World Applied Sciences Journal 11 (7): 840-846, 2010
ISSN 1818-4952


# Clamping Force Optimization for Minimum Deformation of Workpiece by Dynamic Analysis of Workpiece-fixture System

*[1]S. Selvakumar, [2]K.P. Arulshri, [3]K.P. Padmanaban and [1]K.S.K. Sasikumar*

[1]Department of Mechanical Engineering, Kongu Engineering College, Erode, Tamilnadu, 638 052, India
[2]KPR Institute of Engineering and Technology, Coimbatore, Tamilnadu, 641 407, India
[3]SBM College of Engineering and Technology, Dindigul, Tamilnadu, 624 005, India

**Abstract:** In any manufacturing operation, the deformation of the workpiece can be minimized by optimizing the parameters such as Clamping forces, Number of locators and clamps and Positions of locators and clamps. The system gives minimum deformation when clamping forces are minimum. The minimum clamping forces required to hold the workpiece can be determined by using balancing force-moment method and the coulomb static friction law. For a milling operation the enough amount of clamping forces are determined for the five various positions of the tool on the workpiece. Then the maximum values of clamping forces among these are taken as the optimum clamping force. Finally, the deformation of the workpiece for the optimum clamping forces is determined by Harmonic analysis using FEM software.

**Key words:** Clamping force . fixture layout . finite element analysis . harmonic analysis

## INTRODUCTION

Machining fixture is a precision device meant for locating and constraining the workpiece during machining. This work focuses on machining fixtures. A machining fixture is used to establish and maintain the required position and orientation of a workpiece so that cutting operations can be performed on the workpiece. It is a critical link in the machining system as it directly affects operational safety and part quality. A typical machining fixture consists of a base plate and a number of locators and clamps. Locators are passive fixture elements used to position the workpiece while clamps are active fixture elements that can be actuated mechanically, pneumatically, or hydraulically to apply clamping forces onto the workpiece so that it can resist external forces generated by the machining operation. There are a variety of fixture designs. The geometry of the contact region between a fixture element and workpiece can be a point, line, or plane. An important consideration in the fixture design process is to design the fixture layout and optimization of clamping forces required. The elastic deformation of the workpiece can be minimized by designing the optimum fixture layout and clamping forces. Proper fixture design is crucial to product quality in terms of precision, accuracy and surface finish of the machined parts. In this work optimization of the clamping forces for minimum deformation of the work piece is dealt.

## LITERATURE REVIEW

Hameed R.A *et al*. [2] have presented a methodology by which the dynamometer can be replaced effectively by six instrumented locators with uniaxial piezo-electric force sensors in a fixturing setup. A system was developed using the output from six uniaxial force sensors, which are positioned around the workpiece to suit the configuration of the workpiece

Li B *et al*. [1] given the method to solve the clamping force optimization where the locators were assumed as deformable and the workpiece as rigid body. The optimum clamping force is found to reduce the location error duo to the application of the machining forces.

Li B *et al*. [5] presented a model for analyzing the reaction forces and moments for machining fixtures with large contact areas. This model is used to determine the minimum clamping force necessary to keep the workpiece in static equilibrium during machining.

Mohsen Hamedi *et al*. [6] have designed fixtures for machining operations, clamping scheme is a complex and highly nonlinear problem that entails the frictional contact between the workpiece and the clamps. Such parameters as contact area, state of contact, clamping force, wear and damage in the contact area and deformation of the component are of special interest.

**Corresponding Author:** Dr. S. Selvakumar, Department of Mechanical Engineering, Kongu Engineering College, Erode, Tamilnadu, 638 052, India

Weifang Chen *et al*. [8] used a multi objective optimization procedure for minimizing the maximum deformation of the machined surfaces and maximizing the uniformity of the deformation. The ANSYS software package has been used for FEM calculation of fitness values.

Necmettin Kaya *et al*. [7] have used dynamic analysis to find out the deformation of the workpiece under machining.The entire tool path is discretized into 13 load steps. The workpiece-fixture model is analyzed with respect to tool movement. The workpiece is assumed to be elastic. The fixture is assumed as completely rigid.

Krishnakumar *et al*. [4] used FEM to simulate the machining operation. The machining forces are considered as point force acting over the tool path. Static analysis is performed to simulate the machining operation. In which the material removal effect is not considered.

