Design verification through tolerance stack up analysis of mechanical assembly for 3d printed components

R Jafirn Beryl¹, A N Saravanan², Annamalai K³ and K Janardhan Reddy⁴

¹,² PG student, School of Mechanical Engineering, VIT University, Chennai, India. ³,⁴ Professor, School of Mechanical Engineering, VIT University, Chennai, India.

E-mail: ¹jafrinberyl.r2020@vitstudent.ac.in, ²saravanan.an2020@vitstudent.ac.in, ³kannamalai@vit.ac.in and ⁴kjanardhanreddy@vit.ac.in

Abstract. Automobile sector encounters new challenges and hurdles every day. New design trends and day-by-day technology advancement from research, push companies to develop new competitive models. Automobile manufacturing is one of the most competitive business domains where every organization will strive to prove themselves in the society and market. In order to increase the production rate of the company, automobile manufactures can increase the efficiency of their research and development process enabling them to get their product in the market with less time and better quality. Additive manufacturing is being used in the prototyping, tool and dies making process due to less time, labour efforts and cost. But the hurdles faced by company in additive manufacturing are poor dimensional accuracies and tolerances. Automotive industries find difficult to get their exact dimensional tolerance values resulting in failure of the component. In this paper authors demonstrated tolerances stack-up analysis through a case study of critical 3D printed components and its assembly used in automobile. This paper provides a review of role and future scope of additive manufacturing in automobile industries.

1. Introduction

Design verification is an essential step in the development of any product, it makes sure that the final product designed matches the intended product, but many design projects do not complete thorough design qualification resulting in products that do not satisfy customer expectations and then requires a very expensive design modification.

Tolerance Stack-Ups plays a vital role in addressing mechanical fit and performance requirements. Fit(mechanical) simply answers the question, “Do the parts that make up the assembly always go together?” Mechanical performance requirements would include the performance of mechanisms, like latches and actuators. Some other performance requirements are accurate optical alignments and efficiency (of drives).

Additive manufacturing (AM) is a technique of mixing materials by either fusion, binding, or solidifying materials such as liquid resin and powders. It fabricates in a layer-by-layer manner using 3D Cad modelling. The terms such as 3D printing (3DP), direct digital manufacturing (DDM), rapid prototyping (RP), and rapid manufacturing (RM) can be used to describe this process.
Additive manufacturing processes prints components using STL (Standard Tessellation Language) files, which contain information pertaining to the geometry of the object. This manufacturing technique is very useful production volumes is low, presence of high design entanglement, and recurrent design changes are required. This technique helps to fabricate complex parts which will solve the shortcomings of design constraints of conventional manufacturing methods. This manufacturing technique has many gains, but its applications are still narrow because of its poor accuracy and long print times compared to CNC machines. But it does not have the same limitation as CNC machining because it separates the part in cross sections with a resolution equal to that of the process. Nevertheless, the shortcomings such as accuracy and build time can be improved by engaging suitable part orientation. Optimized part orientation can improve the accuracy and the building time and support volume, which in turn reduces the part production cost.

Furthermore, Additive manufacturing consists of additional controllable process parameters and higher active interaction between the material properties and process parameters. There are different kinds of Additive manufacturing processes depending on the material preparation, material type, phase change phenomenon, layer generation technique and application.

In this paper author attempt to do tolerance stack up analysis for 3D printed components and its assembly. Two approaches have been used viz: Worst case (WC) and Root Sum Square (RSS). As a case study, front wheel assembly of an All-terrain vehicle (ATV) has been designed in SOLIDWORKS 2018 and the prototype has been fabricated using Dreamer NX flash forge machine and the tolerance stack analysis were carried out and design verification done for dimensional accuracy.

Based on the result obtained, design modification is recommended to statically distribute appropriate tolerance to fulfil the functionality of the individual components and the whole assembly at product level.

2. Literature review

He and Gibson (1992) [1] developed a computerized trace method which determines the relationship between geometrical tolerances and manufacturing dimensions and tolerances.

Ngoi (1997) [2] presented a refined method by deploying the ‘Quickie’ technique for tolerance stack up analysis for geometrical tolerances.

Ngoi, B.K.A., (1999) [3] also presented a straightforward graphical approach known as the “Catena” method for tolerance stack up, involving geometric characteristics in form control – flatness, straightness, circularity and cylindricity.

