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Dimensional accuracy of an artifact for rapid casting

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Abstract

Stereolithography based Additive Manufacturing (AM) technology has seen ever-increasing popularity in numerous modern applications. High dimensional accuracy, fine detail, high quality surface finish and availability of a wide range of materials makes this technology stand out from the other AM technologies. With decreasing cost, consumer grade printers can even be used at home set up. In addition, recently developed new materials such as castable resins generates greater interest for those involved in the casting production of small parts. Therefore, there is a need among the manufacturers to access qualitatively the innovations, whether it is a hardware improvement or new materials. As the dimensional accuracy of parts has been recognized as one of the most important parameters among the manufacturers, the aim of this paper is to evaluate the dimensional accuracy of SLA manufactured parts printed on the Formlabs Form 2 3D printer (3D Systems). For this evaluation, a benchmark with the external dimension of 60x60x25 mm has been designed which allows to assess the effect of the part position on the build platform, as well as the dimensional accuracy in X, Y and Z axes. To assess the quality of printed parts, the rectangular shape benchmarks have been printed on four locations of the build platform with sides parallel to X/Y axes and measures of several dimensions of the parts were collected. The results of the study show that both the location of the part on the build platform and orientation affect the dimensional accuracy. For instance, it was found that the accuracy in z vertical direction was the lowest, which confirmed the findings from other publications. Additionally, the findings have shown that the accuracy of the part might vary depending on the size of the part. In summary, SLA based AM technology continues to be a great tool for manufacturers in many fields. However, it is important to identify the limits and potential pitfalls that might be encountered during the manufacturing process and this study has attempted to reveal few controllable factors affecting the accuracy. These factors include position of the part on the build platform, build direction and size of the feature.

Dimensional accuracy, Additive manufacturing, Stereolithography, Benchmark

1. Introduction

Since its first appearance in the market, Stereolithography (SLA) based AM has shown great potential for the application in Rapid Casting (RC) industry. However, due to excessively expensive equipment and materials, AM machines were not considered as relevant to the Casting industries. Nevertheless, with the continuous development and innovations, nowadays, it is possible to find different machine configurations with more affordable price and high accuracy on the market. This has created an immense opportunity for small and large companies that are using RC, Investment Casting (IC) and Rapid Prototyping (RP). SLA based AM technology allows manufacturing of parts with complicated shapes and forms directly from a CAD model rapidly and with ease. Moreover, the market offers special types of polymers such as castable resins, making it possible to directly create investment patterns and eliminating the need of tools and reducing lead time and costs.

Among many properties of printed parts, the dimensional accuracy is one of the most important. Failing to produce a part within required dimensional tolerance renders the production process as ineffective. Therefore, it is crucial to identify the capabilities of the SLA technology in terms of accuracy at the earliest stage of designing or planning. By identifying the dimensional accuracy of parts, this research study aims to establish the accuracy level of Formlabs Form 2.

The established practise of identifying the dimensional accuracy of any given AM technology include benchmark/artifact design, manufacturing the benchmark and measuring the accuracy with the available instruments. By evaluating the errors of dimensional and geometric nature, one can identify the accuracy level of the technology concerned. The benchmark designed for this research is of the size of 60x60x25 mm (L*W*H) which allows to place four benchmarks at the four corners of the build platform to assess whether the position of the part on the platform effects the quality of the print or not. Although it is recommended to design an artifact which is large enough to cover the whole build area [1], producing smaller parts also minimizes the possibility of warpage occurrence [2].

It has been reported by several researchers that the build direction has an effect on the accuracy too [3-6]. It is noteworthy to mention that there is a level of contradictory information on whether the vertical Z build direction is better in terms of accuracy or worse. For instance, while Ji et al [4] and Islam et al [5] stated that the Z build direction is more accurate compared to X-Y plane orientation, the findings of Alexey et al [6] has shown the opposite. The present work aims to clarify this contradiction.

