/polym14091754

[10] C.C. Kuo, Y.R. Wu, M.H. Li, H.-W. Wu, *Minimizing warpage of ABS prototypes built with low- cost fused deposition modeling machine using developed closed-chamber and optimal process parameters*, The International Journal of Advanced Manufacturing Technology, vol. 101, iss. 1-4, pp. 593–602, 2019, doi: 10.1007/s00170-018-2969-7

[11] B.T. Challa, S.K. Gummadi, K. Elhattab, J. Ahlstrom, P. Sikder, *In-house processing of 3D printable polyetheretherketone (PEEK) filaments and the effect of fused deposition modeling parameters on 3D-printed PEEK structures*, The Internation Journal of Advanced Manufacturing Technology, vol. 121, iss. 3-4, pp. 1675–1688, 2022, doi: 10.1007/s00170-022-09360-4

[12] M. Harris, H. Mohsin, J. Potgieter, K. Ishfaq, R. Archer, Q. Chen, K. De Silva, M..L Guen, R. Wilson, K.M. Arif, *Partial Biodegradable Blend with High Stability against Biodegradation for Fused Deposition Modeling*, Polymers, vol 14, iss. 8, pp. 1–17, 2022 doi: 10.3390/polym14081541

[13] M.J. Park, J. Bae, Y.K. Ju, *Structural Behavior of a Composite Curtain Wall Fabricated by the Fused Deposition Modeling 3D Printing Method* Polymers, vol. 14, iss. 7, pp. 1–20, 2022 doi: 10.3390/polym14071431

[14] C. Pavon, M. Aldas, M.D. Samper, D.L. Motoc, S. Ferrandiz, J. López-Martínez, *Mechanical, Dynamic-Mechanical, Thermal and Decomposition Behavior of 3D-Printed PLA Reinforced with CaCO3 Fillers from Natural Resources*, Polymers, vol. 14, iss. 13, pp. 1–14, 2022 doi: 10.3390/polym14132646

[15] T. Abdullah, R.O. Qurban, M.S. Abdel-Wahab, N.A. Salah, A.A. Melaibari, M.A. Zamzami, A. Memić, *Development of Nanocoated Filaments for 3D Fused Deposition Modeling of Antibacterial and Antioxidant Materials*, Polymers, vol. 14, iss. 13, pp. 1–14, 2022, doi: 10.3390/polym14132645

[16] L.M. Galantucci, F. Lavecchia, G. Percoco, *Experimental study aiming to enhance the surface finish of fused deposition modeled parts*, CIRP Annals, vol. 58, iss. 1, pp. 189–192, 2009, doi: 10.1016/j.cirp.2009.03.071

[17] L.M. Galantucci, F. Lavecchia, G. Percoco, *Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling*, CIRP Annals, vol. 59, iss. 1, 247–250, 2010, doi: 10.1016/j.cirp.2010.03.074

[18] C.Y. Liaw, M. Guvendiren, *Current and emerging applications of 3D printing in medicine. Biofabrication*, vol. 9, no. 2, 2017, doi: 10.1088/1758-5090/aa7279

[19] F. Lavecchia, M.G. Guerra, L.M. Galantucci, *Chemical vapor treatment to improve surface finish of 3D printed polylactic acid (PLA) parts realized by fused filament fabrication*, Progress in Additive Manufacturing, vol. 7, pp. 65–75, 2022, doi: 10.1007/s40964-021-00213-2

[20] J. Singh, H. Singh, R. Singh, *Harwinder, Repeatability of linear and radial dimension of ABS replicas fabricated by fused deposition modelling and chemical vapor smoothing process: A case study*, Measurement, vol. 94, pp. 5–11, 2016, doi: 10.1016/j.measurement.2016.07.064

[21] J. Lluch-Cerezo, M.D. Meseguer, J.A. García-Manrique, R. Benavente, *Influence of Thermal Annealing Temperatures on Powder Mould Effectiveness to Avoid Deformations in ABS and PLA 3D-Printed Parts*, Polymers, vol. 14, iss. 13, pp. 1–19, 2022, doi: 10.3390/polym14132607

[22] T.H.B. Singh, J, Singh Chohan, R, Kumar, *Performance analysis of vapour finishing apparatus for surface enhancement of FDM parts*, Materials Today: Proceedings, vol. 26, pp. 3497–3502, 2020, doi: 10.1016/j.matpr.2020.04.553

[23] A. Lalehpour, A. Barari, *Post processing for Fused Deposition Modeling Parts with Acetone Vapour Bath*, IFAC-PapersOnLine, vol. 49, iss. 31, pp. 42–48, 2016, doi: 10.1007/ 10.1016/j.ifacol.2016.12.159

[24] A. John Rajan, M. Sugavaneswaran, B. Prashanthi, *Siddhant Deshmukh, Jose S. Influence of Vapour Smoothing Process Parameters on Fused Deposition Modelling Parts Surface Roughness at Different Build Orientation*, Materials Today: Proceedings, vol. 22, pp. 2772–2778, 2020, doi: 10.1016/j.matpr.2020.03.408

[25] A. Coppola, F. Impero, C. Ruggiero, F. Scala, A. Squillace, *Set-Up of an Experimental Procedure for the Surface Smoothing of FDM Parts Through Acetone Vapor*, Key Engineering Materials, vol. 813, pp. 447–452, 2019, doi: 10.4028/www.scientific.net/KEM.813.447

[26] C.-C. Kuo, C.-M. Chen, S.-X. Chang, *Polishing mechanism for ABS parts fabricated by additive manufacturing*, The International Journal of Advanced Manufacturing Technology, vol. 91, pp. 1473–1479, 2017, doi: 10.1007/s00170-016-9845-0

