Development of sacrificial support fixture using deflection analysis

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Abstract. Sacrificial support fixtures are the structures used to hold the part during machining while rotating the part about the fourth axis of CNC machining. In Four axis CNC machining part is held in a indexer which is rotated about the fourth axis of rotation. So using traditional fixturing devices to hold the part during machining such as jigs, v blocks and clamping plates needs a several set ups, manufacturing time which increase the cost associated with it. Since the part is rotated about the axis of rotation in four axis CNC machining so using traditional fixturing devices to hold the part while machining we need to reorient the fixture each time for particular orientation of part about the axis of rotation. So our proposed methodology of fixture design eliminates the cost associate with the complicated fixture design for customized parts which in turn reduces the time of manufacturing of the fixtures. But while designing the layout of the fixtures it is found out that the machining the part using four axis CNC machining the accurate machining of the part is directly proportional to the deflection produced in a part. So to machine an accurate part the deflection produced in a part should be minimum. We assume that the deflection produced in a part is a result of the deflection produced in a sacrificial support fixture while machining. So this paper provides the study of the deflection checking in a part machined using sacrificial support fixture by using FEA analysis.

1. Introduction

The term CNC-RP is combining rapid prototyping (RP) with computer numerical control (CNC). CNC-RP is used to fabricate the low volume part in variety of materials. For CNC-RP fourth axis of rotation is provided to the part using indexer using simple 3 axis CNC machine [1]. For machining a part using CNC-RP, part need to give rotation about the axis of rotation for different orientation until all the necessary surfaces are machined [2]. Conventional fixturing methodology cannot be used for subtractive rapid prototyping (SRM). Using conventional fixturing devices such as vices, clamps and v-blocks, it is very difficult to hold the part during rotation for machining using CNC-RP so required the need to modify the fixturing system. SSF are customized fixture developed during machining of the part simultaneously along with rest of the features using CNC-RP as shown in figure 1 [2,3]. SSF are the cylindrical support structure and can be of any shape [2]. This paper outlines the deflection analysis of the sacrificial support fixture while machining intricate part using CNC-RP. The main advantage of using SSF for CNC-RP is to give support to the moderately intricate part during rapid machining, improved the accuracy of part [4], reduces machining time [5] and saves the cost of complicated fixturing. In this paper, a systematic review of literature was conducted, for deflection checking in a SSF in CNC-RP. The article is organized as follows: “evolution” of SSF for CNC-RP is explained in section 2. Section 3 explained the “methodology”. “Objective” and “FEA analysis and
simple regression analysis for total deflection checking in developed beam model” of SSF for CNC-RP is explained in section 4 and 4.3. Last section explain the “Result and conclusion” of following experimental work.

![Image of design parameters](image)

**Figure 1.** Design parameters: length, shape (circular), size, number (2:2), and location of supports [2]

2. **Evolution of SSF for fabricating intricate parts for CNC-RP**

Conventional fixturing system consist of devices such as vices, v-blocks, clams and modular plates etc. These fixturing methods required a great deal of time, money and technical skill for its making. Moreover these fixturing devices lack the flexibility to hold the intricate parts. The research work on the continuous improvement in the fixture design begins in 1994 to improve the various factors of fixturing system. Researcher works to make the machining process rapid for SRM processes. Some existing methods such as modular, phase change fixturing and dedicated are more suitable for large batches and mass production. These methods required more set up time and investment cost. The research for completely subtractive or hybrid process (additive/subtractive) RP system was done but each has had to confront the problem related to flexibility of fixture to hold the intricate part shape. Merz and Ramaswami worked on Shape deposition manufacturing (SDM) as a hybrid approach using both additive and subtractive processes [6]. They constructed a models using layer-based manner through sequential deposition and machining steps. In this technique support materials are added depending on whether or not the layer contains undercut features. Reference Free Part Encapsulation (RFPE) that uses a low melting point material to encapsulate the stock during machining is presented by [7] and Work on High-speed Rapid Prototyping (HisRP) as a process that combined high-speed machining with an RFPE process is done by [8]. Shin developed fixturing system which provides a rigid support structure for resisting cutting forces during the machining process and can accommodate any arbitrarily shaped work piece. The process introduces thermal shrink and expansion problems which limit the ability to create accurate parts. Work on application of SDTM (Seamless design-to-manufacture) technology to RP is done by [9]. This method was applied to the fabrication of marine propulsers. They used a structure support beam as a fixture to hold the propulsers during the machining process. They did not describe the analysis of the support beam and the applicability of using the approach with parts other than marine propulsers. Lennings research work deals with the development of automatic fixtures for rapid machining [Lennings (2000)]. They use software Millit and DeskProto for their research work for generating NC code from STL (stereolithography) files.

