Investigation of dimensional variation in parts manufactured by fused deposition modeling using Gauge Repeatability and Reproducibility

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Abstract. In the additive manufacturing (AM) market, the question is raised by industry and AM users on how reproducible and repeatable the fused deposition modeling (FDM) process is in providing good dimensional accuracy. This paper aims to investigate and evaluate the repeatability and reproducibility of the FDM process through a systematic approach to answer this frequently asked question. A case study based on the statistical gage repeatability and reproducibility (gage R&R) technique is proposed to investigate the dimensional variations in the printed parts of the FDM process. After running the simulation and analysis of the data, the FDM process capability is evaluated, which would help the industry for better understanding the performance of FDM technology.

Keyword: FDM, gage R&R, dimensional accuracy, variation

1. Introduction

Fused deposition modeling (FDM) developed by Stratasys, is one of the leading additive manufacturing processes for producing three-dimensional (3D) parts from thermoplastic materials. FDM is widely used for manufacturing a variety of complex parts without the need of any tools. It produces 3D model in a layer by layer manner directly from a 3D digital description of the part on the surface of the build sheet. Recent advancements in FDM process have led to its industrial applications not only for rapid prototyping (RP) but also for developing tools and producing a wider range of production 3D components. The variation in the dimensional accuracy of the FDM process is a defect characterized by the printed part dimension varying from batch to batch while the FDM system conditions remain the same. The variability of dimensional accuracy in the manufactured products is often divided into two elements. The first element is caused by operators and the second element is caused by the measurement device itself (the gauge). Design and production engineers distinguish between the meaning of dimensional accuracy and repeatability of the manufactured products. Some additive manufacturing systems have good accuracy but poor repeatability. In FDM, dimensional accuracy is an indication of how close the dimension of the manufactured part is to that of the designed dimension by computer aided design (CAD), which is defined as a system error. Repeatability refers to the variation in repeated dimensional measurement from part to part in a single build on a single machine. Reproducibility is the ability of a manufacturing process or system used by the operators to regularly reproduce the same dimensional measurements of the same part, under the
same settings. Recently several studies [1-8] have been made to improve dimensional accuracy of FDM processed parts. The literature review mostly focuses concerned on evaluating the FDM process parameters to minimize dimensional error and many studies have been performed to optimize the part accuracy using various statistical techniques. However, the main limitation of all the previous studies is that neither of these studies considered the repeatability and reproducibility of the FDM system itself in producing accurate products. Furthermore, the past literature did not provide the answer to the question posed by industry, AM users and production engineer’s on how reproducible the fused deposition modeling is as a highly repeatable manufacturing system. In this study, we examine the stability of the part dimensions using a gage R&R (repeatability and reproducibility) approach. Then we analyse the FDM process capability, which helps the additive manufacturing users for better monitoring of the precision of the FDM process as a highly repeatable and reproducible system.

2. Experimental details
When measuring the dimensional accuracy of manufactured product of any process, there are two sources of dimensional variation. The first dimensional variation is the variation of the process itself. The second variation is the variation of the measurement system. The purpose of performing the Gage R&R is to let us discriminate the variation of one from another, and to minimize the measurement system variation if it is excessive. The two-way ANOVA technique based Gage R&R (crossed) was applied in this study to analyse the data. Gage R&R is an approach to estimate the combined variation of repeatability and reproducibility, which determines how much of the observed variation in the process is due to measurement system variation. In a crossed Gage R&R study, every part is measured by more than one operator/inspector. In this study, a crossed Gage R&R technique was conducted using Minitab version 17 with two operators using a total of 16 samples. Each operator measures 4 parts selected from a process and each part is measured at least twice by each operator. Figure 1 shows the flowchart illustrating the overall methodology, while Table 1 presents Gage R&R study conditions.

![Flow chart of the overall methodology](image_url)

**Figure 1.** Flow chart of the overall methodology.

| Table 1. Gage R&R study conditions. |
|------------------------------------|
| Source                        | Value |
| Number of operators           | 2     |
| Number of replicates          | 2     |
| Number of parts               | 4     |
In this study, a total of 16 samples were manufactured using FDM Fortus 400 system under the same process conditions as shown in Table 2. The material used for test samples is Polycarbonate/Acrylonitrile-Butadiene-Styrene (PC-ABS) alloy supplied by Stratasys. All dimensions were measured using a Mitutoyo micrometer screw gauge having accuracy of ± 0.0001 mm. Five readings on each sample were taken and the average of these values was used as a percentage error in dimension. Table 3 presents Gage R&R study (crossed) matrix along with measured data.

Table 2. Fixed process conditions (factors) and their level.

| Factors                         | Units | Level |
|---------------------------------|-------|-------|
| Layer thickness                 | mm    | 0.2540|
| Raster to raster air gap        | mm    | 0.000 |
| Contour to raster air gap       | mm    | 0.000 |
| Contour to contour air gap      | mm    | 0.000 |
| Raster angle                    | deg   | 45    |
| Build orientation               | deg   | 0     |
| Part raster width               | mm    | 0.5080|
| Number of contours              | -     | 1     |
| Contour width                   | mm    | 0.5080|
| Visible surface style           | -     | Normal|
| Part interior style             | -     | Solid |

Table 3. Gage R&R study (crossed) matrix with measured data.