It appears that very limited information is available concerning the issue of part's location on the build platform and its effect on the accuracy. In general, literature conclude that the parts printed close to the center of the platform show higher accuracy compared to those printed in the periphery. Previous literature mainly compared the dimensional accuracy of parts manufactured throughout the whole area of a build plate. However, the present work aims to make comparisons among benchmarks printed on the four corners of the build plate. In this case, an equal portion of each benchmark is located on both periphery and on the middle part of the build platform as shown in Figure 1. Thus, if the findings reveal a significant difference in accuracy among the four parts, it can be concluded that other locations of the build area might be preferable too in terms of accuracy. Moreover, the study finds it necessary to identify how features differ in accuracy depending on the distance they have from the center of the platform.

It is well known that depending on the size of the part, the accuracy level might change too. For example, as the size of the part increases, the shrinkage value increases proportionally. Therefore, several feature sizes have been introduced in this study for comparison purpose.

By collecting a meaningful measured set of data, this study provides preliminary results to establish whether the printing position on the build platform affects the accuracy of features or not. In addition, this study attempts to find the build directions that might produce higher accuracy and, finally, address the issue of feature size's influence on the accuracy.

2. Benchmark design

As can be seen from Figure 2, the benchmark represents a collection of simple geometrical features positioned on the surface of a base plate. These types of features are representative of the most relevant objects produced by RP processes. The geometrical features are aligned with either X or Y axis of the SLA machine to evaluate the accuracy along those axes. In addition, the sizes and locations of all features are designed to be accessible to a digital calliper's jaws. The number and types of controlled elements are as follows: linear lengths (49), diameters of holes (9) and diameters of cylinders (3).

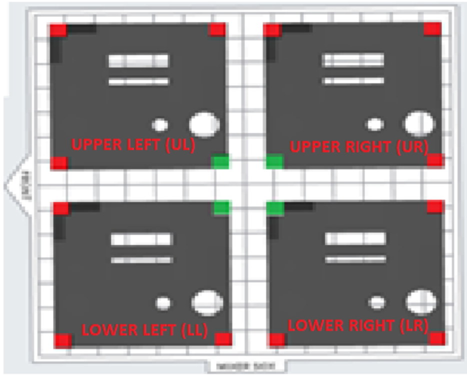
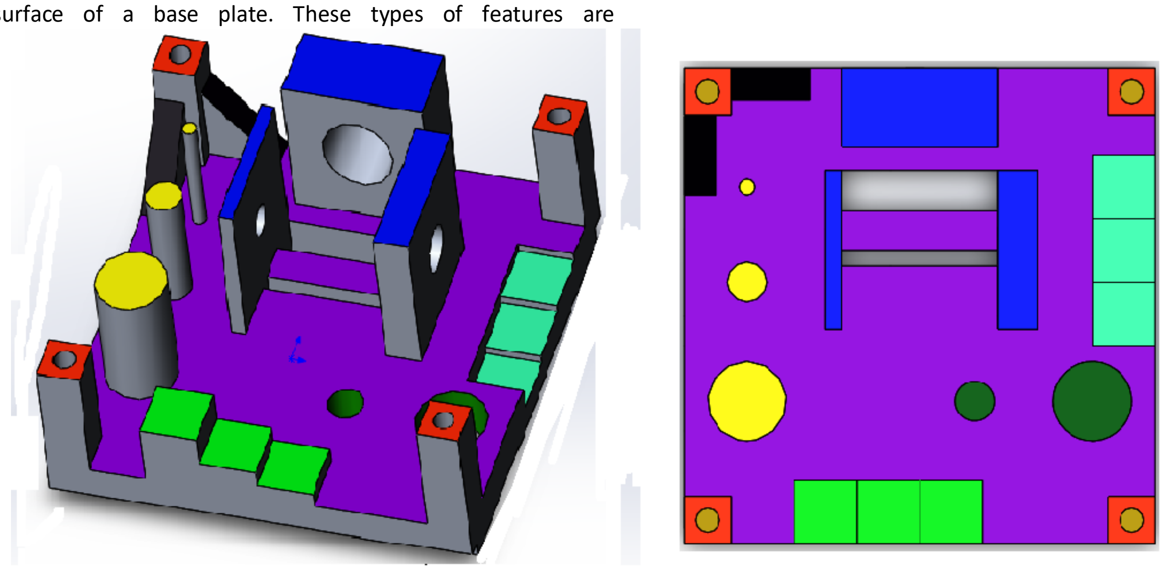


Figure 1. Benchmark's location and orientation on the build plate.



