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Influence of STL File Quality and Printing Parameters on Accuracy of Tolerance for 3D Printed Hole and Shaft Assemblies

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Abstract — **Fused Deposition Modeling (FDM) is one of the most widely used additive manufacturing techniques due to its affordability and flexibility. However, dimensional accuracy remains a major challenge, particularly for tolerance based assemblies such as hole and shaft assemblies. Previous studies have focused on process parameters such as layer height and infill density [1], [2]. There is inadequate emphasis on the quality of the STL file, particularly its normal deviation. The STL file makes use of triangular shapes known as meshing that produce curved surfaces [3], and an increase in the value of normal deviation alters the geometries' post printing process. This paper explores the effects of STL file quality and the changes in layer thickness, dimensions, and infill percentage on the 3D printed cylindrical hole and shaft.**

Keywords - Fused deposition modeling; standard Tessellation language; additive manufacturing; dimensional accuracy; tolerance; Slicing.

I. INTRODUCTION

Additive Manufacturing is an advanced manufacturing technique that is capable of creating intricate shapes directly through the process of digital fabrication without using traditional methods of shaping materials. Among the various AM techniques, fused deposition modeling (FDM) has gained widespread adoption in academic research, prototyping, and industrial applications due to its low cost, accessibility, and material flexibility [4]. However, despite all the above strengths, accuracy in dimensions remains the biggest challenge in FDM construction. This problem is very evident when working with functional assemblies like hole-and-shaft assemblies. Inaccuracies in dimensions may result in a poor fit or assembly failure. Existing research has focused mainly on optimizing the process parameters, such as layer height, infill density, and printing speed, to improve accuracy [1], [2], [21], [22]. Though these parameters affect the physical deposition process, they do not take into account the geometric errors that are introduced while preparing the digital model. The STL file acts as an intermediary between the CAD file and the slicing software. The STL files generate curved surfaces by using triangles [3]. The fidelity of this approximation is governed by tessellation parameters such as normal deviation. As shown in (Fig.1.) and (Fig.2.), higher values of normal deviation will lead to a coarser surface representation in the resulting mesh, which may cause dimensional errors even before printing. Consequently, the need to appreciate the relationship between the quality of an STL file and conventional process variables is paramount.

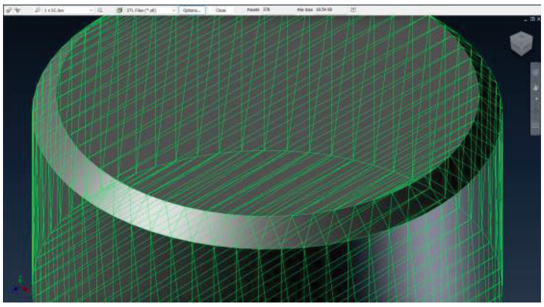

Fig. 1. Meshing surface of low quality STL file

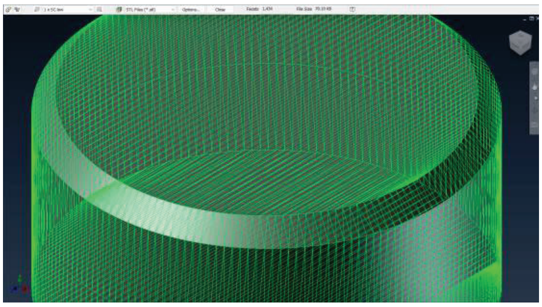

Fig. 2. Meshing surface of high quality STL file

II. BACKGROUND

A. Additive Manufacturing

Additive Manufacturing (AM) is a modern manufacturing process in which components are printed layer-by-layer using G-code of sliced 3D model [10], [22], [11]. Unlike traditional subtractive manufacturing processes, additive manufacturing creates parts by adding material only where needed, leading to reduced material waste and the creation of intricate shapes. [12], [14]. AM systems have found numerous applications in aerospace, automobile, biomedical, education, and industry sectors owing to their capacity to manufacture geometrically complicated and customized products. [15].

Various AM technologies include:

- Fused Deposition Modelling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Digital Light Processing (DLP)

B. Fused Deposition Modelling (FDM)

The fused deposition modelling is an additive manufacturing technique involving material extrusion. In this process, a thermoplastic filament is heated and fed from the nozzle, forming layers. [4], [10]. The filament is fed into the extrusion system where it is then melted before being deposited. [11].