[27] P. Wu, X. Zhao, J.H. Baller, X. Wang, *Developing a conceptual framework to improve the implementation of 3D printing technology in the construction industry*, Architectural Science Review, vol. 61, iss. 3, pp. 133–142, 2018, doi: 10.1080/00038628.2018.1450727

[28] A. Lalehpour, C. Janeteas, A. Barari, *Surface roughness of FDM parts after post-processing with acetone vapor bath smoothing process*, The International Journal of Advanced Manufacturing Technology, vol. 95, pp. 1505–1520, 2018, doi: 10.1007/s00170-017-1165-5

[29] A. Colpani, A. Fiorentino, E. Ceretti, *Characterization of chemical surface finishing with cold acetone vapours on ABS parts fabricated by FDM*, Production Engineering, vol. 13, pp. 437–447, 2019, doi: 10.1007/s11740-019-00894-3

[30] S.-U.k Zhang, J. Han, H.-W. Kang, *Temperature-Dependent Mechanical Properties of ABS Parts Fabricated by Fused Deposition Modeling and Vapor Smoothing*, International Journal Of Precision Engineering And Manufacturing, vol. 18, no. 5, pp. 763-769, 2017, doi: 10.1007/s12541-017-0091-7

[31] J. Singh, R. Singh, H, Singh, *Investigations for improving the surface finish of FDM based ABS replicas by chemical vapor smoothing process: A case study*, Assembly Automation, vol. 37, iss. 1, pp. 13-21. 2017, doi: 10.1108/AA-12-2015-127

[32] S. Hassanifard, K. Behdinan, *Effects of voids and raster orientations on fatigue life of notched additively manufactured PLA components*, The International Journal of Advanced Manufacturing Technology, vol. 120, pp. 6241–6250, 2022, doi: 10.1007/s00170-022-09169-1

[33] M.H. Sehhat, A. Mahdianikhotbesara, F. Yadegari, *Impact of temperature and material variation on mechanical properties of parts fabricated with fused deposition modeling (FDM) additive manufacturing*, International Journal of Advanced Manufacturing Technology, vol. 120, pp. 4791–4801, 2022, doi: 10.1007/s00170-022-09043-0

[34] Q. Zhu, K. Yu, H. Li, Q. Zhang, D. Tu, *Rapid residual stress prediction and feedback control during fused deposition modeling of PLA*, The International Journal of Advanced Manufacturing Technology, vol. 118, pp. 3229–3240, 2022, doi: 10.1007/s00170-021-08158-0

[35] H.T. Nguyen, K. Crittenden, L. Weiss, H. Bardaweel, *Experimental Modal Analysis and Characterization of Additively Manufactured Polymers*, Polymers, vol. 14, iss. 10, pp. 1–18, 2022, doi: 10.3390/polym14102071

[36] M.H. Ab Rahman, N.A. Maidin, M.N. Ahmad, M.K. Wahid, U.H. Ahmad, M.H. Osman, T.H. Sen, N.F.B.W. Anuar, *Effect of Acetone Vapor on Mechanical Properties of Fused Deposition Modeling Printed Part*, Journal of Advanced

Research in Fluid Mechanics and Thermal Sciences, vol. 63, iss. 1, pp. 12–22, 2019.

[37] C.-C. Kuo, R.-C. Mao, *Development of a Precision Surface Polishing System for Parts Fabricated by Fused Deposition Modeling*, Materials and Manufacturing Processes, vol. 31, iss. 8, pp. 1113–1118, 2015, doi: 10.1080/10426914.2015.1090594

[38] M.N. Ahmad, M.R. Ishak, M.M. Taha, F. Mustapha, Z. Leman, D.D.A. Lukista, Irianto, I. Ghazali, *Application of Taguchi Method to Optimize the Parameter of Fused Deposition Modeling (FDM) Using Oil Palm Fiber Reinforced Thermoplastic Composites*, Polymers, vol. 14, iss. 11, pp. 1–15, 2022, doi: 10.3390/polym14112140

[39] S.C. Daminabo, S. Goel, S.A. Grammatikos, H.Y. Nezhad, V.K. Thakur, *Fused deposition modeling-based additive manufacturing (3D printing): Techniques for polymer material systems*, Materials Today Chemistry, vol. 16, 2020, doi: 10.1016/j.mtchem.2020.100248

[40] F. Fina, S. Gaisford, A.W. Basit, *Powder Bed Fusion: The Working Process, Current Applications and Opportunities*, in A.W. Basit, S. Gaisford (Eds): 3D Printing of Pharmaceuticals, Springer, 2018, doi: 10.1007/978-3-319-90755-0_5

[41] R. Bogue, 3D printing: the dawn of a new era in manufacturing?, Assembly Automation, vol. 33, no. 4, pp. 307–311, 2013, doi: 10.1108/AA-06-2013-055

[42] E. Kroll, D. Artzi, *Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models*, Rapid Prototyping Journal, vol. 17, iss. 5, pp. 393–402, 2011, doi: 10.1108/13552541111156522

[43] R. Noorani, *Rapid prototyping – principles and application*, New Jersey: John Wiley & Sons Inc, 2005.

[44] R. Singh, *Three-dimensional printing for casting applications: A state of art review and future perspectives*, Advanced Materials Research, vol. 83-86, pp. 342–349, 2010, doi: 10.4028/www.scientific.net/AMR.83-86.342

[45] M.J. Martin, P.R. Davis, D.F. Bowles, M. Lima, *Incorporation of museum-based service learning into advanced engineering electives in aerospace engineering and 3-D printing*, in: 54th AIAA aerospace sciences meeting, 4-8 January, 2016, San Diego, California, USA, p. 1803, doi: 10.2514/6.2016-1803

[46] ASTM G99-95, (reapproved 2000), Standard test method for wear testing with a pin on disk apparatus, 2000.