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Optimization of Modular Fixture Layout by Minimizing Work-piece Deformation

Muhammad Mohsin Rashid[1], Awais Ahmad Khan[2], Muhammad Usman[1], Muhammad Ayub[1], and Behzad Rustam[1]

[1]Mechanical Engineering Department, The University of Lahore, Lahore, 54000, Pakistan
[2]Department of Mechanical Engineering, University of Engineering and Technology, Lahore, 54890, Pakistan.

Corresponding author: Muhammad Mohsin Rashid (email: mohsinrashid11090@gmail.com).

Abstract- **The fixtures are utilized to locate and restrain a workpiece while different machining processes are performed on it. The workpiece must be properly located and clamped so that it could be manufactured according to the prescribed dimensions and tolerance. The actual purpose of fixture design is to maximize locating accuracy and workpiece firmness while minimizing deformations. The purpose of this work is to conduct a multi-objective optimization in order to minimize workpiece deflections due to clamping forces and optimized fixture layout by taking into consideration the boundary conditions and loads applied during a machining process. The locators are employed in a 3-2-1 fixture configuration. Then the empirical relations are used to calculate the machining forces and moments generated during drilling and milling processes and after that the workpiece is loaded to model those cutting forces. ANSYS parametric design language (APDL) code which made use of sub-approximation method is utilized to automatically optimize locator and clamp positions. Afterwards the clamping forces are being optimized using balancing force-moment method. Lastly, the maximum deformation of the workpiece against the optimum clamping forces is determined by harmonic analysis.**

Index Terms-- **Fixture Layout Design, Clamping Forces, Minimum Deformation, Machining Fixtures, Optimization**

I. INTRODUCTION

Machining fixture is a gadget that is utilized for positioning, clamping and holding up a workpiece against cutting tools during manufacturing while it is being machined. Fixturing elements play crucial role in manufacturing setups as they are necessarily required for many production environments. Many devices e.g. vices, lathe chucks & collets etc. are vastly used in manufacturing facilities for restraining purposes. Normally fixtures are developed exclusively for a specific manufacturing process in order to deal a unique part processing method. Jigs are almost the same as fixturing elements in functionality except that they also direct the cutting gadgets. These devices are communally called as jigs and fixtures.

Moreover, the usage of well-suited fixtures having higher locating and clamping properties allows an increase in cutting speeds and feeds, thereby reducing actual machining time; hence it improves production rates. Previously researchers have worked on fixture design using FEA and simulations. A brief summary of some vital methodologies is given below.

Somashekar R. Subrahmanyam [1] described the technique of fixturing features recognition using design parameters along with features entailed in machining within a feature-based CAD system. An organized approach for calculation of forces and moments produced during drilling and milling machining processes were introduced. Nicholas Amaral et al. [2] established a methodology for determining boundary conditions of the workpiece and calculated machining forces using empirical relations. They also evaluated deflections in contact area of flexible fixturing tools and carried out automatic optimization of fixture layout using FEA. S. Selvakumar et al. [3] considered the factors that impact the workpiece deformation i.e. clamping and cutting forces, number and positions of clamps & locators. They found out the minimum amount of clamping forces that were necessarily required to lock the workpiece by using method of force-moment equilibrium and substantiated it afterwards by applying coulomb's law of static friction.