Ngoi, B.K.A., (2010) [4] discussed the stack up of geometrical tolerances using generic capsule method.

Mansuy (2011) [5] presented a method that helps to solve problems for the case of serial assembly (stacking) without any clearances. This is based on the utilization of influence coefficients to get the relationship between the functional tolerance and the tolerances associated with the geometry of the mechanism’s interface surfaces.

Chetan H (2013) [6], in their research., their aim was to redesign an existing passenger car side door latch to improve the manufacturability using Design for Manufacture (DFM). Tolerance stack up analysis was used to find the clearance or interference between two features on a part and their assembly variation.

A.K Sahani (2014) [7], in their research, aimed towards the systematic solution of tolerance stack up problem involving geometric characteristics. In their work, angularity tolerance has been considered for illustration of the methodology. Two approaches viz. Worst Case (WC) and Root Sum Square (RSS) had been used. An example of dovetail mounting mechanism was taken for purpose of stack up of angularity.

Ahmed Jawad Qureshi (2018) [8] a new geometric deviation modelling is presented based on analytical modelling of the process and specifying its effects on GD&T features. The geometric deviation and compensation model based on the new methodology is being developed to quantify and removes the geometric form and shape error as much as possible.
3. Methodology

3.1. 3D Modelling of Main Assembly

A case study of front wheel assembly as shown in figure 1 of an All-terrain vehicle (ATV) has been taken for stack up analysis. This assembly consists of components like knuckle, disc, hub (rotor), M6 bolt, bearings and circlip. The individual parts of the knuckle assembly are created using Solidworks and its assembly is shown in figure 2.

![Figure 1. Arrangement of the knuckle in all-terrain vehicle.](image1)

![Figure 2. Knuckle assembly.](image2)

Dimensional details and tolerance information for each subassembly is given in the table 1. There are four subassemblies are considered for the tolerance stack-up analysis viz: rotor and bolt, knuckle and bearing, rotor and bearing and disc and bolt.

| Table 1. Dimensions and Tolerances for Subassemblies |
|------------------------------------------------------|
| **(a) Rotor and Bolt**                                   |
| Tolerance (mm) | Basic Dimension (mm) | Rotor (mm) | Bolt (mm) | Tolerance (mm) | Limits (mm) | Fit | Clearance (mm) |
|----------------|----------------------|------------|-----------|----------------|-------------|-----|----------------|
| 0.5            | 6                    | 6.5<sup>a</sup> | M6        | 0.25           | 6.25<sup>a</sup> | Clearance fit | 0.75         |
| 0.5            | 6                    | 5.5<sup>b</sup> | M6        | -0.25          | 5.75<sup>b</sup> |                 |               |

<sup>a</sup> Upper limit, <sup>b</sup> Lower limit
(b) Knuckle and Bearing

| Tolerance (mm) | Basic Dimension (mm) | Knuckle (mm) | Bearing (mm) | Tolerance (mm) | Limits (mm) | Fit | Clearance (mm) |
|----------------|----------------------|-------------|--------------|----------------|-------------|-----|----------------|
| 0.5            | 25                   | 25.5\textsuperscript{a} | 25           | 0              | 25\textsuperscript{b} | Transition fit | 0.62 |
| 0.5            | 25                   | 24.5\textsuperscript{b} | 25           | -0.12          | 24.88\textsuperscript{b} |                |      |

(c) Rotor and Bearing

| Tolerance (mm) | Basic Dimension (mm) | Rotor (mm) | Bearing (mm) | Tolerance (mm) | Limits (mm) | Fit | Clearance (mm) |
|----------------|----------------------|------------|--------------|----------------|-------------|-----|----------------|
| 0.5            | 47                   | 47.5\textsuperscript{a} | 47           | 0              | 47\textsuperscript{a} | Transition fit | 0.62 |
| 0.5            | 47                   | 46.5\textsuperscript{b} | 47           | -0.12          | 46.88\textsuperscript{b} |                |      |