| Run | Operators | Parts | Dimensional error (%) |
|-----|-----------|-------|-----------------------|
| 1   | 1         | 1     | 1.770                 |
| 2   | 1         | 4     | 1.770                 |
| 3   | 1         | 2     | 1.746                 |
| 4   | 1         | 3     | 1.793                 |
| 5   | 2         | 3     | 1.792                 |
| 6   | 2         | 2     | 1.734                 |
| 7   | 2         | 4     | 1.769                 |
| 8   | 2         | 1     | 1.750                 |
| 9   | 1         | 1     | 1.760                 |
| 10  | 1         | 2     | 1.738                 |
| 11  | 1         | 4     | 1.764                 |
| 12  | 1         | 3     | 1.796                 |
| 13  | 2         | 2     | 1.731                 |
| 14  | 2         | 4     | 1.768                 |
| 15  | 2         | 3     | 1.792                 |
| 16  | 2         | 1     | 1.760                 |

3. Results and discussion

3.1. Gage R&R study
Table 4 presents two-way ANOVA results for dimensional variation in the samples. It can be noticed from Table 4 that Parts and Operators correspond to the probably (P-value) of <0.0001 and 0.051, respectively, which implies that they have significant effect on the percentage error in dimension. Table 5 presents Gage R&R results. It can be seen from Table 5 that % Study Variation of 23.99 % along with number of distinct categories of 5 indicates that the measurement system produces acceptable dimensional accuracy of the products (under 30 %). The Repeatability of the gage (19.77 %) is a strong contributor to the overall variation. It also shows that Part-To-Part study variation (97.08 %) is a strong contributor to the measurement system variation. Operators (13.58%) are not a
strong contributor. This indicates that the measurement performance is similar between different operators which mean that the measurement system and the manufactured products by the FDM system have acceptable dimensional variation from the desired dimension.

Table 4. Two-way ANOVA results.

| Source     | DF | SS          | MS          | F            | P        |
|------------|----|-------------|-------------|--------------|----------|
| Parts      | 3  | 0.0064060   | 0.0021353   | 97.4102      | < 0.0001 |
| Operators  | 1  | 0.0001046   | 0.0001046   | 4.7733       | 0.051    |
| Repeatability | 11 | 0.0002411   | 0.0000219   | -            | -        |
| Total      | 15 | 0.0067517   | -           | -            | -        |

Table 5. Gage R&R results.

| Source         | Standard Deviation (SD) | Study Variation (6 × SD) | % Study Variation |
|----------------|-------------------------|--------------------------|-------------------|
| Total Gage R&R | 0.0056798               | 0.034079                 | 23.99 %           |
| Repeatability  | 0.0046820               | 0.028092                 | 19.77 %           |
| Reproducibility| 0.0032155               | 0.019293                 | 13.58 %           |
| Operators      | 0.0032155               | 0.019293                 | 13.58 %           |
| Part-To-Part   | 0.0229859               | 0.137915                 | 97.08 %           |
| Total Variation| 0.0236772               | 0.142063                 | 100 %             |

Number of Distinct Categories = 5

Figure 2 shows Gage R&R analysis plot for dimensional variation in the measurement system. It can be seen from Figure 2 (a-b) that the largest component of variation is Part-to-Part variation. That means the most of the variability in the measurements can be accounted across different parts. Figure 2 (c) shows dimensional error by Operators. It helps to determine whether measurements and variability are consistent across operators. The parallel line to the x-axis in Figure 2 (c) indicates that the operators are measuring the parts similarly. This led to Operator had little effect on the measurement (p= 0.051). Figure 2 (d) shows that the interaction between Parts and Operators agreed fairly well with each other.

![Figure 2](image)

Figure 2. Gage R&R analysis plot for (a) components of variation, (b) dimensional error by Parts, (c) dimensional error by Operators, and (d) interaction between Part and Operations.

The coloured bars in Figure 3 shows the variation in the measurement system as a percentage of all process variation. The general rules are: variation less than 10 % is acceptable and the system should be satisfactory for all applications; the variation between 10 % and 30 % is marginal. The system is
satisfactory depending on the importance of the application. Greater than 30% is not acceptable. It can be seen from Figure 3 (a) that the measurement variation equals 0.3% of the process variation. Moreover, Figure 3 (b) indicates that the measurement system variation equals 2.8% of the tolerance. This indicates that the process variation is acceptable.

According to the above findings, it can be concluded that the measurement system is capable of measuring the FDM part dimension consistently and accurately, and also capable of adequately differentiates between parts.

![Can you adequately assess process performance?](image)

![Can you sort good parts from bad?](image)

**Figure 3.** Gage R&R study showing the performance of the measurement system.

3.2. **FDM process capability analysis**

Process capability analysis was conducted after the measurement system has been validated. Process capability index (Cpk) is a statistical measure of process capability which compares the output of the process to the specification boundaries through capability indices. In industry, the acceptable value of Cpk must be 1.33 [4 sigma] or higher to satisfy customers requirement. In most of the industries, acceptable dimensional variation of the manufactured product should be at least 98% (dimensional error of 2% or less) obtained from the designed or desired dimension. Figure 4 demonstrates that there are no points beyond the control limits, which indicates that the measurement system is adequate. This control chart also suggests that the process and measurement are consistent and predictable with only random variation. From Figure 5, it can be seen that FDM process has Cpk of 3.07 as the dimensional accuracy of the manufactured component is concerned. Therefore the FDM process is considered to be a highly capable additive manufacturing process and is considered to be industry benchmark.

![X-bar Chart](image)

**Figure 4.** X-bar Chart.
4. Conclusions
In this study, Gage R&R technique was applied firstly to evaluate the performance of measurement system. Then the process capability analysis was conducted to evaluate the dimensional accuracy of FDM process. After investigating the results obtained through this study, it can be concluded that FDM process is highly capable additive manufacturing process in producing highly accurate product with good repeatability and reproducibility.

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