Shane P. Siebenaler et al. [4] discussed the influence of compliance in fixture body on the workpiece deformation. Furthermore, the impact of a few FEM variables on accuracy predicting was also considered. Necmettin Kaya [5] optimized fixture layout using genetic algorithms (GAs). The GA approach was combined with FEM in the batch mode for optimization of fixture layout. The values of objective function were also determined against each batch. M.Vasundara et al. [6] optimized the fixture layout by reducing the maximum workpiece deformation during machining to a minimum by utilizing Artificial Neural Networks (ANN) and Response Surface Methodology (RSM). G. Prabhaharan et al. [7] presented a fixture layout optimization scheme that used genetic algorithm (GA) and ant colony algorithm (ACA) discretely. Dongbo Wu et al. [8] used FEA & GA for fixture layout optimization and later used it for evaluation of near-net-shaped jet engine blade. M. Vinosh et al. [9] implemented a hybrid optimization method to reduce the deformation of sheet metal under resistance spot welding. It helped in reducing the fixture based problems faced during production. Rayk Fritzsche et al. [10] created a software code using particle swarm optimization (PSO) in order to develop a product flexible car body fixture. Seloane WT. et al. [11] presented a conceptual model for intelligent reconfigurable welding fixtures (IRWF) using Unigraphics. The aim of this study was to resolve the issues that arise from the usage of dedicated fixtures in railcar manufacturing companies. R. Siva et al. [12] worked on modification of fixture design for planet carrier component in order to ease the manufacturing operation. Solidworks & ANSYS were used for design and analysis respectively. In the end, Renishaw probe technique was to measure the dimensional accuracy of finished component. Dongbo Wu et al. [13] improved fixture layout for adaptive CNC machining process using FEA. The considered. They achieved high accuracy and low deformation for near-net-shaped jet engine blade. After literature review, it was observed that previous research works have considered mostly one or two factors that affect the elastic deformations of the workpiece for a single manufacturing operation. In this research work multi-faceted optimization is carried out in order to have even lesser workpiece deformation. The optimization factors considered in this work are number of locators & clamps as well as clamping forces for two manufacturing processes i.e. drilling and milling using a modular fixture setup with minimum elastic deformation. For that purpose, a symmetrical workpiece was chosen upon which drilling and milling operations were to be performed.

II. METHODOLOGY

The knowledge of cutting forces is very crucial while simulating or designing a machining operation as a lot of factors like required clamping forces, workpiece deformation and surface finish depends upon them.

A. MILLING FORCES

The three forces included in milling are an axial load acting along the end mill axis because of the downward shove to maintain contact between the tool and workpiece, a tangential load because of the linear workpiece feed and a radial load caused by the tool rotation as shown in FIGURE 1.

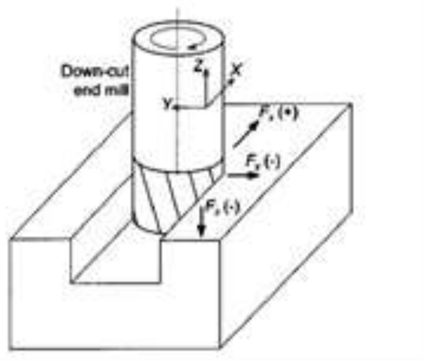

FIGURE 1. FORCE COMPONENTS IN END MILLING [14]

To calculate the magnitude of these forces we will use the empirical relations for aluminum workpieces given in [1].

Tangential Force:

$$Fx = Ktbtc \quad (1)$$

Radial Force:

$$Fy = KrPx \quad (2)$$

Thrust Force:

$$Fz = KcPy \quad (3)$$

Where;

t_c= un-deformed chip thickness

$$tc = \frac{f}{N_t}\, x\, N \quad (4)$$

Here;

f = feed rate

N_t = number of teeth

N = rotational speed (rpm)

V_c = cutting speed = πDN (m/min)

D = tool diameter (mm)

b = depth of cut (mm)

K_t, K_r, K_c = empirical data constants

$$lnKt(t) = 7.28668 - [0.18688 lntc(t)] - [0.08711 lnVc(t)] \quad (5)$$

$$lnKr(t) = 6.58305 - [0.35873 lntc(t)] - [0.33895 lnVc(t)] \quad (6)$$

$$lnKc(t) = 5.98786 - [0.54912 lntc(t)] - [0.48816 lnVc(t)] \quad (7)$$

Now, the machining parameters under which we will be working are as follows:

f = 0.2032 mm/tooth, N_t = 4, N = 660rpm, D = 25.4mm, b = 3.81mm, f = (660 x 4)/60 = 44Hz

By using these parameters, we determined the machining forces to be:

$$Fx = 254.6N, Fy = 886.3N, Fz = 442.1N$$

B. DRILLING FORCES

The drilling force which acts on both the lips of a drill bit can be resolved into three mutually perpendicular components: axial/thrust force along the axis of drill due to the downward push for attaining the motion of drill bit in downward direction, radial force it acts along the radial direction of drill bit and tangential force perpendicular to the other two force components. In an ideal case which happens usually in case of a new drill bit, the bit will have identical lips, so the radial force components at both lips will get cancelled. Forces with which we deal in drilling are shown in FIGURE 2.