The fixturing system they developed consists of outer frame and bridges. These connect component to the frames and act as fixture during machining. Boonsuk and Frank worked on the automated fixture design system for N sided milling using rotary axis for CNC-RP [2, 10]. SSF developed by them can machine any intricate part which is accessible about the axis of rotation. The parts which are not accessible about the axis of rotation cannot be machine by this methodology. Nafis worked on the rapid Optimization of roughing operations in CNC machining for rapid manufacturing processes particularly for parts production through a SRM processes [11]. They worked for CNC-RP machining
for rapid removal rate with wide range of material with great accuracy. Their research work includes adding the benefits of additive manufacturing such as reduction in process planning effort and shape flexibility [12]. They use the visibility programme and four roughing orientation to reduce the machining time. They studied the tool contact length parameters which increase the production rate and longer cutting tool life. Nafis worked on the developing a tool to assist in executing process planning task in CNC machining for RM applications [13]. They developed a customized program for machining all kinds of parts. Their research work helps in reducing the process planning time and planning complexity is reduced. An advanced tool in computer aided manufacturing (CAM) is installed to record and generate programming code for instruction used to construct the operations. Graphical user interface (GUI) is used for modification and integration of code. Then process planning tasks is executed within the CAM system.

3. Methodology
Sacrificial support fixtures are simply extruded cylindrical rod like features created parallel to the axis of rotation of part during the machining of part along with other part features. Sacrificial support structure can be of any shape like square, elliptical, spherical but for our experimental analysis we are considering cylindrical shape sacrificial supports. The proper machining of the part in CNC-RP depends on the various parameters of the sacrificial support fixtures such as length, size (diameter), shape (cross section) and location of supports. Changing size of support affects both its length and its location on the model and vice versa. Finding the optimum solution for each design parameter is difficult since each parameter not only affects the deflection of the part but also interact with other parameters. During machining there are two types of deflection can occurs i.e. bending and torsion. Since we are using smaller support so the deflection of part while machining will be assume as a deflection of supports attached to it.

4. Objective
Deflection checking in a part using improved Beam model i.e. worst known condition by varying length of support and diameter is kept constant using FEA analysis and linear regression

4.1 Existing beam model
Earlier study has been done on the deflection checking in sacrificial support structure considering a worst case scenario assuming only one support on the ends of the part from each side [2]. According to theory of machine figure 2 (a) and (b) shown below explains the deflection of cylindrical beam due to bending and torsion. Since the part is fixed at both ends to the remaining stock material so they assume it as statically indeterminate fixed end beam model as shown in figure 3. From theory of machine maximum deflection due to bending (D_b) of a beam with fixed ends is shown by equation (1):

$$D_b = \frac{(F*L^3)}{(192*E*I)}$$

(1)

Where “F” is the cutting force, “L” is the length of support, “E” is the modulus of elasticity and “I” is moment of inertia. So it is directly shown that the deflection of beam due to bending is directly proportional to the length of the support i.e. as the length increases the deflection due to bending also increases. Now deflection due to torsion (D_t) is given below by equation (2):

$$D_t = \frac{(T*L)}{(4*J*G)}$$

(2)

Total deflection = D_b + D_t

(3)
Where “T” is the torque, “L” length of support, “J” is polar moment of inertia and “G” is shear modulus. So deflection due to torsion is also directly proportional to the length of support. Here they consider the sacrificial supports design is based on the measure deflection source i.e. torsion. Total deflection is the sum of deflection due to bending and due to torsion given by equation (3).

![Figure 2. Beam deflection due to (a) bending and (b) torsion [2].](image1)

![Figure 3. Cylindrical beam used for deflection analysis](image2)

### 4.2 Developed beam model

So here I am studying deflection checking in beam using worst known condition model i.e. using two cylindrical supports on each end of the part. There are two types of supports one is temporary and another is permanent. So we did the total deflection checking in a beam considering it is as a fixed supported beam model with two supports on each end as shown in figure 4. The diameter of the part is 50.8mm; length of cylinder is 87.88mm.

