**An Experimental Study of Surface Improvement in FDM Parts by Vapor Treatment Process**

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**Abstract**

Fused deposition modeling (FDM) is one of the most adaptable additive manufacturing method owing to the cost-effectiveness and environment-friendly nature. However, FDM technique still possesses major difficulties in terms of poor surface quality because of adding layer by layer manufacturing process for the prototypes. It is desirable to explore an efficient technique for FDM parts to enhance the poor surface quality and dimensions precision. In the present paper, an effort has been made to enhance the surface quality and optimize the critical processing parameter of FDM based benchmark using vapor smoothing process (VSP). A comparative experimental study has been performed by design of experiments (DOE), Taguchi technique to find the influence of input design parameters on the surface finish of benchmark FDM parts. The results of the present investigation show that VSP treatment improves the surface quality of FDM parts to micro level with negligible dimensional variation. It is observed that improved surface quality is found in the 1,2, -Dichloroethane chemical at 90° part build orientation, 0.25 mm layer thickness, 10% fill density and 90 second exposure times.

**Keywords:-** FDM, Vapor Chemical Process, Surface Quality, Design of Experiment

**1. Introduction**

Additive manufacturing (AM) process is gaining great importance and industrial demands to because of increase in complexity of product geometries. In this process conceptual model is made in a short span of time, economically with good characteristics [1]. The great spread of AM technologies has progressed as a fabrication method for fast tooling or rapid manufacturing products in low volume industrial applications [2]. Fused deposition modeling (FDM) is one of the most widely used AM technologies. In the FDM technology, prototypes are built up by the data obtained from 3D CAD files and virtual model is converted into .STL (Standard Triangulation Language) format [3]. The FDM also is known as 3-D printing layer-based manufacturing process, as extruding semi-solid thermoplastic materials solidifies in the form of thin slices on a fixtureless table [4]. The support material at the same time must be extruded, which acts as a support for the hanging fragments which can be detached later by manual cleaning or post-processing [5]. The use of FDM technique for the different application is still possessed major difficulties in terms of poor surface finish. The poor surface finish limits the functionality of AM parts, and the reason lies behind is the building strategy, layer thickness, orientation of the part, the geometry of enclosing surface, etc [6]. These drawbacks lead to dimensional inaccuracy and outweigh the advantages in FDM parts [7].

Many studies have been reported in the open literature to improve the quality of FDM parts since the origin of this technology. Galantucci et al. [8] investigated the FDM machining parameters on acrylonitrile butadiene styrene (ABS) prototypes surface finish by chemical post-processing treatment has been investigated and yields a significant improvement of the Ra of the treated specimens. A dimensional accuracy of ABS specimens through post chemical treatment. It is naturally increases the surface finish and dimensional accuracy by Jayanth et al. [9]. J.S. Chohan et al. [10] revealed that, ABS specimens are manufactured by FDM and optimized vapor smoothing (VS) process for biomedical applications.Yifan Jin et al. [11] examine that chemical reaction mechanism during the treating process is analysed surface roughness for polylactic acid (PLA) parts in FDM. R. Singh et al. [13] founded the surface finish of FDM based benchmarks through acetone exposure by using vapor smoothing station (VSS) technique improving the surface finish nano-level with negligible dimensional deviations using a design of experiments (DOE) technique. R. Singh et al. [14] inspect; surface hardness of ABS components has been improved through the HVS process by using acetone as smoothening media by scanning electron microscopic-based characterization of the components were carried out. Garg et al [15] search that, the simultaneous effect of part building orientation and raster angle on surface roughness, tensile strength, a flexural strength of ABS material. Lalehpour A. et al. [16] study the effect of the smoothing parameters on the resulting surface roughness of the final FDM products. The smoothing parameters are divided into the number of smoothing cycles and the cycle duration.

The use of FDM parts in different areas is till doubtful as the final part undergoes from rough geometrical roughness and a smaller amount geometrical tolerances in contrast to other AM technologies. However, various investigators have completed several experiment and investigation to evaluate the surface roughness and dimensional features of FDM parts by optimizing the input parameters.