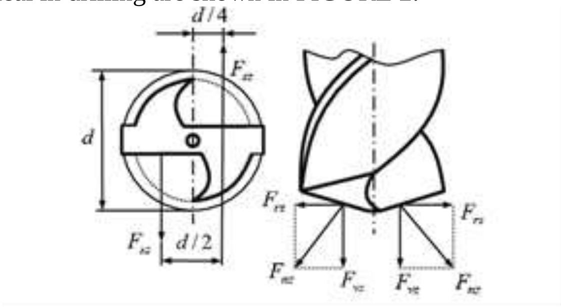

FIGURE 2. FORCE COMPONENTS IN DRILLING [15]

Now to calculate the magnitude of these forces we will again use the empirical relations for aluminum workpieces given in [1].

Tangential Force:

$$Fa = Mp\,(D/20) \quad (8)$$

Thrust Force:

$$Ft = 4.6343 x D^{0.97} x h_{avg}{}^{0.83} x h^{0.5} \quad (9)$$

where:

h_{avg} =chip thickness (mm)

$$h_{avg} = [a.cos(k/2)/Nf] \quad (10)$$

a = advance in one revolution of the spindle (mm/rev)
k = rake angle (rad) ; N_f = Number of Flutes
Drilling Torque:

$$Mp = 0.001542xD^{2.0}xh_{avg}{}^{0.8}xh^{0.55} \qquad (11)$$

D = cutter diameter (mm)
h = hardness of the material (N/mm^2)
Now, the machining parameters under which we will be working are as follows:
a = 0.178 mm/rev, k = 20º, h = 95 (N/mm^2)
RPM = cutting speed x 4/Dia of cutter= 1702rpm
f = 1702 x 2/60 = 56.7Hz, D = 12mm
By using these parameters, we determined the machining forces to be:

$$Fa = 7.26N, Ft = 279.2N$$

III. OPTIMIZATION AND FINITE ELEMENT ANALYSIS

The main theme of this work is multi-faceted optimization i.e. fixture layout optimization using sub-approximation method and clamping forces optimization using balancing force-moment method for drilling as well as milling operations. The materials selected for this study are Aluminum 6061-T6 and AISI 1144 Steel for workpiece & fixture components respectively. The materials properties are provided in the TABLE I.

TABLE I
MATERIAL PROPERTIES OF WORKPIECE & FIXTURE

Material	Young's Modulus (GPa)	Density (kg/m^3)	Poisson's Ratio	Yield Strength (MPa)
Aluminum 6061-T6	70	2700	0.35	170
AISI 1144 Steel	200	7861	0.295	670

A. FIXTURE LAYOUT OPTIMIZATION

We can minimize part deformation and maximize its locating precision through optimization of boundary conditions i.e. the clamp & locator positions and magnitudes of clamping forces. The locators are used to fulfill following purposes:

1. Locating & stabilizing the workpiece
2. Acting as supports and consequently minimizing workpiece deformation

The optimization fulfills both the functional demands by utilizing just single design parameter i.e. the identification of the locator positions on the exterior of the workpiece. The optimization of fixture layout is carried out in ANSYS. It offers two techniques that can deal with a vast variety of optimization scenarios.

1. The sub-problem approximation method is a progressive zero-order technique that can be conveniently opted in order to solve a great deal of engineering problems.
2. The first order method is quite attuned to the design parameters. So, it is quite apt for problems in which higher level of accuracy is desired.

For both of these methods, ANSYS runs an iterative cycle consisting of analysis-assessment-refinement. The optimization variables are defined as; Design Variables (DVs) are independent quantities which are altered to attain the optimum design. The constraints are applied on DVs by defining their upper and lower limits. The design variables in our case are the positions of locators and clamps. State Variables (SVs) are dependent quantities that limit the design and they are functions of the DVs. A state variable can either have a maximum and minimum limit, or it may have only one of these limits. In our case Von Mises Stress is the state variable which must be below the workpiece material's yield strength i.e. 170MPa; so that the material does not deform plastically under any circumstances. The variable dependent on other variables that is to be minimized is termed as objective function. It should essentially be related to the DVs. Objective function for this optimization is maximum deformation of the workpiece. These optimization variables are enlisted in the TABLE II.