![Figure 4. Fixed beam model with two supports on each end](image3)
Figure 5. Drawing of the developed beam model

4.3 FEA Analysis and simple Regression graph for deflection checking in developed beam model

Experimental results on a total deflection analysis by varying the length of support and keeping diameter constant by taking different iteration are shown in section 4.3.1, 4.3.2, 4.3.3, 4.3.4 and 4.3.5. As the deflection is directly proportional to the length of the beam experimental result is calculated using FEA analysis by varying the length of supports and keeping radius constants by taking different iterations.

4.3.1 When length of supports is changed and diameter is kept constant. Here Diameter=2mm.

As shown in table 1 as the length of support is increases from 2mm to 30 mm keeping the radius constant i.e. 1mm correspondingly total deflection in a beam is increasing from $4.0843 \times 10^{-6}$ to 0.0028836. The minimum distance between two supports so that tools can access the proper machining between the supports is greater than or equal to 44.8mm. It is calculated by using formula given by equation (4). The graph of deflection versus L/R ratio using simple linear regression technique is shown in figure 6. Anova and simple regression model of the graph is shown in figure 7.

Minimum distance between two supports= $D_t+2*R$  \hspace{1cm} (4)

Where $D_t$ is the diameter of tool and it should be greater than or equal to the length of support.

Table 1. Total deflection result for different length and constant radius equal to 1mm.

| Length in mm | Radius in mm | $D_t+2*R$\leq 44.8mm | Total deflection |
|--------------|--------------|----------------------|-----------------|
| 2            | 1            | 4                    | $4.0843 \times 10^{-6}$ |
| 4            | 1            | 6                    | $1.32 \times 10^{-5}$ |
| 6            | 1            | 8                    | $3.33 \times 10^{-5}$ |
| 8            | 1            | 10                   | $6.92 \times 10^{-5}$ |
| 10           | 1            | 12                   | 0.00012583       |
| 12           | 1            | 14                   | 0.00020791       |
| L/R | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
|-----|----|----|----|----|----|----|----|----|
| Deflection | 0.00038437 | 0.00046824 | 0.00065591 | 0.0008883 | 0.0011704 | 0.0015061 | 0.001901 | 0.002381 |
| DEFLECTION in MM | Series1 | Linear (Series1) |

**Figure 6.** Simple linear regression graph for total deflection a beam versus L/R having r=1mm constant

| Regression Statistics |
|---|
| Multiple R | 0.930 |
| R Square | 0.884 |
| Adjusted R Square | 0.884 |
| Standard Error | 0.000 |
| Observations | 15000 |

### ANOVA

| Source | df | SS | MS | F | Significance F |
|---|---|---|---|---|---|
| Regression | 1 | 1.05E-05 | 1.05E-05 | 8.27E+01 | 5.35E-07 |
| Residual | 13 | 1.05E-05 | 1.29E-07 | | |
| Total | 14 | 1.20E-05 | | | |

**Regression equation:** \( \text{Deflection} = 1E-04/L/R - 0.0007 \)

R\(^2\) = 0.864

| Coefficients | Standard Error | t Stat | P-Value | Lower 95% | Upper 95% | Lower 99% | Upper 99% |
|---|---|---|---|---|---|---|---|
| L/R | 0.0001 | 0.0001 | 1.6305 | 0.0500 | -0.0011 | 0.0000 | -0.0001 | 0.0001 |

**Figure 7.** Anova model for Simple linear regression graph for r=1mm
4.3.2 When length of supports is changed and diameter is kept constant. Here Diameter=4mm.

As shown in table 2 as the length of support is increases from 2mm to 20 mm keeping the radius constant i.e. 2 mm correspondingly total deflection in a beam is increasing from $1.106 \times 10^{-6}$ to $6.2723 \times 10^{-5}$. The minimum distance between two supports so that tools can access the proper machining between the supports is greater than or equal to 38.8mm. The graph of deflection versus L/R ratio using simple linear regression technique is shown in figure 8. Anova and simple regression model of the graph is shown in figure 9.