The present study work, the authors is concentrated to improve the surface finish of FDM parts by using an alternative, cost effective volatile fluid (acetone, one-two-dichloroethane, butylalcohal). **because it necessities marginal human intervention, the cost is very low and curing times are about few minutes.** Taguchi L9 OA has been used to investigate the influence of factors such like as density of the parts, layer thickness, surface finish, build orientation and chemical exposure time for treated and untreated PLA samples.

In this paper the authors investigate the link between the FDM process parameters and the surface aspect of prototypes, studying a chemical method to improve the surface finish of the products. This method performs better if compared to that reported in refs.

[16,17], because it needs marginal human intervention, the cost is very low and curing times are about few minutes. Fig. 1 shows the workflow of the present paper. The experimental activity was carried out over two phases, focusing on independent variables in both the FDM process and the chemical finishing. In the first phase, consisting of specimens manufacturing

**2. Experimental Methodologies**

To investigate the influence of layer thickness, the infill pattern and infill percentage, we used the Taguchi’s L9 DOE. Taguchi’s DOE was chosen because it adopts orthogonal arrays. This means that each parameter has equal weights and can achieve an optimum design with the lowest number of runs and minimum cost. The L9 array requires only 9 runs, however, for four parameter for three levels each, only the main effects can be observed and no interactions, therefore, this work focuses on the main effects. A four main parameters are selected for three level of each input factor by literature survey the experiments were designed by Taguchi L18 orthogonal array along with independent variables. Table 1 reveals the experimentation factors and levels.

Fused Deposition Models(FDM)

CAD Model

ASTM Flexural D790-17

ASTM Compression D695 -15

ASTM Tensile D638-14

Part Fabrication

Vapor Chemical Process

Surface Finish

Figure 1 Experiment Strategy

Table 1 Experiment designed with L18 orthogonal array for selected input factors at different levels

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sr.no.** | **Layer thickness** | **Build orientation(°)** | **Fill Density** | **Vapourization Time (sec)** |
| 1 | 0.20 | 0 | 10 | 90 |
| 2 | 0.20 | 90 | 50 | 120 |
| 3 | 0.20 | 90 | 100 | 150 |
| 4 | 0.25 | 90 | 10 | 90 |
| 5 | 0.25 | 90 | 50 | 120 |
| 6 | 0.25 | 0 | 100 | 150 |
| 7 | 0.30 | 90 | 10 | 90 |
| 8 | 0.30 | 0 | 50 | 120 |
| 9 | 0.30 | 90 | 100 | 150 |

**2.1 Specimen Material**

In the present work, all the specimens are built using PLA material is used for support structure generation, while building the test specimens. PLA material has the following properties, tensile strength = 57.8 MPa, tensile modulus = 3.3 GPa and flexural strength = 55.3MPa. Layer of support material at desired locations are deposited based on the part orientation and geometric complexity. After building the component, the support materials are dissolved in a support cleaning station. Academic computer Aided design (CAD) software inventor is used to create the models of the test specimens ASTM D638-14, ASTM D695 -15 and ASTM D790-17 are used for deciding the detailed dimensions of tensile, compression and flexural test specimens respectively. The models are saved in .stl format for slicing layer generation and building of the specimens. All specimensare built by depositing layer of 0.20, 0.25, 0.30 mm thickness.

**2.2 Chemical Solvent**

**2.2.1 Acetone**

The physical and chemical properties of acetone are given in Table 2. The physical properties of acetone, such as high evaporation rate, low viscosity, and miscibility with water and several organic solvents make it suitable for use as a solvent. Because of its ability to undergo addition, oxidation/reduction, and condensation reactions, acetone is used as a raw material in the chemical synthesis of many commercial products.

Table 2 Acetone properties

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Molecular weight** | **Colour** | **Physical state** | **Melting Point** | **Boiling point** | **Solubility (water at 20°C)** | **Density (20°C,25°C,30°C)** | **Solubility (organic solvent)** |
| 58.08 | Colorless | Liquid | -95.35°C | 56.2oC at 1 atm | Completely miscible | (0.78998g/ml,0.78440g/ml,0.78033g/ml) | Soluble in benzene and ethanol |

**2.2.2 One, two Dichloromethane**

Ethylene dichloride is primarily used in the production of vinyl chloride as well as other chemicals. The properties of chemical shows in table 3. It is used in solvents in closed systems for various extraction and cleaning purposes in organic synthesis. It is also added to leaded gasoline as a lead scavenger. It is also used as a dispersant in rubber and plastics, as a wetting and penetrating agent. It was formerly used in ore flotation, as a grain fumigant, as a metal degreaser, and in textile and PVC cleaning.