TABLE II
OPTIMIZATION VARIABLES

Design Variables	Position of Locators Locator 1 (X_1, Y_1, Z_1) Locator 2 (X_2, Y_2, Z_2) Locator 3 (X_3, Y_3, Z_3) Locator 4 (X_4, Y_4, Z_4) Locator 5 (X_5, Y_5, Z_5) Locator 6 (X_6, Y_6, Z_6) Position of Clamps Clamp 1 (X_1, Y_1, Z_1) Clamp 2 (X_2, Y_2, Z_2) Clamp 3 (X_3, Y_3, Z_3)
State Variables	Von Misses Stress (VONMISES < Yield Strength)
Objective Function	Maximum Displacement (DMAX)

Now in order to start our analysis we have to prescribe the upper and lower limits for the design variables which are given in TABLE III.

TABLE III
DV'S LOWER & UPPER LIMITS

Variable	Lower (mm)			Upper (mm)		
Name	X	Y	Z	X	Y	Z
L_1	0	0	63.5	0	19.05	127
L_2	0	0	0	0	19.05	63.5
L_3	0	0	0	127	38.1	0
L_4	63.5	0	0	127	0	63.5
L_5	63.5	0	63.5	127	0	127
L_6	0	0	0	63.5	0	127
C_1	127	0	0	127	38.1	127
C_2	0	0	127	127	38.1	127
C_3	0	38.1	0	127	38.1	127

The next step is to select optimization technique. We chose sub-problem approximation method because it is not computationally intense and can be easily applied to an extensive variety of engineering problems. It uses curve fitting in order to approximate all dependent variables i.e. SVs and the objective function. Then looping controls were defined. We set the number of iterations to hundred and commenced optimization. After the completion of optimization, we reviewed the results which will be presented in the results and discussion section.

B. CLAMPING FORCES OPTIMIZATION

The clamping forces are being optimized through balancing force-moment method. As we know the equilibrium state occurs only when the resultant of all forces in the X, Y and Z directions is zero and as well as the resultant of moments at any point is zero.

$$\Sigma F = 0, \Sigma M = 0$$

In order to do this, we discretized the two machining processes into five load steps each. The load steps are formed with respect to the tool position relative to the workpiece as the machining forces will be applied to different locations on the workpiece and the corresponding fixture layout will provide different stability against each load step. To do so we developed nine equations; three of them involve summation of forces in each direction and the other six involve summation of moments at each locator.

The reactions at the locators are denoted by the R_1, R_2, R_3, R_4, R_5 and R_6 respectively and the clamping forces are denoted by C_1, C_2 and C_3 respectively. The nomenclature scheme and workpiece dimensions are shown in FIGURE 3.

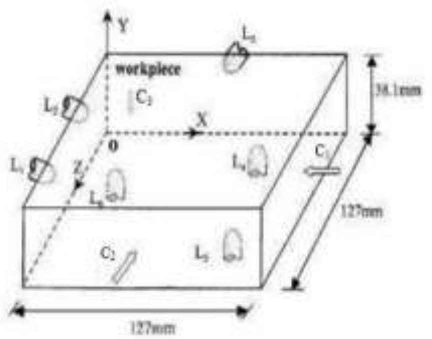

FIGURE 3. WORKPIECE MODEL

At load step 1 the tool position is 101.6mm, 34.29mm, 127mm:

$$\Sigma F_X = 0 \quad \Sigma F_Y = 0 \quad \Sigma F_Z = 0$$
$$-C1 + R1 + R2 - Fx = 0$$
$$-C3 + R4 + R5 + R6 - FY = 0$$
$$-C2 + R3 - FZ = 0$$

$$-C1 + R1 + R2 = 886.3 \tag{12}$$

$$-C3 + R4 + R5 + R6 = 442.1 \tag{13}$$

$$-C2 + R3 = 254.6 \tag{14}$$

$\Sigma ML1 = 0$

$C1x49.7 + C2x63.5 + C3x54.8 - R2x85.3 + R3x63.5 + R4x110.1 + R5x110.1 + R6x11.5 = -51630$ (15)