Prabharan *et al*. [10] modeled the workpiece-fixture system by considering workpiece as an elastic body and fixture as a rigid body. The locators were modeled as displacement constraints that prevent workpiece translation in the normal direction. The clamping force was modeled as point force. The workpiece is considered as 2D by assuming the workpiece is subjected to plane stress. Static analysis is used to find out the elastic deformation of the workpiece under machining.

**Summary of literature review:** A review of the literature reveals the following shortcomings:

- Most of the studies use either the rigid-body model or workpiece-elastic contact model andthese studies do not consider the workpiece elastic deformation.
- To calculate the minimum clamping forces required to hold the workpiece, the friction forces due to locators and clamps are considered.
- The balancing force-moment equations are also used here to calculate the clamping forces and the reaction forces due to the locators.
- Although, the finite-element method is best suited for predicting an elastic deformation of the workpiece and reaction forces, it has been mainly used for determining the elastic deformation at workpiece-fixture contact points.
- Most of the studies do not consider the dynamic machining forces in the fixture optimization design to minimize the dynamic response of the workpiece.
- Most researchers did not consider the material removal effect in the analysis.

## METHODOLOGY

**Workpiece geometry and properties:** An example of clamping force optimization problem for a prismatic workpiece displayed by Li and Melkote [1] is considered as example for the fixture layout optimization problem described in this work.

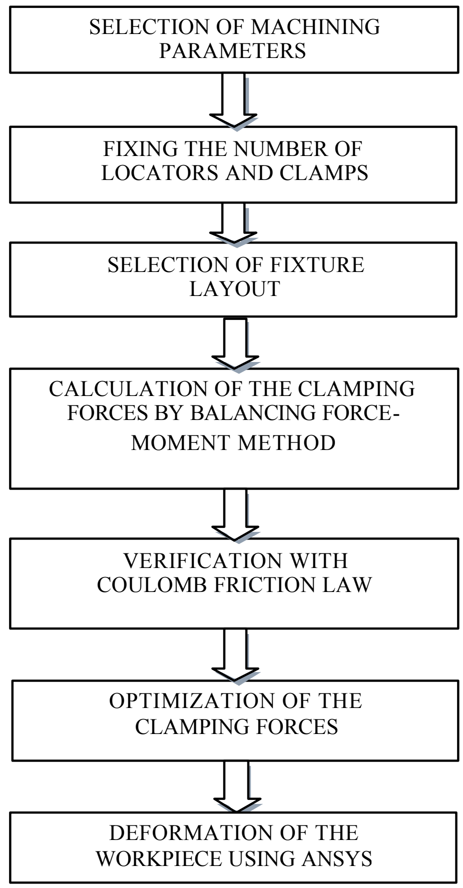


Fig. 1: Methodology chart

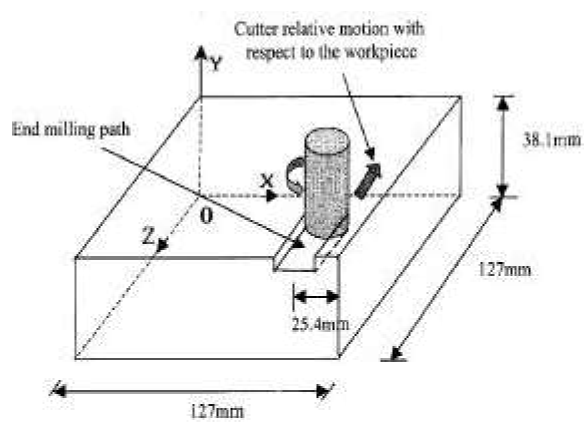


Fig. 2: Prismatic workpiece and end milling path

| | |
|---|---|
| Material | : Aluminum 7075 T-6 |
| Density ($\rho$) | : 2795 kg/m$^3$ |
| Young's modulus (E) | : 72 GPa |
| Poisson ratio | : 0.33 |

Table 1: Machining parameters

| Types of operation | End milling |
|---|---|
| Cutter diameter | 25.4 mm |
| Number of flute | 4 |
| Spindle speed | 660 (rpm) |
| Feed | 0.2032 (mm/tooth) |
| Radial depth | 25.4 mm |
| Axial depth | 3.81 mm |
| Helix angle | 45° |
| Radial rake angle | 10° |
| Machining Forces | $F_x$ = 1105.67 N |
| | $F_y$ = 442.1 N |
| | $F_z$ = 283.56 N |