The filament is fed into the extrusion system where it is then melted before being deposited. When deposited, the filament cools down and solidifies, forming the final structure. [12]. The whole process continues till the complete component is formed. This method has gained wide adoption because of its simplicity and ease of use. [15].

Common materials used in FDM include:

- PLA
- PLA+
- ABS
- PETG
- TPU

C. 3D Modelling

The creation of digital three-dimensional objects via computer software such as Computer Aided Design (CAD) is called 3D modeling [13]. In the case of additive manufacturing, the CAD model becomes the basis for all the rest of the manufacturing process [10]. Geometrical properties, tolerance levels, dimensions, and assembly requirements are defined at this stage [11].

D. STL File Generation and Tessellation

After completion of 3D modelling, CAD geometries are exported into STL format for slicing operations [3]. STL (Standard Tessellation Language) files represent surfaces using interconnected triangular facets [5]. Curved geometries such as cylinders are approximated using polygonal tessellation during STL conversion [19].

Lower normal deviation values produce finer mesh representations, while higher values create coarse geometry that may affect dimensional accuracy.

E. Slicing Process

The slicing process is responsible for transforming the STL geometry into G-code instructions that machines can read. This process involves partitioning the model along the z-axis. In this study, Ultimaker Cura is used for slicing operations.

Important slicing parameters include:

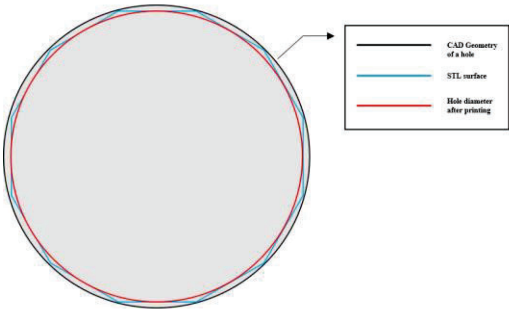

Fig. 3. Dimensional changes between CAD geometry and printed geometry.

- Layer height
- Infill density
- Printing speed
- Nozzle temperature
- Bed temperature
- Wall line count
- Infill pattern (Gyroid)

F. Dimensional Accuracy and Hole and Shaft Fit

Dimensional accuracy is the degree of similarity between printed dimensions and CAD dimensions. Hole-and-shaft systems require precise dimensional control for proper fit conditions such as:

- Clearance fit
- Transition fit
- Interference fit

In FDM printing, dimensions may vary from both CAD geometry and physical deposition behavior.

III. RELATED WORK

Dimensional accuracy represents one of the key issues in Fused Deposition Modelling (FDM) and especially for complex assemblies like hole and shaft system. Popescu et al. [1] ound out that smaller layer heights contribute to increase the cylindrical features' dimensional accuracy and uniformity. Many scientists have described problems of dimensional deviation related to additive manufacturing process. Dimensional tolerance variation in additive manufacturing systems was emphasized by Lieneke et al. [2], while the significant influence of the stepping of stairs on the accuracy of curved geometries like holes and shafts was proven by Budinoff and McMains [9]. Moreover, Ahn et al. [20] stated that higher layer height causes surface finish deterioration and geometry inaccuracy.

Preparation of digital geometry represents another problem area related to dimensional inaccuracy. According to Gokhare et al. [3], STL format converts CAD models into triangular mesh geometry necessary for the additive manufacturing processes. The importance of sufficient mesh resolution during STL file generation to avoid geometrical errors after printing was underlined by Marbun et al. [5]. Furthermore, according to Shahrubudin et al. [4], additive manufacturing systems use digital models to fabricate the part, hence geometric deviations in STL geometry will be replicated after printing.

The basics of additive manufacturing and its industrial applications were comprehensively analyzed by Gibson et al. [10], Chua and Leong [11], and Gebhardt and Hötter [12].

IV. Influence of STL Conversion

The tessellation of a CAD model into an STL file is an essential step in the additive manufacturing process which influences the final geometry of fabricated parts. The STL representation approximates smooth CAD surfaces by forming a set of triangles, forming a polygon mesh used for printing [3], [5]. Tessellation quality depends on parameters such as normal deviation and chord height.