$\Sigma ML2 = 0$

$C1x35.6 + C2x63.5 + C3x60.3 - R1x85.3 + R3x63.5 + R4x110.1 + R5x110.1 + R6x11.5 = 23909.9$ (16)

$\Sigma ML3 = 0$

$C1x55.7 + C2x0 + C3x60.3 + R1x110.1 + R2x20.1 - R4x11.5 - R5x110.1 + R6x38.1 = -46713.1$ (17)

$\Sigma ML4 = 0$

$C1x16.9 + C2x115.5 + C3x55.3 + R1x110.1 + R2x110.1 + R3x11.5 - R5x98.6 + R6x38.1 = 18569.7$ (18)

$\Sigma ML5 = 0$

$C1x16.9 - C2x16.9 - C3x49.8 - R1x19.05 - R2x110.1 + R3x110.1 + R4x98.6 + R6x98.6 = 11809.7$ (19)

$\Sigma ML6 = 0$

$C1x115.5 + C2x63.5 + C3x3.2 + R1x11.5 + R2x11.5 + R3x63.5 + R4x52 + R5x63.5 = -78008.5$ (20)

These nine equations are converted to matrices form and then solved in MATLAB R2009b to get the solution.

So, clamping forces at load step 1 when the tool position is 101.6mm, 34.29mm, 127mm are:

$$C1 = 810.1N \; C2 = 376.8N \; C3 = 341.3N$$

Similarly, we applied the balancing force-moment method on the remaining nine load steps and obtained the values of corresponding required clamping forces.

At load step 2 when the tool position is 101.6mm, 34.29mm, 101.6mm:

$$C1 = 722.5N \; C2 = 70.9N \; C3 = 1456.5N$$

At load step 3 when the tool position is 101.6mm, 34.29mm, 76.2mm:

$$C1 = 902.3N \; C2 = 489.2N \; C3 = 1792.6N$$

At load step 4 when the tool position is 101.6mm, 34.29mm, 50.8mm:

$$C1 = 1103.1N \; C2 = 565.1N \; C3 = 1507.2N$$

At load step 5 when the tool position is 101.6mm, 34.29mm, 25.4mm:

$$C1 = 875.2N \; C2 = 301.7N \; C3 = 1628.9N$$

At load step 6 when the tool position is 31.92mm, 38.1mm, 63.64mm:

$$C1 = 395.1N \; C2 = 266.8N \; C3 = 242.1N$$

At load step 7 when the tool position is 31.92mm, 30.48mm, 63.64mm:

$$C1 = 340.7N \; C2 = 298.1N \; C3 = 199.5N$$

At load step 8 when the tool position is 31.92mm, 22.86mm, 63.64mm:

$$C1 = 321.1N \; C2 = 210.1N \; C3 = 187.6N$$

At load step 9 when the tool position is 31.92mm, 15.24mm, 63.64mm:

$$C1 = 410.8N \; C2 = 303.3N \; C3 = 180.1N$$

At load step 10 when the tool position is 31.92mm, 7.62mm, 63.64mm:

$$C1 = 450.6N \; C2 = 321.6N \; C3 = 171.2N$$

So, we will pick the maximum values for each clamping force which are actually the optimized clamping forces for our case:

$$C1 = 1103.1N \; C2 = 565.1N \; C3 = 1792.6N$$

Reactions at the locators corresponding to these clamping forces are:

$$R1 = 455.9N \; R2 = 109.9N \; R3 = 528.1N$$
$$R4 = 1000.6N \; R5 = 891.5N \; R6 = 768.7N$$

Now the final step is to determine the deformation of the workpiece at all load steps as well as against the optimized clamping forces and compare their values. For that purpose, we performed the finite element analysis of the workpiece against the above mentioned machining processes in ANSYS using harmonic analysis as the machining forces are cyclic in nature. The FEA models of all the load steps are given below. The locators are modeled as displacement constraints while clamps are modeled as concentrated point loads.

