Investigation For Shrinkage Deformation In The Desktop 3D Printer Process By Using DOE Approach Of The ABS Materials

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Abstract: Nowadays, 3D printing (3DP) has become a popular personal approach as it being able to produce a product more quickly and increased accessibility. 3DP was also known as Rapid Prototyping (RP) where it builds three-dimensional (3D) products using layer by layer method from a Computer Aided Design (CAD) files. However, dimensional accuracy (DA) was one of the major problems of these technologies. Thus, it is important to evaluate the best parameter in order to find out the best adjustment to avoid the dimensional error. The objectives of this study were to find the best parameter setting and to evaluate the influence of the changing parameter in 3D part shrinkage error. This study only focused on desktop 3D printer machines, which was the Odyssex Designex X2 and the material used was Acrylonitrile Butadiene Styrene (ABS). In investigate which factors that most significant to shrinkage, DOE approach was used with parameters such as layer thickness (LT), nozzle temperature (NT), print speed (PS), infill density (ID) and bed temperature (BT). Minitab software has been used for analysis purposes. The significant process parameter effect and the best setting of parameter were determined from ANOVA, Main Effect Plot (MEP) and regression method. Finally, from the results of this study, BT was the most significant effect to shrinkage (SK) and the best setting for achieving less value in SK in ABS materials was LT= 0.25mm , NT= 235°C , PS= 55mm/s , ID= 25% and BT= 100°C. The validation runs was conducted based on the best setting value and it shows that the different between predicted value and actual value was 2.56%. This means that the model was reasonably accurate and the best parameter setting was highly recommended. The results also proved the quality of products was improved by using the DOE approach.

Keywords: FDM, Rapid Prototyping, Shrinkage, ANOVA, Acrylonitrile Butadiene Styrene (ABS)

1. INTRODUCTION

The world of 3D printing (3DP) has been in its infancy and there has been growing in the last few years. 3DP is now revolutionized with the technology of additive manufacturing (AM). Generally, 3DP technology creates physical products from a computer generated design or better known as computer aided design (CAD) file by joining or forming input substrate materials layer by layer. It is known as additive manufacturing (AM) in order to differentiate it from traditional substractive manufacturing processes. The key principle behind additive processes is layerization which slicing digital 3D models into horizontal layers and building one layer at a time. 3DP has been used for more
than two decades mainly for rapid part prototyping and small run production in various industries [1]. Printing an object using a 3DP is different than printing a word document, 3DP used a process to shape or print physical objects layer by layer until the final model is finished. This is different with subtractive manufacturing, in which a machine reshapes or removes the unwanted material from an existing mold. In the scope of product quality, the dimensional accuracy (DA) is one of major challenges in improving the quality of end product for 3DP. Shrinkage is one of the factor that should be strictly considered in order to achieve the best result of dimensional accuracy. It is believe that by applied the best parameters setting of FDM, the dimensional accuracy of the fabrication parts can be improved. There are several variable parameters that can be adjusted to make improvement such as layer thickness (LT), nozzle temperature (NT), print speed (PS), infill density (ID) and bed temperature (BT).

2. LITERATURE REVIEW

Additive manufacturing (AM) is the formalized term for what used to be called Rapid Prototyping (RP) and is popularly called 3DP. There are several types of 3DP and it comes with different processes, for example Stereolithography (SLA), Selective Laser Sintering (SLS), Inkjet Modeling (UM), Di-rect Metal Deposition (DMD) and Fused Deposition Modeling (FDM) [2]. Although there are different terms in name and different working process but they still have a same purposes which is rapidly create a 3D part object.

3D printers were spreading rapidly, because of the business accessibility of simple to use and modest desktop printers. However, the improvement of dimensional accuracy (DA) is considered to be one of the major scientific challenges in improving product quality by using 3DP. Some attempts have been made to improve dimensional accuracy of FDM fabricated parts through appropriate adjustments in the process parameters[10]. From previous study, Ab. Rahman [3] has suggested that parameter such as bed temperature and shrinkage factor are need to be considered in order to get the accurate results. According to Gregorian et al., [4], although 3DP has great potential, it is constrained due to its relatively low dimensional accuracy and also lack of methodology for wider applications beyond the current application on high-value and complex products. The aforesaid discussions reveal that properties of RP parts are dependent on various process related parameters. With proper adjustment of the build parameters, quality can be significantly improved without incurring additional expenses in changing developed hardware and software [9].The area using 3DP can be diversifed if the accuracy of the product can be improved and therefore its quality could be increased. Furthermore, controlling dimensional accuracy as a build parts can greatly reduce the cost and time of post-build finishing processes in 3DP.