-60*60mm base; -rectangular bosses, 2*20, 5*20, 10*20mm with equal heights (H) of 19mm, each boss has an horizontal hole with d = 4, 6 and 10mm respectively; -cylindrical bosses with d = 2, 5 and 10mm of H = 15mm; -6*6mm four rectangular bosses with equal H = 15mm; -cylindrical holes with d = 5 and 10mm; -three positive stairs with 8*8mm and H = 2, 4 and 8mm; -three negative stairs with 8*8mm and H=1mm each; -two ramps of 45^0; -d=3mm blind holes with a depth of 7mm each; -two rectangular slots, 2*20 and 5*20mm

Figure 2. CAD model of the benchmark showing top view (right) and oblique view (left).

3. Experimental details

This section describes experimental procedures and methodology pertained to three main aspects of the study. Namely, the effects of part's position, orientation, and size on the accuracy.

3.1 The effect of part's position on the build platform

To identify the effect of part's position on the build plate using ANOVA (Analysis of Variance), the sixteen benchmark samples have been printed with 4 of 16 parts at each corner of the built platform as shown in Figure 1. Individual samples were labelled as Lower Left (LL1), Lower Right (LR1), Upper Left (UL1) or Upper Right (UR1). The number after two capital letters corresponds to an order the sample was printed within its group. For example, if the LL1 was printed first among LL group, an LL4 was printed last.

General purpose resin from Formlabs was used. The layer thickness was 0.1 mm, and all samples were printed one at a time with minimum support structures. After printing process, the samples were washed in Isopropyl alcohol for ten minutes and cured by the exposure to sunlight for eight hours. The measurements were performed using a digital calliper with resolution = 0.01 mm, accuracy = 0.02 mm, and repeatability = 0.01 mm.

The confidence level α for One-Way ANOVA test was taken as 0.05. The Null hypothesis states that the mean values of absolute average deviations between groups of LL, LR, UL and UR are equal. In other words, if we assume that the absolute average deviation values of four benchmarks printed on lower left corner of the build platform are labelled as LL1….LL4, the Null hypothesis is accepted if the total variance within the group LL is equal to the total variance between the rest of the groups (LR, UL and UR). The average deviation values in the test were taken as absolute i.e., the negative values corresponding to undersized features were treated as positive.

The measured dimensions for which the deviation values have been recorded are listed in table 2.

To find the difference in accuracies between features printed close to the center and those on the periphery, the identical features have been chosen for the comparison as shown in Figure 1.

The features in Figure 1 are 6×6×15 mm (L×W×H) rectangular bosses located at four corners of the benchmark. In total, the average of deviations in heights (15 mm) of 48 periphery red bosses, representing 16 samples, were compared to corresponding 16 central green bosses' average deviation values.

3.2 Effect of build direction on the accuracy

For this type of study, certain features of the benchmark have been chosen for comparison purpose as highlighted in Figure 3.

