Surface roughness of PLA parts by FDM with chemical treatment

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Abstract. Chemical treatment can effectively reduce the surface roughness of fused deposition modeling (FDM) parts. An effort is made in this study to appraise the surface finish of poly lactic acid (PLA) parts by FDM with hot vapor smoothing treatment. The tests were designed as per the Taguchi L16 orthogonal array based factorial design of experimentation while varying process parameters such as time, temperature and solution concentration of hot vapor smoothing. The surface roughness of PLA parts after chemical treatment reduces in different degrees compared with FDM prototypes. The results of the statistical study indicate that the surface roughness is affected by treatment temperature. The optimum parameters that have been verified by performing the experiments may provide a theoretical basis for FDM parts in practical application.

1. Introduction

Fused Deposition Modeling (FDM) with low cost, simple operation is a kind of rapid prototyping technology and becomes one of the high popularity of 3D printing technologies currently [1]. FDM is widely used in the product appearance design, functional testing, automotive, electronic appliances and other fields [2-3]. Due to the existence of staircase effect in FDM, the surface of the model is rough, which limits the development of FDM technology to a certain extent [4].

Chemical treatment was widely used in post-processing of FDM parts because of the characteristics of economic, fast and simple operation. Gantalucci et al. found that the surface roughness of ABS prototypes decreased through immersed with 90% acetone and 10% organic solvent of water directly [5]. Garg et al. proposed a method that can enhance the surface roughness of ABS parts by exposing to cold vapors of acetone (99% concentration) [6]. Jin et al. built a geometrical model of PLA parts about the evolution of surface topography between adjacent layers during the chemical finishing operation [7]. Kuo et al. developed an apparatus for enhancing the surface quality of FDM parts, and they found that the surface quality improvement rate for parts with different curvatures and tilt angles was about 83%-90% and 84%-96%, respectively [8]. Rao et al. found that acetone concentration, the interaction of concentration and temperature and the initial surface roughness were important factors that affect surface roughness of ABS parts [9]. Chohan et al. explored the effects of vapor smoothing on dimensional accuracy of replicas of biomedical implants [10].

Detailed literature survey reveals that a lot of studies have been investigated on improving the surface quality of FDM parts. The primary purpose of this work is to investigate the influence of
chemical treatment on surface roughness of FDM parts by optimizing the parameters of hot vapor smoothing. In the present work, the influence of three parameters (treatment time, treatment temperature and solution concentration) on chemical treatment is researched, and the optimum surface roughness value is presented. Subsequently, confirmation tests are carried out.

2. Methods and Experiment
The Taguchi method can greatly improve the experimental efficiency and save the cost of testing, and the optimal results of the experimental design can be achieved in the process. In Taguchi method, the deviation between the ideal quality and the actual quality is measured mainly by calculating the signal-to-noise ratio (S/N, SNR). The main purpose of chemical treatment is to reduce the surface roughness of PLA parts. The SNR based on “lower is better” has been calculated for the results of the surface roughness using Equation (1). In Equation (1), \( Y \) is the deviations from the surface roughness, \( n \) is the number of repetitions which as three in this study.

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SNR = 10 \log (\frac{1}{n} \sum_{i=1}^{n} Y_i^2)
\]  

Three chemical treatment parameters are selected as the control factors. Four levels of each factor have been shown in Table 1.

| Factors          | Notation | Level 1 | Level 2 | Level 3 | Level 4 |
|------------------|----------|---------|---------|---------|---------|
| Time (min)       | A        | 3       | 5       | 7       | 10      |
| Temperature (℃)  | B        | 40      | 50      | 60      | 65      |
| Concentration (%)| C        | 70      | 80      | 90      | 100     |

Taguchi’ orthogonal array has been selected to plan and analyze the number and sequence of experiments with different combinations of factors and levels. The orthogonal array of L\(_{16}(4^3)\) is established. Detailed information on the orthogonal array is in Table 2.