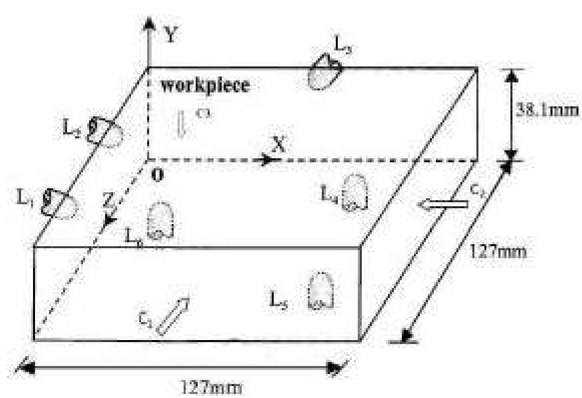


Fig. 3: Workpiece-fixture configuration

**Machining operation:** An end milling operation is carried out on the example workpiece. The machining parameters of the operation are given in Table 1. The entire tool path is discredited into 5 load steps and cutting force directions are determined by the cutter position.

**Fixture design plan:** The 3-2-1 locator principle is used in fixture design [1, 5]. This method provides the maximum rigidity with the minimum number of fixture elements. A workpiece in 3D may be positively located by means of six points positioned so that they restrict nine degrees of freedom of the workpiece. The other three degrees of freedom are removed by clamp elements. Here three clamps are used to restrain the workpiece. The fixture plan for holding the workpiece in the machining operation is shown in Fig. 3.

Table 2: Optimum fixture layout

| Fixture eliments | Position (mm) X | Y | Z |
|---|---|---|---|
| L 1 | 0.0 | 19.05 | 114.3 |
| L 2 | 0.0 | 19.05 | 12.7 |
| L 3 | 63.5 | 19.05 | 0.0 |
| L 4 | 114.3 | 0.00 | 12.7 |
| L 5 | 114.3 | 0.00 | 114.3 |
| L 6 | 12.7 | 0.00 | 63.5 |
| $C_1$ | 12.7 | 19.05 | 53.3 |
| $C_2$ | 63.5 | 19.05 | 127.0 |
| $C_3$ | 50.8 | 38.10 | 50.8 |

**Parameters involved:** In the fixture optimization problem, we need to minimize the maximum deformation in the workpiece. The parameters which influence the deformation of the workpiece are

- Clamping forces
- Machining forces
- Position of locators and clamps
- Material of the workpiece
- Number of locators and clamps

In this work, minimum clamping forces to restrain the workpiece and the machining forces that are required to carry out the end milling operation is selected for analysis. By optimizing the clamping force, the deformation of the workpiece can be minimized. So the design variables are three clamping forces.The design variables are, clamping forces $C_1$, $C_2$ and $C_3$.Clamping devices are used to hold the workpiece in the correct relative position in jig or fixture. It should ensure that the workpiece is not displaced under the action of cutting force,for efficient operation, firm clamping of the workpiece is must, adequate clamping is designed for minimum operation and handling time.

**Optimum fixture layout:** The layout which has been optimized for the particular the workpiece to produce minimum deformation on the workpiece is called as optimum fixture layout which is shown in Table 2.

**Basic theory:** Calculations to find the necessary clamping force can be quite complicated. In many situations, however, an approximate determination of these values is sufficient. Required clamping force can be calculated based on cutting forces on applied on the work piece.

$$\text{Required Clamping force} = (\text{Cutting Force} \div \text{Static friction of coefficient}) \times \text{Factor of safety}$$

**Balancing force-moment method:** Equilibrium occurs when the sum of all forces in the x, y andz direction is zero and the sum of moments at any point is zero [1].

$$\sum F = 0, \qquad \sum M = 0$$

**Coulomb friction law:** To verify the calculated clamping forces are enough to hold the workpiece, the forces in the each direction are multiplied by the static friction coefficient value. This will give the friction force values due to the clamps and locators. For equilibrium condition, the amount of friction force should be greater than or equal to the machining force in that direction [1].