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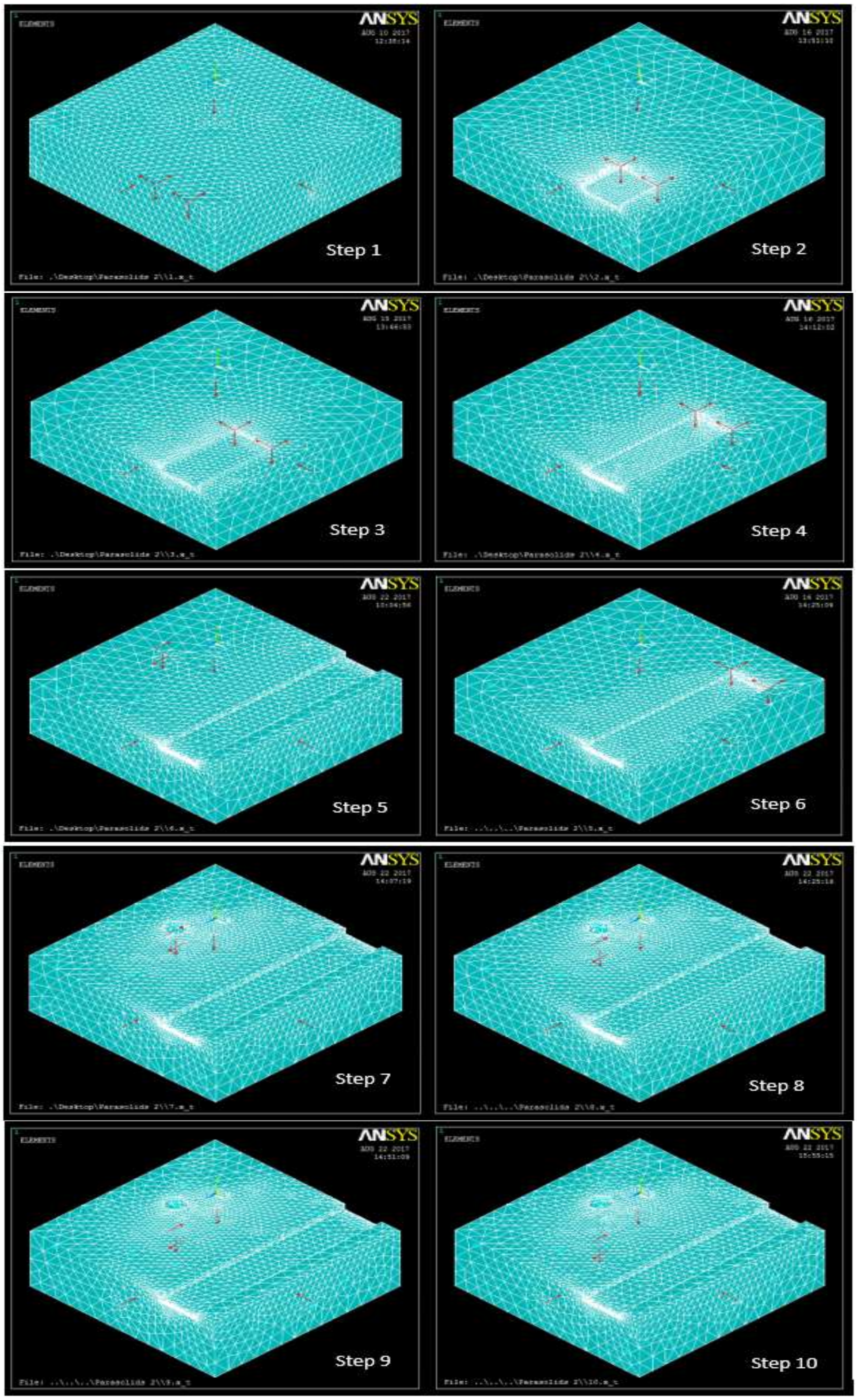

FIGURE 4. WORKPIECE MODEL

IV. SIMULATIONS AND RESULTS

A. OPTIMIZED FIXTURE LAYOUT

The fixture layout provided initially by considering the workpiece symmetry served as the reference for commencing the optimization process and later the comparisons were made with it to quantify the deformation reduced during the whole process. TABLE provides the comparison between initial and optimized fixture layouts.