Table 3 one,two dichloroethane properties

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Molecular weight** | **Colour** | **Physical State** | **Vapour pressure** | **water partition coefficient** |
| 98.96 g/mol | Colorless | heavy liquid that is slightly soluble in water | 64 mm Hg at 20°C | 1.48(log kow) |

**2.2.3 Butyl alcohol**

1-Butanol is a type of alcohol with four carbon atoms being contained per molecule. Its molecular formula is CH3CH2CH2CH2OH with three isomers, namely iso-butanol, sec-butanol and tert-butanol. It is colorless liquid with alcohol odor. A table 4 shows the properties detail.

Table 4 butyl alcohal properties

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Melting point** | **Boiling point** | **Density** | **vapour density** | **Solubility** |
| 89 °C | 117.6 °C | 0.81 g/ml at 25 °C (lit.) | 2.55 (vs. air) | water soluble |

**3 Results and Discussion**

Surface roughness of FDM printed PLA samples are measured before and after chemical treatment with acetone, dichloroethane and 1-2 dichloroethane. The parts are fabricated at different part building orientations and their surface roughness, tensile; compression and flexural strength are measured. Measurements are carried out for all parts treatment and compared to study and analyze the effect of the different parameters. Table 2, 3 and 4 shows the outcomes results of surface roughness values after chemical vaporization process on PLA specimens.

A surface roughness is measured using a surface roughness tester (SJ 400, Mitutoyo, Kawasaki, Japan) selecting a 0.25 mm cutoff length. Roughness is measured twice and the average value is considered and root men square roughness (Rq) values are measured both along and across the length of the specimens. Surface roughness of the components are measured along and across the length of the specimens twice on flat surface and average surface roughness (Ra) and root mean square roughness (Rq) values are considered variations of Ra and Rq for each test samples built at different orientation.

The entire fabricated components are treated by exposing the test specimens to cold vapor of acetone, One, two Dichloromethane and Butyl alcohol. Due to acetone, one-two Dichloromethane and Butyl alcohol toxicity low or high cost and value evaporation rate of acetone, one-two Dichloromethane and Butyl alcohol. But the chemical reaction with hot vapors or liquid acetone is found aggressive and sometimes, it became difficult to control the damage of the part surfaces. To reduce damage short exposure duration is opted for hot vapor. However, it is again observed that all surfaces are not treated uniformly. Treatment by hanging of components would require proper balance of acetone, One-two Dichloromethane and Butyl alcohol acceptable surface quality. However, the authors noted that in treatment with hot vapors of acetone, One-two Dichloromethane and Butyl alcohol smoothen the part surface uniformly. The container is kept at a vaporization temperature for at vaporization time. In present research work, improvement in surface finish and deviation encountered after vapor processing were quantified by subtracting the initial and final values by using the following equation

Percentage change = [(Initial value –Final value)/Initial value x 100] (1)

Using Taguchi’s design For dimensional analysis, height of the benchmarks was selected judicially. Mintitab-17 statistical software package was used to find out the effect of processing of input parameters on the quality characteristics of the patterns. Table No, no and no shows the improved value of surface finish of the patterns , dimensional deviation and their respective signal to noise (S/N) responses. Further ANOVA has been conducted for calculating the percentage contribution of input process parameters in surface roughness and dimensional deviation,

Fig. 4 (a) and (b) shows the main effect of S/N ratio on selected process parameters for surface roughness and dimensional deviation respectively. Further ANOVA has been conducted for calculating the percentage contribution of input process parameters in surface roughness and dimensional deviation, shown in table 2 Parametric response of S/N ratio for surface roughness and dimensional deviation is given in table 2.