**Table 2.** Total deflection result for different length and constant radius equal to 2mm.

| Length in mm | Radius in mm | Dt+2*R<=38.8mm | Total deflection |
|--------------|--------------|----------------|-----------------|
| 2            | 2            | 6              | $1.106 \times 10^{-6}$ |
| 4            | 2            | 8              | $2.1846 \times 10^{-6}$ |
| 6            | 2            | 10             | $4.0157 \times 10^{-6}$ |
| 8            | 2            | 12             | $6.8983 \times 10^{-6}$ |
| 10           | 2            | 14             | $1.1141 \times 10^{-5}$ |
| 12           | 2            | 16             | $1.7028 \times 10^{-5}$ |
| 14           | 2            | 18             | $2.4833 \times 10^{-5}$ |
| 16           | 2            | 20             | $3.4877 \times 10^{-5}$ |
| 18           | 2            | 22             | $4.7429 \times 10^{-5}$ |
| 20           | 2            | 24             | $6.2723 \times 10^{-5}$ |

![Figure 8. Simple linear regression graph for total deflection a beam versus L/R having r=2mm constant](image-url)
4.3.3 When length of supports is changed and diameter is kept constant. Here Diameter=6mm.
As shown in table 3 as the length of support is increases from 2mm to 18 mm keeping the radius constant i.e. 3 mm correspondingly total deflection in a beam is increasing from $5.8237 \times 10^{-7}$ to $1.0995 \times 10^{-5}$. The minimum distance between two supports so that tools can access the proper machining between the supports is greater than or equal to 32.8 mm. The graph of deflection versus L/R ratio using simple linear regression technique is shown in figure 10. Anova and simple regression model of the graph is shown in figure 11.

**Table 3.** Total deflection result for different length and constant radius equal to 3mm.

| Length in mm | Radius in mm | $D_t+2^*R\leq 32.8mm$ | Total deflection |
|--------------|--------------|------------------------|-----------------|
| 2            | 3            | 8                      | $5.8237 \times 10^{-7}$ |
| 4            | 3            | 10                     | $9.3381 \times 10^{-7}$ |
| 6            | 3            | 12                     | $1.4422 \times 10^{-6}$ |
| 8            | 3            | 14                     | $2.1663 \times 10^{-6}$ |
| 10           | 3            | 16                     | $3.1641 \times 10^{-6}$ |
| 12           | 3            | 18                     | $4.4917 \times 10^{-6}$ |
| 14           | 3            | 20                     | $6.2022 \times 10^{-6}$ |
| 16           | 3            | 22                     | $8.353 \times 10^{-6}$ |
| 18           | 3            | 24                     | $1.0995 \times 10^{-5}$ |
Figure 10. Simple linear regression graph for total deflection a beam versus L/R having r=3mm constant

![Simple linear regression graph](image)

Deflection = 2E-06*L/R - 3E-06  
R² = 0.912

Figure 11. Anova model for Simple linear regression graph for r=3mm

| SUMMARY OUTPUT |
|----------------|
| Regression Statistics |
| Multiple R | 0.955 |
| R Square | 0.912 |
| Adjusted R Square | 0.901 |
| Standard Error | 0.000 |
| Observations | 10.000 |

| ANOVA | df | SS | MS | F | Significance F |
|-------|----|----|----|---|----------------|
| Regression | 1 | 1.8E-10 | 1.8E-10 | 8.3E+01 | 1.7E-05 |
| Residual | 8 | 1.7E-11 | 2.1E-12 | | |
| Total | 9 | 1.9E-10 | | | |

| Coefficient | t-Stat | P-value | Lower 95% | Upper 95% | Lower 90.0% | Upper 90.0% |
|-------------|--------|---------|-----------|-----------|-------------|-------------|
| Intercept   | -3E-06 | 2E-02   | -5E-06   | -5E-06   | -5E-06     | -5E-06     |
| L/R         | 2E-06  | 2E-07   | 9E-07    | 2E-06    | 2E-06      | 2E-06      |

4.3.4 When length of supports is changed and diameter is kept constant. Here Diameter=8mm.

As shown in table 4 as the length of support is increases from 2mm to 16 mm keeping the radius constant i.e. 3 mm correspondingly total deflection in a beam is increasing from 4.0392*10^-7 to 3.3377*10^-6. The minimum distance between two supports so that tools can access the proper machining between the supports is greater than or equal to 26.8 mm. The graph of deflection versus L/R ratio using simple linear regression technique is shown in figure 12. Anova and simple regression model of the graph is shown in figure 13.
Table 4. Total deflection result for different length and constant radius equal to 4mm.

| Length in mm | Radius in mm | Dt+2*R<= 26.8mm | Total deflection |
|--------------|--------------|-----------------|-----------------|
| 2            | 4            | 10              | 4.0392*10^-7    |
| 4            | 4            | 12              | 5.7699*10^-7    |
| 6            | 4            | 14              | 8.026*10^-7     |
| 8            | 4            | 16              | 1.099*10^-6     |
| 10           | 4            | 18              | 1.4836*10^-6    |
| 12           | 4            | 20              | 1.9734*10^-6    |
| 14           | 4            | 22              | 2.5857*10^-6    |
| 16           | 4            | 24              | 3.3377*10^-6    |

Figure 12. Simple linear regression graph for total deflection a beam versus L/R having r=4mm constant

Figure 13. Anova model for Simple linear regression graph for r=4mm
4.3.5 When length of supports is changed and diameter is kept constant. Here Diameter=10mm.