TABLE IV
INITIAL & OPTIMIZED FIXTURE LAYOUT

Element Name	Initial Configuration (mm)			Optimized Configuration (mm)		
	X	Y	Z	X	Y	Z
L_1	0	19.05	84.66	0	19.05	105.4
L_2	0	19.05	42.33	0	19.05	20.1
L_3	63.5	19.05	0	63.5	19.05	0
L_4	95.25	0	42.33	110.1	0	11.5
L_5	95.25	0	84.66	110.1	0	110.1
L_6	31.75	0	63.5	11.5	0	63.5
C_1	127	19.05	63.5	127	19.05	55.7
C_2	63.5	19.05	127	63.5	19.05	127
C_3	44.45	38.1	40	54.8	38.1	60.3

- Locations of L_1 & L_2 are altered by moving them closer to edges of their respective faces.
- Position of L_3 remains unchanged and it keeps following the workpiece symmetry.
- The locators L_4, L_5 & L_6 are repositioned as well; resulting in an increase in the area of triangle formed them.
- The clamp C_1 is marginally moved to the right edge of the concerned face.
- The clamp C_2 remains in the initial position.
- The locality of clamp C_3 is minimally moved nearer to drilling spot.

B. DEFORMATION ANALSIS

Now in order to see what significance these changes in the fixture layout have brought we will have a look at the workpiece maximum deformations under both conditions. The analysis for the deformation at initial and optimized fixture layout is shown in FIGURE 5 & FIGURE 6 respectively.

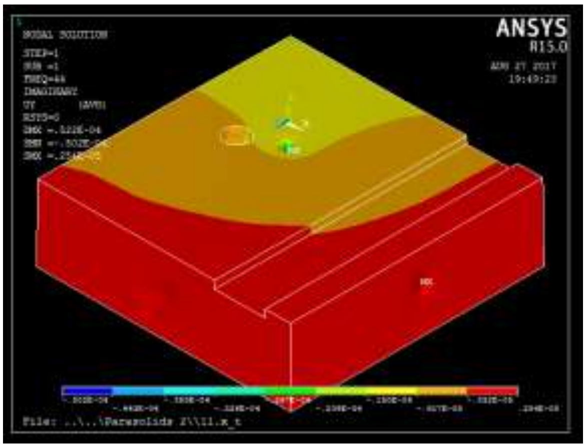

FIGURE 5. MAXIMUM WORKPIECE DEFORMATION AT IFL

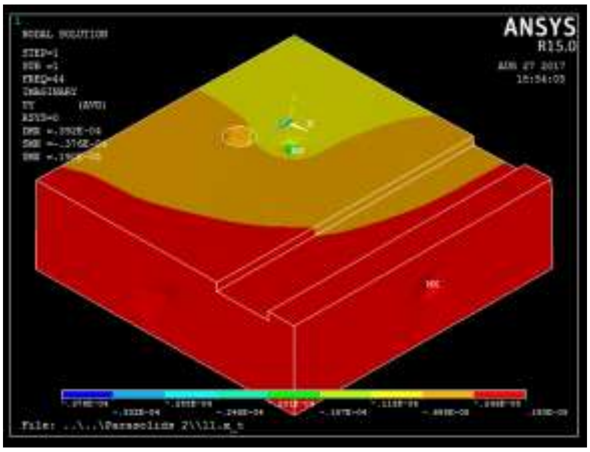

FIGURE 6. MAXIMUM WORKPIECE DEFORMATION AT OFL

As it is evident from the analysis that the maximum deformation has been reduced from 0.0522mm to 0.0392mm. So, this optimization has proved useful in reduction of workpiece deformations.

C. CLAMPING FORCES

Initially we considered all the clamping forces equals to 3000N during optimizing the fixture layout because their optimized magnitudes were not determined yet. After the determination of optimized fixture layout; force-moment equilibrium was applied in order to calculate clamping forces all the load steps. It was observed that these clamping forces had lesser magnitude than the ones assumed initially.