3. METHODOLOGY

Several attempts have been made to evaluate the influence of the changing parameter in 3D part shrinkage error by using design of experiment (DOE) approach. By using DOE method, the practical steps are needed for planning and conducting the experiment. There are several steps in planning phase, firstly recognizing the objective of the experiment, then do selection of design, factors and the response. After completing planning phase step, the experiments can be carried out and then the analysis can be made. Lastly, draw the conclusions and making a recommendations of the experiments [5].

Acrylonitrile Butadiene Styrene (ABS) product pattern were built on Odyssey Designex X2 desktop 3D printer which is one type of fused deposition modeling (FDM) machine in additive manufacturing. For evaluation of process performance of this machine, it can be determined by proposed benchmark that has been designed in Figure 1. Benchmarking process will help to identify the factors that can affect the measurement and accuracy of benchmark parts [6].
The CAD model was designed by using SolidWorks, then it is converted into stereolithography (STL) format. After the STL file has been formed, then the STL are imported into one of Stratasys software program which is Cura 3D software. All the selected parameters have been set up in this software and finally it would transfer to 3D printer controller which is Pronterface. Pronterface setting is the last stop before 3D printer start into action to create the product pattern. This is how the 3D printer will be controlled during printing process, the set temperatures, jog the axes and many things inside this software can be set before running the fabrication process.

3.1 DOE Preparation

In order to get the best setting of parameters in desktop 3DP process, several parameters was selected. The parameters are layer thickness (LT), nozzle temperature (NT), print speed (PS), infill density (ID) and bed temperature (BT). The main point of experiment was to conduct test and observe how the process parameters affect the response variable which is shrinkage. In the process of DOE preparation, the $2^5$ full factorial design were chosen from the Minitab based on the total of parameters selected. For that design, it will carrying out the total of 32 experiments. However, in this study fractional factorial design was used which is means only 16 experiments will be runs by using $1/2$ fractional design ($2^{5-1} = 2^4 = 16$) instead of 32. By adding 3 centers point to the fractional factorial, total all experiment run became 19. Center point is used to estimate variation without having to replicate all the corner points and to increase the power of test. Table 1 below indicates the factor and level selected in this study.

| Factors                  | Level |
|--------------------------|-------|
|                          | Low   | Center | High |
| Layer Thickness (LT) (mm)| 0.2   | 0.25   | 0.3  |
| Nozzle Temperature (NT) (°C) | 230 | 235     | 240  |
| Print Speed (PS) (mm/s)  | 50    | 55     | 60   |
| Infill Density (ID) (%)  | 20    | 25     | 30   |
| Bed Temperature (BT) (°C) | 90   | 95     | 100  |

4. RESULTS AND DISCUSSION

The experimental results of this study are listed in this Table 2. There are 19 product prototype were built by with a different parameter setting according to the experimental layout. It can be seen that each benchmark produced different value of shrinkage.
Table 2. Experimental results.

| No of Exp. | Process Parameter | Response |
|------------|-------------------|----------|
|            | LT (mm) | NT (°C) | PS (mm/s) | ID (%) | BT (°C) | SK     |
| 1          | 0.25    | 235     | 55        | 25     | 95      | -0.4682 |
| 2          | 0.2     | 230     | 60        | 20     | 90      | -0.3604 |
| 3          | 0.3     | 240     | 60        | 20     | 90      | -0.7875 |
| 4          | 0.2     | 240     | 60        | 30     | 90      | -0.7494 |
| 5          | 0.2     | 230     | 50        | 20     | 100     | -0.4038 |
| 6          | 0.2     | 230     | 50        | 30     | 90      | -0.6254 |
| 7          | 0.25    | 235     | 55        | 25     | 95      | -0.3932 |
| 8          | 0.3     | 230     | 60        | 20     | 100     | -0.5005 |
| 9          | 0.3     | 240     | 50        | 30     | 90      | -0.5014 |
| 10         | 0.2     | 240     | 50        | 30     | 100     | -0.4498 |
| 11         | 0.2     | 240     | 50        | 20     | 90      | -0.9176 |
| 12         | 0.2     | 240     | 60        | 20     | 100     | -0.4178 |
| 13         | 0.25    | 235     | 55        | 25     | 95      | -0.4611 |
| 14         | 0.3     | 230     | 50        | 30     | 100     | -0.4270 |
| 15         | 0.3     | 240     | 50        | 20     | 100     | -0.4726 |
| 16         | 0.3     | 230     | 60        | 30     | 90      | -0.6962 |
| 17         | 0.2     | 230     | 60        | 30     | 100     | -0.3909 |
| 18         | 0.3     | 240     | 60        | 30     | 100     | -0.4086 |
| 19         | 0.3     | 230     | 50        | 20     | 90      | -1.0957 |

All measurement readings for shrinkage (SK) were obtained from Mitutoyo Flexible Measuring Machine (FMM) and the readings was taken based on X, Y and Z axis.