As shown in table 5 as the length of support is increases from 2mm to 10 mm keeping the radius constant i.e. 3 mm correspondingly total deflection in a beam is increasing from $3.1596 \times 10^{-7}$ to $8.9049 \times 10^{-7}$. The minimum distance between two supports so that tools can access the proper machining between the supports is greater than or equal to 20.8 mm. The graph of deflection versus L/R ratio using simple linear regression technique is shown in figure 14. Anova and simple regression model of the graph is shown in figure 15.

Table 5. Total deflection result for different length and constant radius equal to 5mm.

| Length in mm | Radius in mm=5mm | Dt+2*R<= 20.8mm | Total deflection |
|--------------|------------------|------------------|-----------------|
| 2            | 5                | 12               | $3.1596 \times 10^{-7}$ |
| 4            | 5                | 14               | $4.1867 \times 10^{-7}$ |
| 6            | 5                | 16               | $5.4398 \times 10^{-7}$ |
| 8            | 5                | 18               | $6.991 \times 10^{-7}$  |
| 10           | 5                | 20               | $8.9049 \times 10^{-7}$ |

![Figure 14](image)

Figure 14. Simple linear regression graph for total deflection a beam versus L/R having r=5mm constant
5 Result and conclusion

5.1. Conclusion 1
From the table 6 it shown that the L/R ration of 2 is having the minimum value of total deflection produced in a beam while machining. Support having length of 10mm and radius of 5mm is having the least value of total deflection. So for the design of sacrificial support fixture length of support is limited to 10mm and radius of support is limited to 5mm for a part of 50.8mm diameter for minimum value of deflection. From the figures 16, 17, 18, 19, 20 shown below red colour shows the maximum values of deflection while blue colour shows the minimum value of deflection.

Table 6. Total deflection result for different length and different diameter having minimum deflection value from all iteration.

| Sr. No | L in mm | R in mm | L/R | Deflection in mm   |
|--------|---------|---------|------|--------------------|
| 1      | 2       | 1       | 2    | 4.0843*10^-6       |
| 2      | 4       | 2       | 2    | 2.1846*10^-6       |
| 3      | 6       | 3       | 2    | 1.4422*10^-6       |
| 4      | 8       | 4       | 2    | 1.099*10^-6        |
| 5      | 10      | 5       | 2    | 8.9049*10^-7       |

5.1.1. Total deflection for L=2mm and R=1mm.
Figure 16 shown that the ends of the support having minimum value of deflection i.e. 0 and maximum value of the deflection is 4.0843*10^-6 which is also very less.
5.1.2. Total deflection for $D=4\text{mm}$ and $R=2\text{mm}$.
Figure 17 shown that the ends of the support having minimum value of deflection i.e. 0 and maximum value of the deflection is $2.1846\times10^{-6}$ which is also very less.

5.1.3. Total deflection for $L=6\text{mm}$ and $R=3\text{mm}$.
The minimum value of deflection i.e. 0 and maximum value of the deflection is $1.4422\times10^{-6}$ which is also very less as shown in figure 18.
5.1.4. Total deflection for \( L = 8 \text{mm} \) and \( R = 4 \text{mm} \).
The minimum value of deflection i.e. 0 and maximum value of the deflection is \( 1.099 \times 10^{-6} \) which is also very less as shown in figure 19.

5.1.5. Total deflection for \( L = 10 \text{mm} \) and \( R = 5 \text{mm} \).
The minimum value of deflection i.e. 0 and maximum value of the deflection is \( 8.9049 \times 10^{-7} \) which is also very less as shown in figure 20.
5.2. Conclusion 2.

For the accessibility of machining the space between the two supports are should be greater than or equal to the $D_t + 2R$ as shown in figure. Where “$D_t$” is tool diameter and $R$ is radius of support. Minimum length of supports in mm is equal to tool diameter. So we conclude that the maximum radius of the support used is 5mm and the maximum length of support is 10mm for a part of 50.8mm diameter for proper tool accessibility.

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