(d) Disc and Bolt

| Tolerance (mm) | Basic Dimension (mm) | Disc (mm) | Bolt (mm) | Tolerance (mm) | Limits (mm) | Fit | Clearance (mm) |
|----------------|----------------------|----------|----------|----------------|-------------|-----|----------------|
| 0.5            | 6                    | 6.5\textsuperscript{a} | M6       | 0.25           | 6.25\textsuperscript{a} | Clearance fit | 0.75 |
| 0.5            | 6                    | 5.5\textsuperscript{b} | M6       | -0.25          | 5.75\textsuperscript{b} |                |      |

\textsuperscript{a} Upper limit
\textsuperscript{b} Lower limit

3.2. Positional tolerance.

It is required to estimate the position tolerance for each assembly feature for implement the tolerance stack analysis. In this case study positional tolerance for main and subassembly feature are calculated and given in the table 2,3 and 4

Table 2. Positional tolerance for disc bolt and rotor.

| Bolt outer diameter (mm) | Tolerance type | Tolerance (mm) | Positional tolerance (mm) | Rotor inner diameter (mm) |
|--------------------------|----------------|----------------|----------------------------|---------------------------|
| 5.99                     | Fixed          | 0.498          | 3.302                      | 9.296                     |
Table 3. Positional tolerance for rotor and bearings.

| Bearing outer diameter (mm) | Clearance (mm) | Rotor inner diameter (mm) |
|---------------------------|----------------|--------------------------|
| 47                        | 3.302          | 50.3174                  |

Table 4. Positional tolerance for bearing and shaft

| Shaft outer diameter (mm) | Clearance (mm) | Bearing inner diameter (mm) |
|---------------------------|----------------|-----------------------------|
| 25                        | 3.302          | 28.321                      |

3.3. Assembly shift

The main reason for finding the assembly shift is to avoid the linear movement of the component and allowing the rotational movement the component.

3.3.1. Assembly shift between Rotor (hole) and Bearing (shaft).

In this assembly, there are pairs of hole and shaft. The main function of this assembly is to provide rotational movement instead of linear movement in order to arrest linear movement. Assembly shift is calculated as follows

\[
\text{Hole} = 47 \text{mm (maximum = 47.5mm)} \\
\text{Bearings} = 47 \text{mm} \\
\text{Clearance} = \text{Hole value} - \text{Shaft value} \\
\text{Clearance} = 0.5 \text{mm} \\
\text{Both sides} = 0.5/2 = 0.25 \text{mm}
\]

In this assembly we have two bearings, so 0.25x2 = 0.5mm is the clearance value provided for both the bearings.

3.3.2. Assembly shift between Bearing (hole) and knuckle (shaft).

Here, the assembly shift is calculated between bearing (hole) and knuckle (shaft), where the bearing is placed over the knuckle shaft which provides rotational movement.

\[
\text{Bearings inner diameter} = 25 \text{ mm} \\
\text{Shaft diameter} = 24.5 \\
\text{Max bearings diameter} = 25 \text{mm} \\
\text{Clearance} = \text{Bearing (Hole)} - \text{Knuckle (Shaft)} \\
\text{Clearance} = 25 \text{mm}-24.5 \text{mm} = 0.5 \text{mm} \\
\text{Per axis} = 0.5/2 = 0.25 \text{mm} \\
\text{Clearance} = 0.5 \text{mm}
\]

In this assembly we have two bearings so, 0.25x2 = 0.5mm is the clearance value provided for both the bearings.
3.4. **Design of Knuckle assembly**

In the existing knuckle assembly, the knuckle is attached with two bearings and over this rotor is placed for providing rotational movement of the vehicle. During assembly due to improper tolerance valve the bearing is coming out from the knuckle and which leads to improper function of assembly.

To avoid this, design modification for the knuckle-bearing assembly is proposed as shown in figure 3, which will support the bearing and it also control the assembly.

![Knuckle and bearing misalignment](figure3.png)  
**Figure 3.** Knuckle and bearing misalignment.  

![Knuckle dimensions](figure4.png)  
**Figure 4.** Knuckle dimensions.

3.4.1. **Individual tolerance values**

Tolerance values for individual dimensions of knuckle – bearing sub assembly are calculated and shown in the table 5.