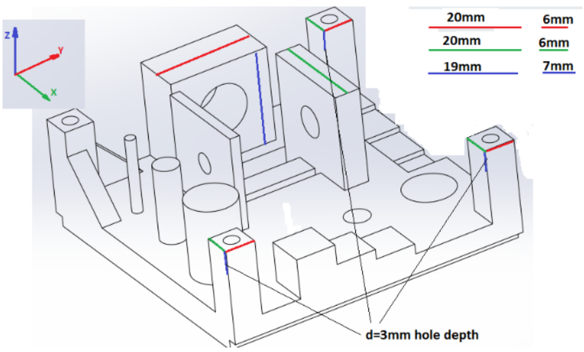


Figure 3. The dimensions of selected features for comparison (shown as red, green, and blue)

The values to be compared are chosen to be deviations of dimensions along XYZ axes corresponding to features indicated as red, green, and blue in Figure 3. In other words, the deviation values of dimensions that are similar in colour were compared to those of different colour. The main requirement for the features subject to comparison is the size compatibility. In addition, it was decided to not include features with dimensions over 20 mm for comparison as the maximum height of the features in Z build direction is 19 mm.

3.3 Effect of Feature's size on accuracy

In order to make comparison among features of varying sizes, it was necessary to divide features subject to analysis according to their sizes. For this purpose, table 1 was prepared that shows the classification of features for the analysis. It should be noted that the classification was according to the Standard tolerance grades gradation of sizes. The measured values are the linear dimensions along XYZ axes. The share of measured features along XYZ axes are almost equal.

Table 1. Features classified according to their sizes.

Feature type	Size range, mm	Number of measured values
Small	≤6	17(×16)
Medium	6<…<18	13(×16)
Large	>18	9(×16)

4. Results and discussion

The P values for One-Way ANOVA test have been found and listed in table 2.

Table 2. P values found for all measured deviations.

Measured dimensions	P value
Linear length of features measured along X axis (17*)	0.027
Linear length of features measured along Y axis (14)	0.025
Linear length of features measured along Z axis (20)	0.817
Diameters of holes and cylinders (12)	0.468

* - the numbers in brackets correspond to a number of measured values for one benchmark

As can be seen from table 2, a half of P values favour the alternative hypothesis. Therefore, dimensional comparison supports the notion that the position of the part on the build platform does influence the accuracy.

There are numerous explanations that have been reported by others regarding how the position might affect the accuracy. They include the localized wear of silicon layer that covers the resin tank, angulation of the laser beam, material properties and even position with regards to the wiper location. As for the following research, it is difficult to draw any solid conclusion on the source of the errors and it is beyond the scope of the study. Another important observation was noticed when comparing accuracies of identical features such as four 6×6 mm rectangular bosses located at corners of the benchmarks (see Figure 1). The differences among deviations in Z axis corresponding to features printed close to the center and peripheries were very small. For instance, it was found that the absolute average deviation values in heights of 6×6 mm rectangular bosses were 60 μm for features located close to the center and 70 μm for those in periphery. Thus, the findings support the view that the features printed at the periphery are not inferior to ones printed at the center with respect to accuracy.

As far as the build orientation is concerned, the boxplot in Figure 4 clearly shows the presence of its influence on the accuracy. According to the results of the comparison, the least accurate build orientation appears to be along Z axis. As for the remaining two axes, the highest accuracy was achieved in Y axis direction. Another significant observation to notice from Figure 4 is the ratio between oversized and undersized values. For instance, in the case of Y build direction, there is an almost equal share between oversized and undersized values. If we look at the remaining axes, Z build direction values are nearly all undersized. As for X axis, approximately 2/3 of the data is undersized. Two main causes can explain the prevalence of undersized features. One is the effect of shrinkage due to polymer cure. The other cause is the vertical pressure exerted from the build plate on the resin layer surface during laser scanning. Especially it is true for the parts printed flat on the platform[6]. Due to absence of supports, the pressure exerted from the build plate is applied directly to first polymer layers on the flat bottom of the part. As for the accuracy for X axis direction, it is interesting to observe that the movement of the resin tank occurs in X axis. As was indicated by Alexey et al [6], a "peel-force" might be a cause of discrepancies for those objects lined up in the direction of the tank movement.