**From table no it has been found that out of three input selected parameters only AVE is found to have significant affected on the surface roughness**

**3.1. Discussion of Surface Roughness effect of Butyl alcohol chemical vapor**

In this section represents the surface roughness improvement by butyl alcohol chemical vapor. The result of Surface roughness (SR) is shown in table 2 and figure 3. A figure 5 (a) shows the minimum surface roughness is achieved at 0.25 mm layer thickness, 0° angle build orientation, 100 fill density and figure 5 (b) shows the minimum surface roughness is achieved at 0.25 mm layer thickness, 90⁰ angle build orientation, 10 fill density and 90 sec time duration.

Table 2 surface roughness results before chemical process

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sr. No** | **Layer Thickness(mm)** | **Build Orientation (°)** | **Fill density** | **Time (Sec)** | **SR before chemical process (µm)** | **SR after chemical process (µm)** |
| 1 | 0.2 | 0 | 10 | 90 | 11.938 | 13.593 |
| 2 | 0.2 | 90 | 50 | 120 | 21.824 | 22.461 |
| 3 | 0.2 | 90 | 100 | 150 | 5.203 | 12.471 |
| 4 | 0.25 | 90 | 10 | 90 | 6.201 | 2.319 |
| 5 | 0.25 | 90 | 50 | 120 | 4.365 | 5.091 |
| 6 | 0.25 | 0 | 100 | 150 | 5.047 | 2.644 |
| 7 | 0.3 | 90 | 10 | 90 | 3.796 | 1.357 |
| 8 | 0.3 | 0 | 50 | 120 | 5.861 | 1.445 |
| 9 | 0.3 | 90 | 100 | 150 | 8.7963 | 2.225 |

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| **`**tensile specimen.jpg |
| Figure 3 ASTM D638-14 Tensile Specimen |

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| --- | --- |
|  |  |
| (a) Surface Roughness before chemical vaporization | (b) Surface Roughness after chemical vaporization |
|  |  |
| (c) Surface Roughness plot before chemical vaporization | (d) Surface Roughness plot after chemical vaporization |
| Figure 4 Surface roughness result of Butanol or butyl alcohol | |

In figure **4** (a) shows the surface roughness is very rough at 0.20 mm thickness. This surface finish is very good at the 0.25mm and it is slightly rough at 0.30 mm thickness. The build orientation is not much effect on SR. where, fill density and chemical exposure time same affect on SR. It ia observes that, 100 % fill density and more chemical time exposure gives a good surface improvement this result is vice versa in figure 4(b).

**3.2 Surface Roughness effect by Acetone chemical vapor**

Surface roughness effect by acetone chemical vapor shown in table 3. A Figure 6 (a) observed that the minimum surface roughness is achieved at 0.30 mm layer thickness, 90⁰ angle build orientation and 10 fill density Figure 6 (b) observed the minimum surface roughness is achieved at 0.30 mm layer thickness, 90⁰ angle build orientation and 10 and 100 fill density and 90 and 150 sec time duration.

Table 3 surface roughness results withAcetone chemical vapor

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sr. No** | **Layer Thickness(mm)** | **Build Orientation (°)** | **Fill density** | **Time (Sec)** | **SR after chemical process (µm)** | **SR after chemical process (µm)** |
| 10 | 0.2 | 0 | 10 | 90 | 13.593 | 6.710 |
| 11 | 0.2 | 90 | 50 | 120 | 22.461 | 19.604 |
| 12 | 0.2 | 90 | 100 | 150 | 12.471 | 12.865 |
| 13 | 0.25 | 90 | 10 | 90 | 2.319 | 3.521 |
| 14 | 0.25 | 90 | 50 | 120 | 5.091 | 2.718 |
| 15 | 0.25 | 0 | 100 | 150 | 2.644 | 16.986 |
| 16 | 0.3 | 90 | 10 | 90 | 1.357 | 12.826 |
| 17 | 0.3 | 0 | 50 | 120 | 1.445 | 13.209 |
| 18 | 0.3 | 90 | 100 | 150 | 2.225 | 11.958 |