Small normal deviation results in good geometric precision in the tessellation since a finer representation is generated while large normal deviations lead to course geometry which may result in poor precision [3]. Any approximation introduced during the tessellation process will be propagated into the final part when slicing software form toolpaths based on STL geometry [5].

Tessellation quality is even more important for geometries with cylindrical elements like holes and shafts since coarse tessellation may deform circular cross-sections resulting in dimensional and form errors [4], [9]. Such geometric errors will be transferred to the physical parts when printing FDM components [10].

V. Methodology

Samples of cylindrical hole and shaft were exported at 10 and 30percent normally distributed. Samples were printed using PLA+ material with an Ender 3 3D printer with 0° orientation to avoid any orientation effect. The layer heights used were 0.12 mm and 0.2 mm, while the infill densities were 3 to 80percent (based on the size of various samples). Thus, there were a total of 36 samples with 72 prints. Each configuration has one hole (H) and one shaft (S).

A. Slicing Parameters

Slicing parameters play an important role in determining the dimensional accuracy, surface quality, and mechanical behavior of FDM printed components [1], [6]. In this study, Ultimaker Cura slicing software was used to generate the G-code for printing. The primary slicing parameters considered were layer height and infill density, 2layer heights, 0.2 mm and 0.12 mm. For printing 36 parts “18 Holes and 18 Shafts”, set up the printer with the calibration of 0.2 mm and for another 36 parts with 0.12 mm all over the build area of the printer. After this, set the other parameters in the slicing software according to the part size and set the infill density according to the hollow spaces under the wall of the geometry. Usually smaller part prints with higher density and bigger part prints with lower density, also setting the speed according to the size of the part, smaller parts with a low speed and bigger parts with a high speed. Common slicing parameters were “wall line count” of 2, “infill pattern” was gyroid, “support overhang angle” was 50° to eliminate the support below fillets of holes and shafts.

B. Specimen Geometry

TABLE I
Dimensions of Hole and Shaft Assemblies

Scale	**Hole Dimensions**	**Shaft Dimensions**
Small (A)	Outer Diameter (D_a) = 15 mm Length (L_a) = 10 mm Inner Diameter (d_a) = 5 mm	Diameter (S_a) = 5 mm Length (l_a) = 20 mm
Medium (B)	Outer Diameter (D_b) = 30 mm Length (L_b) = 20 mm Inner Diameter (d_b) = 20 mm	Diameter (S_b) = 20 mm Length (l_b) = 30 mm
Large (C)	Outer Diameter (D_c) = 50 mm Length (L_c) = 20 mm Inner Diameter (d_c) = 40 mm	Diameter (S_c) = 40 mm Length (l_c) = 30 mm

The aim of printing three different sizes is to approximate the perfect fit and tolerance variation across a range of hole and shaft diameters printed with the Ender 3. These results will be used for predicting accurate tolerances before printing hole and shaft assemblies within similar diameter ranges using the same printer, material, and process conditions. All parts will be printed using Numaker’s PLA+ filament on an “Ender 3” FDM 3D Printer under constant thermal conditions:

Nozzle temperature: 220°C
Bed temperature: 55°C

C. Measured Fit Tolerance

Print the Experimental Configuration: All holes and shafts are printed according to the selected experimental parameters. After Printing, the printed parts are cleaned and prepared for dimensional measurement.

Measure Printed Dimensions: The dimensions of both mating parts are measured using a digital vernier caliper having 0.01 mm precision. Measured values:

- Measured diameter of Hole
- Measured diameter of Shaft

Calculate Dimensional Deviation: The dimensional deviation of both parts is calculated by comparing the measured diameter of hole and shaft with the original CAD dimensions.

$$\text{Dev. of H} = \text{measured dia. of H} - \text{CAD dia. of H} \quad (1)$$

$$\text{Dev. of S} = \text{measured dia. of S} - \text{CAD dia. of S} \quad (2)$$

Apply Sign Convention: A sign convention is used to identify looseness and tightness behavior.

- Taking positive value for Looseness / clearance tendency
- Taking negative value for Tightness / interference tendency

Calculate Measured Fit Tolerance: The measured fit tolerance is obtained by adding the deviation values of the mating hole and shaft.

$$\text{Measured Fit Tol.} = \text{Dev. of H} + \text{Dev. of S} \quad (3)$$

This value represents a fit obtained after printing experimental configuration under specific experimental parameters.