| No. | Code | A (min) | B (℃) | C (%) | Ra (μm) | SNR (dB) |
|-----|------|---------|-------|-------|---------|----------|
| 1   | A1B1C1 | 3       | 40    | 70    | 14.563  | -23.2650 |
| 2   | A1B2C2 | 3       | 50    | 80    | 5.778   | -15.2356 |
| 3   | A1B3C3 | 3       | 60    | 90    | 8.057   | -18.1235 |
| 4   | A1B4C4 | 3       | 65    | 100   | 3.82    | -11.6413 |
| 5   | A2B1C2 | 5       | 40    | 80    | 16.38   | -24.2863 |
| 6   | A2B2C1 | 5       | 50    | 70    | 13.402  | -22.5434 |
| 7   | A2B3C4 | 5       | 60    | 100   | 2.443   | -7.7585  |
| 8   | A2B4C3 | 5       | 65    | 90    | 2.474   | -7.8680  |
| 9   | A3B1C3 | 7       | 40    | 90    | 12.951  | -22.2461 |
| 10  | A3B2C4 | 7       | 50    | 100   | 2.01    | -6.0639  |
| 11  | A3B3C1 | 7       | 60    | 70    | 7.337   | -17.3104 |
| 12  | A3B4C2 | 7       | 65    | 80    | 7.799   | -17.8408 |
| 13  | A4B1C4 | 10      | 40    | 100   | 13.395  | -22.5389 |
| 14  | A4B2C3 | 10      | 50    | 90    | 11.74   | -21.3934 |
| 15  | A4B3C2 | 10      | 60    | 80    | 7.693   | -17.7219 |
| 16  | A4B4C1 | 10      | 65    | 70    | 4.534   | -13.1296 |
The experimental process is shown in Figure 1. The specimens for the experiment are fabricated using the Einstart-S Desktop 3D Printer (Figure 1a), and the model material is PLA. The printing parameters were adopted by empirical values and kept constant during the experiment. Extrusion temperature was 195 °C, while the extrusion speed and printing speed kept at 40 mm/s and 60 mm/s, respectively. Other printing parameters were maintained at their default levels. The specimens were built up in the flat direction in the air gap of 0 mm and the layer thickness of 0.2 mm, meanwhile no supporting structure was required.

The built specimens were subjected to chemical treatment by exposing the test specimens to hot vapors of chloroform solution in a special heating thermostatic system (Figure 1b). The chloroform solution was selected because its solubility parameters are comparable with PLA. The specimens were placed in the same position as the printing position on the bracket during the process. The liquid level of chloroform solution should be guaranteed to be lower than the height of the bracket, so that the surface of the specimens can fully contact with hot vapors. The reason why we choose hot vapors instead of direct immersing or cold vapors are that the chemical reaction between the solution and material is strong and not easy to control in direct immersing, and cold vapors evaporates slowly and takes a long time. SJ210 surface roughness meter (Figure 1c) was used to provide the roughness value of the surface, and 3D vision (Figure 1d) was utilized to capture the surface morphology of the parts.

3. Results and Discussion

Figure 2(a, b) shows the morphology of surface before chemical treatment and after chemical treatment (A2B3C4), Figure 2(c, d) shows the morphology of surface before chemical treatment and after chemical treatment (A4B1C4), and Figure 2(e, f) depicts the morphology of surface before chemical treatment and after chemical treatment (A4B3C2).

It can be seen from Figure 2 that the surface of the untreated samples have obvious wavy lines which are caused by the step effect. After chemical treatment, the wavy lines on the surface of the parts are more or less reduced. This indicates that different chemical treatment parameters have different changes in surface roughness. This is because the hot vapors dissolves the surface layer of the polymer material, breaking secondary bonds between the polymer chains and allowing the chains
to flow to each other in a more stable position. The surface tension of the molten polymer layer reduces the crest of the ripple and flattens the trough, thus reducing the gap between adjacent steps.

The measured surface roughness values (Ra) are listed in Table 2. Minitab 17 statistical software was used to find out the effects of processing parameters on surface roughness. The factorial effects on surface roughness are shown in Table 3. Ranks of R and contribution ratio values are two indicators to depict the effectiveness of control factors in intuitive analysis. R is the change of three level average SNRs for each factor. It can be seen from Table 3 that the macroscopic order of the three control factors is B>C>A for the surface roughness.

| Level | A    | B    | C    |
|-------|------|------|------|
| 1     | -17.07 | -23.08 | -19.06 |
| 2     | -15.61 | -16.31 | -18.77 |
| 3     | -15.87 | -15.23 | -17.41 |
| 4     | -18.70 | -12.62 | -12.00 |
| R     | 3.08  | 10.46 | 7.06  |
| Rank  | 3     | 1     | 2     |

According to the calculated average SNRs of each factor, the main effect plots are drawn to illustrate the effects of control factors. The contribution ratios and the main effect plots of each factor plot of surface roughness are shown in Figures 3 and Figures 4, respectively.

From Figure 3, the time (A), the temperature (B) and the concentration (C) all have significant effects on surface roughness. The order of the factors effective for the surface roughness is B>C>A, which is identical to the result from Table 3. From a quantitative perspective, the contribution ratio for surface roughness of the time (A) is 14.95%, the temperature (B) 50.78% and the concentration (C) 34.27%. It shows that the factor of temperature (B) and the concentration (C) has a great influence on the surface roughness.