$$\left|F^i_x\right| + \left|F^i_x\right| \le \mu^i_s \times F^i_z$$

- Number of Contact Point

## RESULTS AND DISCUSSION

$$\sum F_x = 0$$
$$C_1 + R_1 + R_2 + F_x = 0$$
$$\sum F_y = 0$$
$$C_3 + R_4 + R_5 + R_5 + F_x = 0$$
$$\sum F_z = 0$$
$$C_2 + R_3 + F_z = 0$$

$R_1$ to $R_6$ are reactions at $L_1$ to $L_6$.
When tool is at initial Position (101.6 mm, 0, 127 mm)

$$\sum M_{L1} = 0$$
$$\begin{bmatrix} (C_1\times 61)+(C_2\times 63.5)+(C_3\times 50.8)+ \\ (R_2\times 101.6)+(R_3\times 63.5)+(R_4\times 114.3)+ \\ +(R_5\times 114.3)+(R_6\times 12.7)+(F_x\times 12.7)+ \\ (F_y\times 101.6)+(F_z\times 101.6) \end{bmatrix} = 0$$

$$\sum M_{L2} = 0$$
$$\begin{bmatrix} (C_1\times 40.6)+(C_2\times 63.5)+(C_3\times 50.8)+ \\ (R_1\times 101.6)+(R_3\times 63.5)+(R_4\times 114.3)+ \\ +(R_5\times 114.3)+(R_6\times 12.7)+(F_x\times 114.3)+ \\ (F_y\times 101.6)+(F_z\times 101.6) \end{bmatrix} = 0$$

$$\sum M_{L3} = 0$$
$$\begin{bmatrix} (C_1\times 53.3)+(C_2\times 0)+(C_3\times 50.8)+ \\ (R_1\times 114.3)+(R_2\times 12.7)+(R_4\times 12.7)+ \\ +(R_5\times 114.3)+(R_6\times 63.5)+(F_x\times 127)+ \\ (F_y\times 127)+(F_z\times 38.1) \end{bmatrix} = 0$$

$$\sum M_{L4} = 0$$
$$\begin{bmatrix} (C_1\times 12.7)+(C_2\times 114.3)+(C_3\times 63.5)+ \\ (R_1\times 114.3)+(R_2\times 114.3)+(R_3\times 12.7)+ \\ +(R_5\times 101.6)+(R_6\times 38.1)+(F_x\times 12.7)+ \\ (F_y\times 114.3)+(F_z\times 114.3) \end{bmatrix} = 0$$

$$\sum M_{L5} = 0$$
$$\begin{bmatrix} (C_1\times 12.7)+(C_2\times 12.7)+(C_3\times 63.5)+ \\ (R_1\times 19.05)+(R_2\times 114.3)+(R_3\times 114.3)+ \\ +(R_4\times 101.6)+(R_6\times 63.5)+(F_x\times 12.7)+ \\ (F_y\times 12.7)+(F_z\times 12.7) \end{bmatrix} = 0$$

$$\sum M_{L6} = 0$$
$$\begin{bmatrix} (C_1\times 114.3)+(C_2\times 63.5)+(C_3\times 12.7)+ \\ (R_1\times 12.7)+(R_2\times 12.7)+(R_3\times 63.5)+ \\ +(R_4\times 38.1)+(R_5\times 63.5)+(F_x\times 38.1)+ \\ (F_y\times 63.5)+(F_z\times 63.5) \end{bmatrix} = 0$$

MAT Lab software was used to solve the above equations. The required Clamping forces are,

C1 =704.26 N C2 =353.42 N C3 =321.78 N

Like the above when tool is at (101.6 mm, 0, 101.6 mm) the required Clamping forces are,

C1 =678.7 N C2 =48.6 N C3 =1324.9 N

when tool is at (101.6 mm, 0, 76.2 mm) the required Clamping forces are,

C1 =742.4 N C2 =465.2 N C3 =2436.13 N

when tool is at (101.6 mm, 0, 50.8 mm) the required Clamping forces are,

C1 =1002.6 N C2 =548.0 N C3 =1906.6 N

when tool is at (101.6 mm, 0, 25.4 mm) the required Clamping forces are,

C1 = 874.3 N C2 =266.6 N C3 =1537.2 N

The maximum clamping forces among these values are,

C1=1002.6 N C2=548.0 N C3 =2436.1 N

The reaction forces at each locator for these clamping forces are,

R1 = 455.9 N  R2 =103.6 N  R3 =831.56 N
R4 =1484.6 N  R5 =2057.2 N  R6 =1370.7 N

**Verification of the calculated clamping forces:** To verify the calculated clamping forces are enough to hold the workpiece, the forces in the each direction are multiplied by the static friction coefficient value. This will give the friction force values due to the clamps and locators. For equilibrium condition, the amount of friction force should be greater than or equal to the machining force in that direction.
In the X-direction,