**Table 5.** Knuckle tolerance calculation

| Positive value (mm) | Negative value (mm) | Tolerance (mm) |
|---------------------|---------------------|----------------|
| ---                 | 13.02               | 0.05           |
| ---                 | 30.48               | 0.05           |
| ---                 | 30.30               | 0.01           |
| ---                 | 64.75               | 0.01           |
| 64.75               | ---                 | 0.05           |
| 40.05               | ---                 | 0.03           |
| 35.15               | ---                 | 0.05           |
| Total= 139.95       | 138.55              | 0.29           |
In order to arrest the linear movement of bearing and to provide a proper assembly, tolerance stack up analysis is carried out for the knuckle. And the knuckle dimensions are separated into positive and negative columns (Table 5).

Two points are considered in the knuckle i.e., point A and point B (Figure 4). The arrow mark pointing away from point A is considered as a negative value and the arrow mark pointing towards the point B is considered as a positive value.

Now, the difference between the positive and negative value in mm are

Positive value       = 139.95
Negative value       = 138.55
Nominal distance     = 1.4
Clearance             = +/- 0.29

From the above calculation, the maximum distance is 1.69 mm and 1.11 mm is the minimum distance. In order to arrest linear bearing movement and providing rotational movement, a component is selected based on the above-mentioned value. As it an interference fit, we are considering a constant dimension circlip as 1.2 mm thickness which will arrest the bearing linear movement and provide proper assembly.

3.4.2. Circlip thickness

In section 3.4.1 we have calculated the thickness (of circlip) for bearing assembly. The placement of circlip is also very important in order to get proper assembly. The circlip and bearing distance should be as minimum as possible. Distance $AC^*$ (Figure 5) is considered from the right end of the knuckle and the distance is calculated for the circlip to fit in the groove.

![Figure 5. Knuckle shaft dimensions with circlip groove.](image)

![Figure 6. GD&T model for knuckle shaft.](image)
WORST CASE METHOD

AC* is the distance where the circlip will be placed.
C*C is the vertical distance from the dept.
The dimensions are separated into positive and negative values. The clockwise dimensions are considered to be positive value and the anti-clockwise are considered to be negative value.
Now,
\[ AC* + C*C - CB - BA = 0 \]
\[ X + (0.5543 \pm 0.02) - (1.3 \pm 0.01) - (2.4 \pm 0.01) = 0 \]
\[ X = 3.15 \pm 0.04 \]
\[ X_{\text{MAX}} = 3.19 \]
\[ X_{\text{MIN}} = 3.11 \]

ROOT SUM SQUARE METHOD (RSS) METHOD

\[ X = 3.15 \pm \sqrt{((0.02 \times 0.02) + (0.01 \times 0.01) + (0.01 \times 0.01))} \]
\[ X = 3.15 \pm (0.024) \]
\[ X_{\text{MAX}} = 3.174 \]
\[ X_{\text{MIN}} = 3.13 \]

From calculation it can be found that 3.2mm is the distance where we need to place the circlip. Now the problem is to fit circlip in the respective depth. But as per the design one end of the circlip is placed but the other end of the circlip is not locating exactly.

3.4.3. Circlip gap
To achieve the proper assembly of circlip we have to measure the distance between AB1 and AB*. Both C1 and C* are combined together but B1 and B* are not joined there is a gap between these two points. In order to reduce the gap, we need to find the difference between AB1 and AB* which are explained geometrically in figures 7 and 8

**Figure 7. GD&T model for knuckle shaft.**

**Figure 8. GD&T model assembly.**
Let’s consider AB* as P and AB1 as Q

TO FIND P

\[ AB^* + BB^* - BA = 0 \]

WORST CASE METHOD

\[
\begin{align*}
P &+ (0.5543 \pm 0.02) - (2.4 \pm 0.01) = 0 \\
P_{\text{MAX}} &= 1.87 \\
P_{\text{MIN}} &= 1.82 \\
\end{align*}
\]

ROOT SUM SQUARE METHOD

\[
1.8457 \pm \sqrt{((0.02 \times 0.02) + (0.01 \times 0.01))} \\
1.8457 \pm 0.224 \\
P_{\text{MAX}} &= 1.87 \\
P_{\text{MIN}} &= 1.83 \\
\]

TO FIND Q

\[ AB1 + B1C1 + C1C^* + CC^* - CB - BA = 0 \]