Figure 5 ASTM D695 -15 Compression Specimen

|  |  |
| --- | --- |
| https://lh4.googleusercontent.com/Pj083-AIXycTmd-vZvDsCGFJtoSjPoPnxMWwvsMYqvLOsyDvtK3nNLV-IO78FIw5t9-b59VG-DtmJwKZ3EdIwLB664siDbETxGt7a_Ze7GjVxcZZ7VU98zo15yZgSgQldesG9msJMzLaHZAn2A | https://lh3.googleusercontent.com/K4UX2keHP02fhtxbi-HP0T3ZyrJi84vlEO3ZDKFZTcMao8Jaf9GYx6ccx7EiZVX1aiyYyqlo7D7yQdaHn3oq2yy8bIAwFKi4mS9ptOylnf_HdS1E_jhKwzkOXA_Q_ghRZ7pkYIPExNvgMvcqEQ |
| (a) Surface Roughness before chemical vaporization | (b) Surface Roughness after chemical vaporization |
|  |  |
| (c) Surface Roughness plot before chemical vaporization | (d) Surface Roughness plot after chemical vaporization |
| Figure 6 Surface roughness result of Acetone | |

**3.3 Discussion of Surface Roughness effect by 1,2 dichloroethane chemical vapor**

Table 4 reveals the SR results of one-two dichloroethane. The minimum surface roughness is achieved at 0.20 mm layer thickness, 0⁰ angle build orientation and 100 fill density in figure 7(a) and figure 6(b) observed the minimum surface roughness is achieved at 0.25mm layer thickness, 0⁰ angle Build orientation, 100 fill density and 150 sec time duration.

Table 4 surface roughness results with one-two dichloroethane

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sr. No** | **Layer Thickness(mm)** | **Build Orientation (°)** | **Fill density** | **Time (Sec)** | **SR Before chemical process (µm)** | **SR after chemical process (µm)** |
| 19 | 0.2 | 0 | 10 | 90 | 2.144 | 1.101 |
| 20 | 0.2 | 90 | 50 | 120 | 1.754 | 4.198 |
| 21 | 0.2 | 90 | 100 | 150 | 1.760 | 0.988 |
| 22 | 0.25 | 90 | 10 | 90 | 19.172 | 3.723 |
| 23 | 0.25 | 90 | 50 | 120 | 0.528 | 0.576 |
| 24 | 0.25 | 0 | 100 | 150 | 1.708 | 1.265 |
| 25 | 0.3 | 90 | 10 | 90 | 1.937 | 6.527 |
| 26 | 0.3 | 0 | 50 | 120 | 5.234 | 2.172 |
| 27 | 0.3 | 90 | 100 | 150 | 3.493 | 0.804 |



Figure 7 ASTM D790-17 Flextural Specimen

|  |  |
| --- | --- |
| https://lh6.googleusercontent.com/AFs5CdhUI0Mqxi371XOu2WC5ldHv0uYDL7xRnNpFO4YDJbWf3S6V7OCYrgOz3jm1_EEsTYUmussYR3-jAg8lT8z7H-ZySe9lf7wykWo2h0AdcxfHpTYS_3to5ojsquJCvgSJM49Cfjp6f7Sqwg | https://lh6.googleusercontent.com/A89hkVEWzdzVnnOjnigoq_PzaTGz7cNi5yLBz7J2J0o0icXuFVy1xdlDPNdQ922wSIdwoiO2Chao7m0qNr_e8guMJHoheTVgcBlsFKLDiD6uBGQgIg2fWKx0Vh2WxdLSqZGdzO6flZ2XrdUVeA |
| (a) Surface Roughness before chemical vaporization | (b)Surface Roughness after chemical vaporization |
|  |  |
| (c) Surface Roughness plot before chemical vaporization | (d) Surface Roughness plot after chemical vaporization |
| Figure 8 Surface roughness result of 1, 2 dichloroethane | |

**3.4. Discussion on Scanning Electron Microscopy (SEM) analysis**

SEM services are used to study surface and particles, targeting failure analysis of the components, visualization of texture and morphology**,** or contamination of material SEM analyses the surfaces of the materials, particles and fibers so that fine details can be measured and assessed via image analysis. One of the key parameters of this study evaluates the surface roughness of vapor polishing. Figure 8, 9 and 10 compares the top sections on the surface roughness of 3D printed part when observed using SEM before and after the post-processing.