$$\left[\left(C_2 + C_3 + R_3 + R_4 + R_5 + R_6\right) \times 0.25\right] \geq F_x$$
$$(8728.16 \times 0.25) = 2182.04 > 1105.67$$

In the Y-direction,

$$\left[\left(C_1 + C_3 + R_1 + R_2 + R_4 + R_5 + R_6\right) \times 0.25\right] \geq F_y$$
$$(8910 \times 0.25) = 2227.5 > 442.1$$

In the Z-direction,

$$\left[\left(C_1 + C_2 + R_1 + R_2 + R_3\right) \times 0.25\right] \geq F_z$$
$$(2941.66 \times 0.25) = 735.415 > 283.56$$

Thus, the calculated clamping forces are verified by the coulomb friction law.

**Deformation of the workpiece:** Finite element model of the workpiece-fixture system.

FEM software ansys was used to fine the deformation of the work piece.

| | |
|---|---|
| Number of elements | = 6120 |
| Number of nodes | = 7315 |
| Type of element | = solid 45 |
| The natural frequency of the system | = 56.332 Hz |
| Excitation frequency of the system | = 44 Hz |
| Spindle speed | = 660/60 = 11 rps |
| So time taken for one cycle | = 1/44 sec |
| Frequency | = 1/T = 44 Hz |

**Harmonic analysis:** Static analysis is conducted by considering the clamping forces and the displacement constraints. After the static analysis, pre stressed harmonic analysis is conducted by considering the machining forces and the harmonic frequency. The entire tool path is discretized into five load steps.

The model is analyzed with respect to the tool movement and material removed effect. After the completion of each load step the elements in the load path for the previous load steps to current load step are deactivated. The harmonic frequency range = 0 to 44 HZ.

**Deformation for load steps:** The deformation of the workpiece is calculated at five positions of the machining tool with respect to workpiece. The deformation of the workpiece will vary with respect to the positions of the tool on the workpiece. The workpiece along the tool path is divided into five load steps such as 0 mm, 25.4 mm, 50.8 mm, 76.2 mm and101.6 mm.The material removal effect is also considered. When the tool is at zero position is shown in Fig. 8.1, there is no material is removed. When the tool is at 25.4 mm, the material behind the tool is removed . This material removal effect plays the major role to determining the deformation of a workpiece. The keyword called EKILL is used to remove the material along the tool path.