WORST CASE METHOD

\[
\begin{align*}
Q &+ (1.2 \pm 0.01) + (0) + (0.5543 \pm 0.02) - (1.3 \pm 0.01) - (2.4 \pm 0.01) = 0 \\
Q_{\text{MAX}} &= 1.95 \pm 0.5 \\
Q_{\text{MIN}} &= 1.90 \\
\end{align*}
\]

ROOT SUM SQUARE METHOD

\[
1.95 + \sqrt{(0.01 \times 0.01) + (0.02 \times 0.02) + (0.01 \times 0.01) + (0.01 \times 0.01)} \\
1.95 \pm 0.0265 \\
Q_{\text{MAX}} &= 1.97 \\
Q_{\text{MIN}} &= 1.92 \\
\]

TO CALCULATE CLEARANCE

WORST CASE METHOD GIVES

\[
\begin{align*}
Q_{\text{MAX}} &= 2.00 \\
P_{\text{MIN}} &= 1.82 \\
\end{align*}
\]

MAX CLEARANCE

\[
R_{\text{MAX}} = Q_{\text{MAX}} - P_{\text{MIN}} \\
R_{\text{MAX}} &= 0.18 \\
\]
MIN CLEARENCE

\[ R_{\text{MIN}} = Q_{\text{MIN}} - P_{\text{MAX}} \]
\[ Q_{\text{MIN}} = 1.90 \]
\[ P_{\text{MAX}} = 1.87 \]
\[ R_{\text{MIN}} = 1.90 - 1.87 \]
\[ R_{\text{MIN}} = 0.03 \]

ROOT SUM SQUARE METHOD GIVES

MAX CLEARENCE

\[ R_{\text{MAX}} = Q_{\text{MAX}} - P_{\text{MIN}} \]
\[ Q_{\text{MAX}} = 1.97 \]
\[ P_{\text{MIN}} = 1.83 \]
\[ R_{\text{MAX}} = 0.14 \]

MIN CLEARENCE

\[ R_{\text{MIN}} = Q_{\text{MIN}} - P_{\text{MAX}} \]
\[ Q_{\text{MIN}} = 1.92 \]
\[ P_{\text{MAX}} = 1.87 \]
\[ R_{\text{MIN}} = 1.92 - 1.87 \]
\[ R_{\text{MIN}} = 0.05 \]

4. Results

Tolerance values obtained from Worst Case (WC) and Root Sum Square (RSS) approach for individual parts and their assembly are shown in table 6. The result of the stack-up analysis shows that the maximum clearance value and minimum clearance value are positive. From the calculation we got 0.05 as a clearance value and this value engages the point B1 and B* as shown in the figure 7.

Table 6 Dimensional and tolerance values

| Part Name                  | Alphabet | Maximum Value | Minimum Value | Maximum Value | Minimum Value |
|----------------------------|----------|---------------|---------------|---------------|---------------|
| Knuckle                    | X        | 3.19          | 3.11          | 3.17          | 3.13          |
| Knuckle and Circlip Assembly | Q        | 2             | 1.9           | 1.97          | 1.92          |
|                            | R        | 0.18          | 0.03          | 0.14          | 0.05          |

Design verification:

After completing the tolerance calculation, 3D printing is done using polylactic acid (PLA) material in the dreamer NX flash forge machine which is shown in the figure 9. Tolerance verification was done using SolidWorks 2016 and the complete assembly is shown in figure 10. The tolerance values shown in the result (Table 6) is applied to assemble the 3D printed component. The final assembled view of the 3D printed component is shown in the figure 11. The calculated tolerance values are used for both CAD model assembly and working of the 3D printed component assembly.
Figure 9. Dreamer NX flash forge machine.

Figure 10. Assembly after verification.

Figure 11. Assembled view of the 3D printed component.

5. Conclusions
In this paper, a graphical approach is demonstrated for tolerance stack up analysis. As a case study knuckle assembly used in All Terrain Vehicle is chosen. Dimensional details are physically measured and assembly tolerances are estimated. A graphical approach is employed to determine individual tolerance values for the all the components in the assembly and corresponding tolerance values are obtained using Worst Case (WC) analysis and Root Mean Square (RMS) values methods. The result is validated through 3D printed components fabricated using polylactic acid (PLA) material in the dreamer NX flash forge machine which shows that maximum clearance and minimum clearance value is positive as found in the graphical approach.
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