From Figure 4, the variation in the surface roughness after chemical treatment first decreases and then increases with the increase in the processing time. It has been observed that variation in the surface roughness of 5 min of chemical treatment was less as compared to other times. The reason for this phenomenon is that the contact area between the hot vapor and the sample surface increases with the increase of time. When the time exceeds 5 min, the material will reflow in hot vapor. The surface roughness variation tends to decrease with the increase of the temperature and the concentration of hot
vapors. This may be the fact that the vapor cannot completely evaporate because the temperature does not reach the boiling point of the solution, resulting in low concentration of vapors in the closed space. Once the temperature reaches the boiling point, the concentration of hot vapors in the space rises rapidly. High concentration will make the hot vapors and the sample surface in full contact.

We can also find that factor B has the largest variation on surface roughness compared with factor A and C, and factors A and C have the larger variations compared with factor B. This further demonstrates that the surface roughness of the specimens after chemical treatment is sensitive to the temperature of hot vapor. According to the “lower is better” criterion, it can be seen from Figure 4 that the optimum values of the factors for minimum surface roughness variations is A2B4C4.

Analysis of variance (ANVOA) has been performed on the relative significance of the factors in surface roughness errors. The factor with a larger variance is more significant. The results of ANOVA of Ra is listed in Tables 4, respectively. DOF means the degree of freedom in the orthogonal array; Adj SS means the sum of squares; Adj MS means the sum of squares which are obtained from Adj SS divided by DOF. F is the value calculated by the Adj MS divided by the Adj MS of error. The value of P less than 0.05 indicates that the model terms are significant.

Because the values of P for factor A and C are more than 0.05, while the factor B is less than 0.05, factor B is significant model term in Table 4. A larger value of F for factor B indicates that variation in this factor causes a large variation in surface roughness. Because the value of P for factor of all terms in Table 4 is more than 0.05, none of the terms is significant at 95% confidence level. Lower value of F for factor B indicates that variation in this factor causes low variation in performance characteristics. The results of ANOVA are consistent with the intuitive analysis.

Table 4. ANOVA results for surface roughness.

| Factor | DOF | Adj SS | Adj MS | F   | P  | Contribution(%) |
|--------|-----|--------|--------|-----|----|-----------------|
| A      | 3   | 7.385  | 2.462  | 0.21| 0.885 | 11.88           |
| B      | 3   | 212.733| 70.911 | 6.11| 0.030 | 58.68           |
| C      | 3   | 50.073 | 16.691 | 1.44| 0.322 | 12.88           |
| Error  | 6   | 69.65  | 11.608 | 1.44| 0.322 | 16.56           |
| Total  | 15  | 339.841|        |     |      | 100             |

4. Optimization and Confirmation Experiments

According to Taguchi method criterion, the SNRs under the parameters above mentioned for variation of surface roughness can be predicted by using the optimal chemical processing parameters. The respective values of SNR for variation of surface roughness under the optimum conditions can be calculated using Equation (2).

Optimum value of SNR for variation of surface roughness SNRb as follows:

\[
SNR = SNR_m + (SNR_A - SNR_m) + (SNR_B - SNR_m) + (SNR_C - SNR_m) = -6.6138
\]  

(2)

where SNRm is the mean of SNR of all 16 cases in Table 3; SNRA, SNRB and SNRC are the optimal level average SNR of factors A, B and C, respectively.

Furthermore, to validate the surface roughness of predicting output responses, confirmation experiments for 3 times were performed at the suggested optimized values. Table 5 depicts the predicted and confirmatory experimental results for the output responses. The predicted and verified results show a good correlation, and validate Taguchi analysis.

Table 5. Statistically predicted and confirmatory experimental values for output responses.

| Output Response | Predicted | Experimental | Deviation (±) |
|-----------------|-----------|--------------|---------------|
| Ra (μm)         | 1.95      | 1.984        | 0.034         |
5. Conclusions
In this study, factor optimization of surface finish of FDM parts with chemical treatment is carried out using the Taguchi method. The influences of three hot vapor smoothing parameters on surface roughness of FDM parts are experimentally analyzed. The initial value in surface roughness of the prototypes before the chemical treatment process has also been analyzed, and it has been observed that the surface roughness of PLA parts can be effectively reduced by chemical treatment. Furthermore, the optimization results show that the order of the factor effectiveness for surface roughness is temperature (B), concentration (C) and time (A). In addition, the temperature has a significant influence on surface roughness. For the surface roughness of FDM parts with chemical treatment, optimal parameter combinations is A2B4C4. In order to prove the accuracy of the optimization, verification test solutions of the surface roughness was compared with optimum solutions. The experimental results were basically consistent with the optimum results.

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