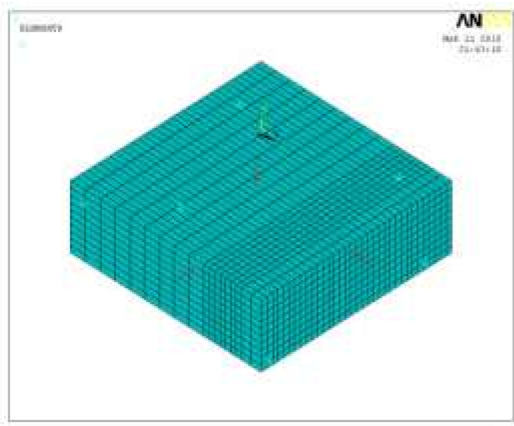

Fig. 4: FE model of the workpiece

**Load step 1**

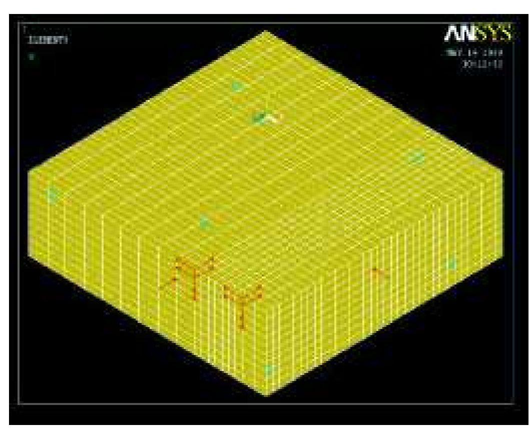


Fig. 5: FE model load step 1

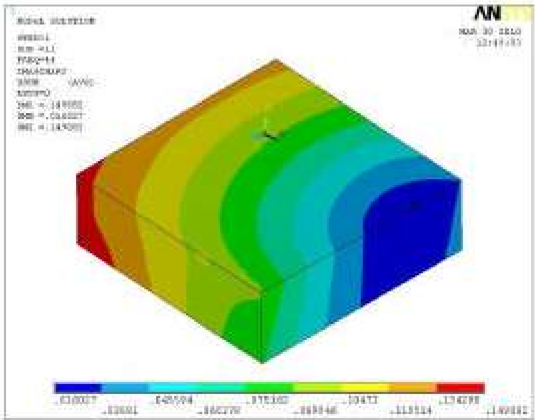

Fig. 6: Deformation for load step 1

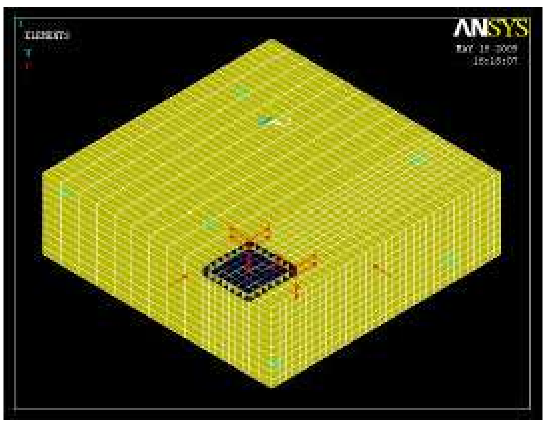


Fig. 7: FE Model load step 2

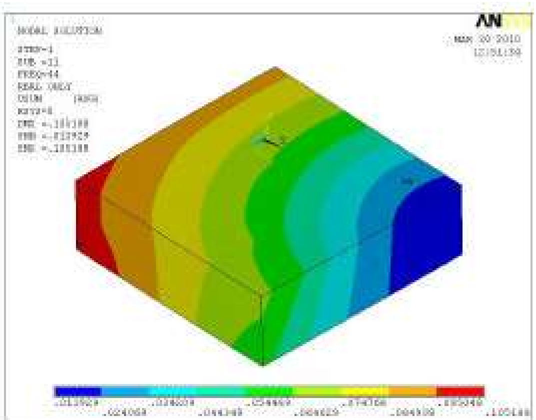

Fig. 8: Deformation for load step 2

The deformation of the workpiece for first load step is 0.149082 mm

**Load step 2:** The deformation of the workpiece is determined by considering the material removal between initial position of tool to tool at 25.4 mm. By using ANSYS software is shown in Fig. 6.1, the EKILL option is used to remove the material. Actually this option enables to deactivate the elements in that area. The deformation of the workpiece is 0.10538 mm. Similarly deformation for load step 3 and 4 had been found.

**Load step 5:** During load step 5, the material along the tool path is almost removed. So the deformation of the workpiece may be increased as that of last two load steps. This is shown in Fig. 8.5. The deformation of the workpiece is 0.065876 mm.

From the above five load steps, the maximum deformation of the workpiece is occurred at the first load step. The the maximum deformation value is 0.149082 mm.