TABLE II
CONFIGURATION MATRIX FOR LAYER HEIGHT = 0.2 MM

Cfg.	Size	STL	Infill H/S (%)	Printing Speed H/S (mm/s)
1	A	Low	20	80/50
2	A	Low	50	80/50
3	A	Low	80	80/50
4	A	High	20	80/50
5	A	High	50	80/50
6	A	High	80	80/50
7	B	Low	5	100
8	B	Low	15	100
9	B	Low	40	100
10	B	High	5	100
11	B	High	15	100
12	B	High	40	100
13	C	Low	3	125
14	C	Low	10/8	125
15	C	Low	30/20	125
16	C	High	3	125
17	C	High	10/8	125
18	C	High	30/20	125

TABLE III
CONFIGURATION MATRIX FOR LAYER HEIGHT = 0.12 MM, H-HOLE, S-SHAFT

Cfg	Size	STL	Infill H/S (%)	Printing Speed H/S (mm/s)
19	A	Low	20	80/50
20	A	Low	50	80/50
21	A	Low	80	80/50
22	A	High	20	80/50
23	A	High	50	80/50
24	A	High	80	80/50
25	B	Low	5	125
26	B	Low	15	125
27	B	Low	40	125
28	B	High	5	125
29	B	High	15	125
30	B	High	40	125
31	C	Low	3	125
32	C	Low	8	125
33	C	Low	20	125
34	C	High	3	125
35	C	High	8	125
36	C	High	20	125

VI. RESULTS AND DISCUSSION

The measured values of hole diameter and shaft diameter will be compared with the CAD diameter to determine the accurate tolerance. The final fit condition between mating hole and shaft assemblies will then be classified as clearance fit, transition fit, or interference fit.

A. Actual Fit Tolerance

After obtaining the measured fit tolerance, the required CAD tolerance for any Hole and Shaft assembly can be calculated. To achieve a desired fit condition, an additional tolerance value approximately within (±0.1 mm to ±0.5 mm) is applied to the CAD geometry before exporting the STL file. Note: This tolerance is applied either to the hole or to the shaft only.

Actual Fit Conversions:

- **If Measured Fit is Clearance Fit then,** To obtain Actual Transition Fit Tolerance, add a negative tolerance in Measured Clearance Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} - 0.2\ \text{mm} = \text{Actual Fit Tol.} \tag{4}$$

  Or to obtain Actual Interference Fit Tolerance, add a larger negative tolerance in Measured Clearance Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} - 0.5\ \text{mm} = \text{Actual Fit Tol.} \tag{5}$$

- **If Measured Fit is Transition Fit then,** To obtain Actual Clearance Fit Tolerance, add a positive tolerance in Measured Transition Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} + 0.2\ \text{mm} = \text{Actual Fit Tol.} \tag{6}$$

  Or to obtain Actual Interference Fit Tolerance, add a negative tolerance in Measured Transition Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} - 0.2\ \text{mm} = \text{Actual Fit Tol.} \tag{7}$$

- **If Measured Fit is Interference Fit then,** To obtain Actual Transition Fit Tolerance, add a positive tolerance in Measured Interference Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} + 0.2\ \text{mm} = \text{Actual Fit Tol.} \tag{8}$$

  Or, to obtain Actual Clearance Fit Tolerance, add a larger positive tolerance in Measured Interference Fit Tolerance. For example,

  $$\text{Measured Fit Tol.} + 0.5\ \text{mm} = \text{Actual Fit Tol.} \tag{9}$$

The values: ±0.2 mm, ±0.5 mm are for example only. The actual tolerance adjustment may vary depending on other process conditions.

VII. CONCLUSION

In this research, an analytical approach has been developed for investigating the effects of STL file quality and slicing parameter settings on the dimensional accuracy and fit type of FDM manufactured hole and shaft assemblies. This study investigates the joint effects of STL quality, layer height, infill percentage, and dimensional scale using the “Ender 3” FDM 3D printer and PLA+ material.

The experimental approach proposed in this study offers a practical way to assess dimensional deviation and predict fit type in given range of parameters for any hole and shaft assemblies. By assessing the dimensions of the fabricated hole and shaft and estimating the deviation from CAD geometry,