4.1 Shrinkage

The significant factors and interactions were identified using analysis of variance (ANOVA). Figure 2 shows the Pareto chart of the standardized effect for shrinkage (SK). The chart clearly shows a few factors that most significant effects to SK, it indicates that the significant effects on the percent reacted were due to BT, LT-NT interaction, PS-ID interaction and LT-ID interaction. It can be said that all these factors were significant effects because the bars for all the factors cross the reference line at 2.262. Based on the Pareto chart, BT contributed highest influenced effect to the shrinkage of the product.
Table 3 indicates for ANOVA table for SK. DF is representing for degrees of freedom, Adj SS is adjusted sum of squares and F-value is ratio of two variances while P-value is the probability. When a p-value is lower than the alpha value which is 0.05, it can be claimed as statistically significant. From the ANOVA table, there is evident that BT with a p-value of 0.000 had the greatest impact on the response variable of shrinkage from the five factors tested. This is means that shrinkage effect are highly influenced by BT value in this study. Besides that, one can see LT and NT interacted with a low p-value of 0.007, LT and ID interacted with a p-value of 0.032 and also PS and ID showed an interaction with low p-value of 0.019.

Table 3. ANOVA table for shrinkage (SK).

| Source          | DF | Adj SS   | Adj MS   | F-Value | P-Value |
|-----------------|----|----------|----------|---------|---------|
| Model           | 9  | 0.673467 | 0.074831 | 8.68    | 0.002   |
| Linear          | 5  | 0.395631 | 0.079126 | 9.18    | 0.002   |
| LT              | 1  | 0.020621 | 0.020621 | 2.39    | 0.156   |
| NT              | 1  | 0.002621 | 0.002621 | 0.30    | 0.595   |
| PS              | 1  | 0.021170 | 0.021170 | 2.45    | 0.152   |
| ID              | 1  | 0.031258 | 0.031258 | 3.62    | 0.089   |
| BT              | 1  | 0.319960 | 0.319960 | 37.10   | 0.000   |
| 2-Way Interactions | 3  | 0.232175 | 0.077392 | 8.97    | 0.005   |
| LT*NT           | 1  | 0.106178 | 0.106178 | 12.31   | 0.007   |
| LT*ID           | 1  | 0.055108 | 0.055108 | 6.39    | 0.032   |
| PS*ID           | 1  | 0.070889 | 0.070889 | 8.22    | 0.019   |
| Curvature       | 1  | 0.045671 | 0.045671 | 5.30    | 0.047   |
| Error           | 9  | 0.077614 | 0.008624 |         |         |
| Lack-of-fit     | 7  | 0.074186 | 0.010598 | 6.18    | 0.146   |
| Pure Error      | 2  | 0.003429 | 0.001714 |         |         |
| Total           | 18 | 0.751091 |          |         |         |

Figure 3 illustrates the Main Effect Plot (MEP) of the five factors on the response variable of shrinkage. The vertical axis are represents as means values in the scale of microns, while the horizontal axis is grouped into five sections for each factor and illustrates each level of the factors in their own respective units.
As observed from the plot, it can be seen that the BT contribute the biggest impact on shrinkage. According to Choi et al, [7] , they stated that to minimize the shape errors attributable to the heat shrinkage in ABS materials, the temperature bed needs to remain close to the ABS softening temperature during fabricating process. They also claimed that the softening temperature of ABS materials is 104°C. Thus, from the plot, when the value of BT at 90°C it gives highest reduction while when the value of BT at 100°C it gives lowest reduction to shrinkage. Apart from that, process parameter in the center point level are seems low reduction in shrinkage. This is means that the best setting to get the best quality of the product in this study when at the center point value which are LT= 0.25mm, NT= 235°C, PS= 55mm/s and ID= 25%.

5. CONCLUSION

The distinctive capabilities of 3DP enable new opportunity for designers to explore new methods for improving product performance, customizing products and in general developing new ways to conceptualize product. Thus, the best setting of process parameters was an important element to be considered to achieve best quality product from 3DP process. In this study, different parameters were used as a framework of an experiment by using DOE approach. DOE was used to find the significant of factors and their interactions in order to certifying the best factors level. After all, the best setting of parameters was successfully validated by comparing the result between predicted and actual.

Based on the result obtained, this study has succeeded one of its objectives which was to analyze the best parameters for 3DP process by using DOE method. The investigation using DOE approach has determined the factors that affect to SK. From the results of this study, it was found that BT is the most significant effect to SK. Then, the best setting for achieving less value in SK for ABS materials was LT= 0.25mm, NT= 235°C, PS= 55mm/s, ID= 25% and BT= 100°C. The validation runs for SK was conducted based on the best setting value and it shows that the different between predicted value and actual value was 2.56%. That is means, the model is reasonably accurate and the best parameter setting is highly recommended. The results also proved the quality of products can be improved by using the DOE approach.

Lastly, for further improvement, DOE analysis tool such as Response Surface method are recommended to be used in future study to determine and analyze the optimum setting of parameters.

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