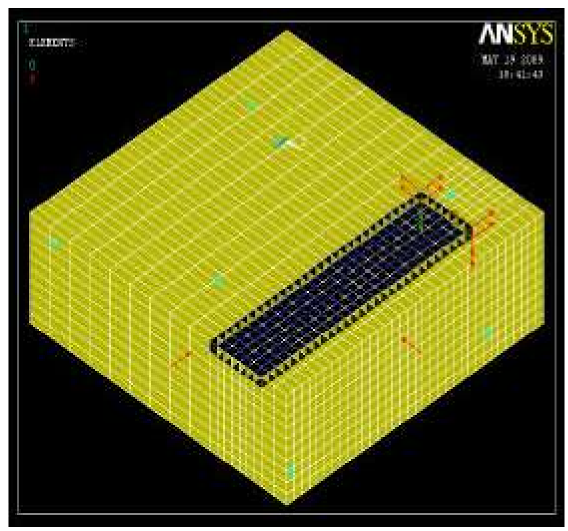


Fig. 9: FE Model load step 5

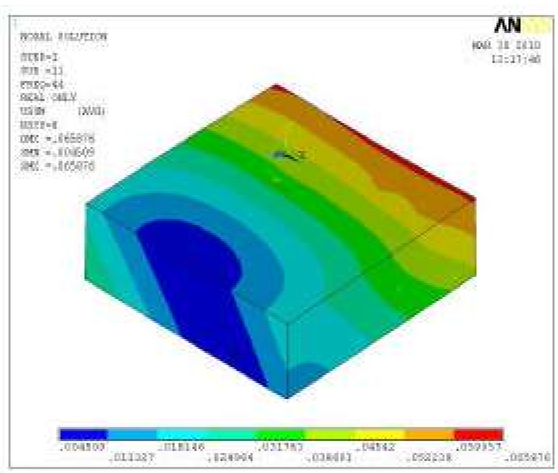

Fig. 10: Deformation for load step 5

## CONCLUSION

Hence the minimum clamping forces which are enough to hold the workpiece are determined. The balancing force-moment method and coulomb friction law are used to determine the clamping forces. The clamping forces required to hold the workpiece are calculated for five positions of the machining tool with respect to workpiece. This force calculation gives the different magnitute of forces for every position of the tool. The maximum value among these calculated values are taken as the optimum clamping forces. By calculating the optimum clamping forces the deformation of the workpiece may be minimized. Because of minimum deformation, the dimensional and form errors of the workpiece may be reduced. To determine the deformation of the workpiece the tool path is divided into five load steps.The material removal effect was also considered. Then, the deformation of the workpiece is determined by harmonic analysis using ANSYS software.

## SCOPE FOR FUTURE WORK

The clamping force is optimized to minimize the workpiece deformation while machining. The other parameters which influence the deformation of the workpiece are not considered in this work. So this work can be extended for optimizing the fixture layout and number of locators and clamps.

## REFERENCES


1. Li, B. and S.N. Melkote, 2001. Fixture Clamping Force Optimisation and its Impact on Workpiece Location Accuracy. International Journal of Advanced Manufacturing Technology, 17: 104-113.
2. Hameed, R.A, M.A. Mannan and A.Y.C. Nee, 2004. The cutting force measurement in a fixturing setup with instrumented locators. International Journal of Advanced Manufacturing Technology, 23: 783-793.
3. Kaya, N. and F. Ozturk, 2003. The Application of Chip Removal and Frictional Contact Analysis for Workpiece-Fixture Layout Verification. International Journal of Advanced Manufacturing Technology, 21: 411-419.
4. Krishnakumar Kulankara, Srinath Satyanarayana and Shreyes N. Melkote, 2002. Iterative Fixture Layout and Clamping Force Optimization Using the Genetic Algorithm. ASME Journal of Manufacturing Science and Engineering, 124: 119-125.
5. Li, B., S.N. Melkote and S.Y. Liang, 2000. Analysis of Reactions and Minimum Clamping Force for Machining Fixtures with Large Contact Areas. International Journal of Advanced Manufacturing Technology, 16: 79-84.
6. Mohsen Hamedi, 2005. Intelligent Fixture Design through a Hybrid System of Artificial Neural Network and Genetic Algorithm. Artificial Intelligence Review, 23: 295-311.
7. Necmettin Kaya, 2006. Machining fixture locating and clamping position optimizationusing genetic algorithms. Computers in Industry, 57: 112-120.
8. Weifang Chen, 2007. Fixture layout design and clamping force optimization procedure based on the GA and FEM.
9. Bo, Li andShreyes N. Melkote, 1999. An Elastic Contact Model for the Prediction of Workpiece-Fixture Contact Forces in Clamping. Transactions of the ASME. Journal of Manufacturing Science and Engineering, 121 (3): 485-493.
10. Prabhaharan, G., K.P. Padmanaban and R. Krishnakumar, 2007. Machining fixture layout optimization using FEM and evolutionary techniques. International Journal of Advanced Manufacturing Technology, 32: 1090-1103.