The microscopic image of the untreated PLA sample shown in Figure 9 (a), 10(a) and 11 (a). But from the microscopic images shown in Figure 9(b), 10(b) and 11(b), it is evident that the demarcation due to the 3D-printed raster disappears gradually due to the chemical treatment and the material in the top surface gets dissolved which fills the gap between the raster to form a uniform smoother outer surface, this is in accordance with the 2D roughness profile, i.e. as the immersion time increases, the surface roughness value decreases.

In all the cases the tensile strength of acetone-treated samples is higher than dichloroethane-treated samples but a lower surface roughness value is obtained by using dichloroethane. This is due to the fact that PLA dissolves at a higher rate in dichloroethane when compared to acetone and it makes the samples smoother and softer. From these results, a better surface finish is obtained using dichloroethane. Hence, dichloroethane can be used as an alternative chemical to acetone for higher surface finish improvement.

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| (a) | (b) |
| Figure 9 SEM images of ASTM D695-15 Tensile specimenbutanol | |

Figure 9 (a) shows the line of deposited filament which were well arranged at the raster angle of 90º during printing. Whereas Figure 9 (b) illustrated the surfaces of the same surfaces after being exposed to cold vapor treatment. By comparing these figures, it shows that the cylindrical shape of the ABS filaments has dissolved by the chemical vapor to become a smooth surface after being exposed to the vaporization process.

Figure 9 show the ASTM D695-15 Standard specimen SEM images for improve the surface finish by chemical vapor process PLA parts with acetone chemical. It is observed that the minimum surface roughness is achieved at 0.30 mm layer thickness, 900 angle build orientation and 10 and 100 fill density and 90 and 150 sec time duration is achieved in part number 14.

|  |  |
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| C:\Users\Manufacturing Engg\Downloads\2 (1).jpg | **C:\Users\Manufacturing Engg\Downloads\5.jpg** |
| (a) | (b) |
| Figure 10 SEM images of ASTM D790-17 Flexural specimenacetone | |

A flexural ASTM D790-17 Standard specimen SEM images shows in figure 10. It is improve the surface finish by chemical vapor process PLA parts with 1, 2 dichloroethane. The minimum surface roughness is achieved at 0.25mm layer thickness, 00 angle build orientation, 100 fill density and 150 sec time duration and it is good surface finish in part number 22.

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| C:\Users\Manufacturing Engg\Downloads\3 (1).jpg | C:\Users\Manufacturing Engg\Downloads\2 (2).jpg |
| (a) | (b) |
| Figure 11 SEM images of ASTM D638-14 Compression specimen1, 2 dichloroethane | |

Figure 11 ASTM D638-14 Standard specimen for improve the surface finish by chemical vapor process PLA parts with butanol chemical. A minimum surface roughness is achieved at 0.25 mm layer thickness, 900 angle build orientation, 10 fill density and 90 sec time duration and good surface finish is achieved in part number 1.

**Conclusion**

In this present work, effect of part build, layer thickness, fill density and orientation. Surface roughness of FDM test specimens are investigated. The responses are also measured post built treatment by hot vapours of one-two-dichloroethane, chemical name, butanol acetone. The roughness of FDM printed parts is analysed process parameters have been shown to affect the Ra. process parameters have been shown to affect the Ra. The surface roughness of FDM parts built at two different part orientations (0° and 90°) with chemical vapour treatment. It has been observed that the optimum surface finish is obtained at 90° part build orientation, 0.25 mm, layer thickness, 10% fill density and 90 second exposure time.

* The results are compared based on the results obtained and fractographic studies the following conclusions are:
* A butanol chemical vapour conditions of optimum parameters are 0° build orientation, 0.2 mm layer thickness, 10 % fill density and 90 second exposure time
* An acetone chemical vapour, the conditions of optimum surface finish are 90° build orientation, 0.25 mm layer thickness, 50 % fill density and 120 second exposure time.
* One –two dichloroethane chemical vapour experiment gives a rough surface, butanol gives little bit rough surface, while One –two dichloroethane gives a good surface finish improvement.

The optimum results of surface finish are One–two dichloroethane > butanol > acetone and optimum surface roughness is achieved by One –two dichloroethane.

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