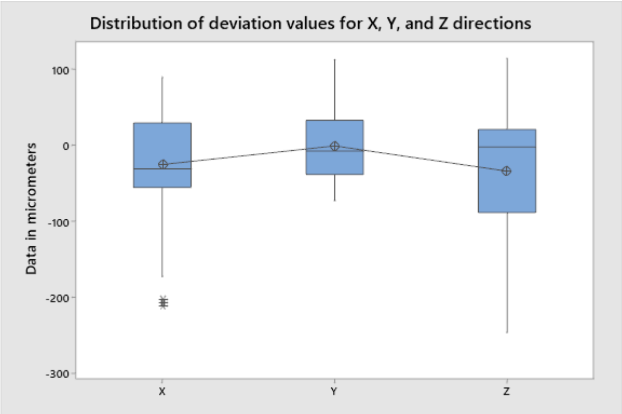


Figure 4. The boxplot of compared data.

A general trend observed in the size/accuracy analysis is the increase of errors with sizes of the features and it can be seen from the boxplot in Figure 5 and a graph in Figure 6. Important to note that the largest deviations were observed in features such as negative stair lengths, slots, and overall length of 60 mm base. Those highest deviations are shown as stars in Figure 6. According to the research conducted by Islam et al [5] in 2016, the volumetric shrinkage of parts is the main reason that explains the trend in Figure 6, where it is obvious that with the size increase the errors become more negative.

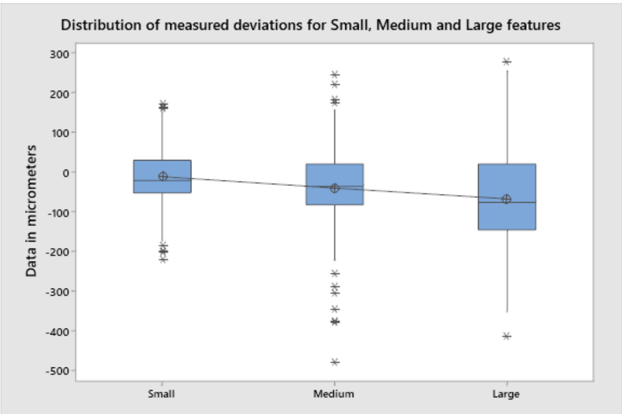


Figure 5. Measured deviation values for feature size effect analysis.

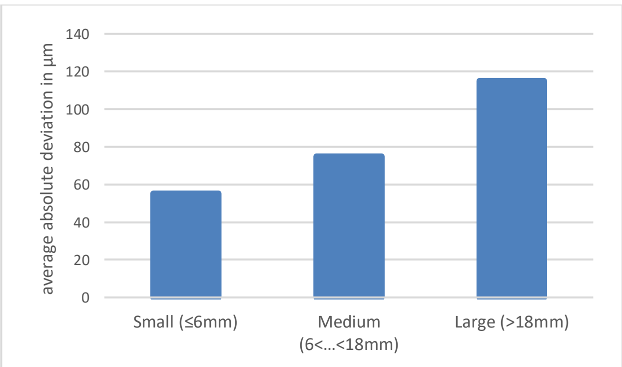


Figure 6. Comparison between absolute average deviation values for features of varied sizes.

5. Conclusion

This study has analyzed dimensional properties of a part manufactured using desktop SLA 3D printer. By measuring the dimensional accuracy of the designed benchmark, the obtained data has helped to identify important parameters affecting the accuracy of printed samples. The preliminary findings show that part's position on the build platform has an influence on the dimensional accuracy of features. P values identified for sizes along X and Y axes are 0.027 and 0.025 respectively, whereas differences between features in Z build direction have not been noticed. In addition, the research revealed that the orientation of the features along X, Y or Z direction affects the accuracy. The features of similar sizes aligned in three different axes showed the next range of deviations. For X axis {-210, 90} in µm, Y axis {-70, 110}, and Z axis {110, -250}. Therefore, features' sizes along Y axes seems to be the most accurate while Z axis build direction was prone to show the highest values of error. Finally, it was found that the accuracy of the manufactured part might be high or low depending on its size.

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