D. DEFORMATION AGAINST ALL LOAD STEPS

To estimate influence of the machining forces that acts at various workpiece localities; harmonic analysis was carried out against each load step. The similar procedure was adapted against the optimized clamping forces as well as shown in the figures below.

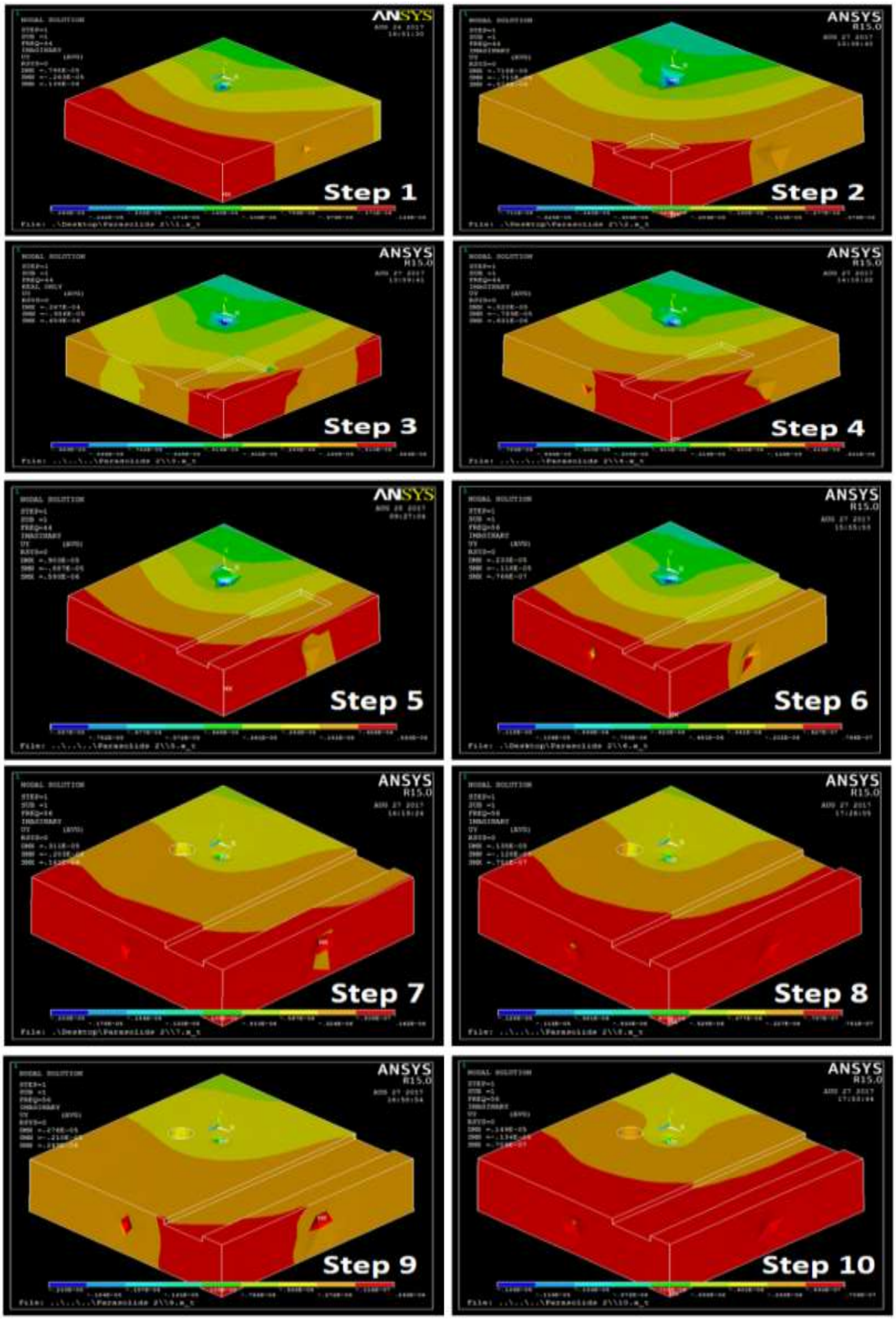

FIGURE 7. MAXIMUM DEFORMATION AT LOAD

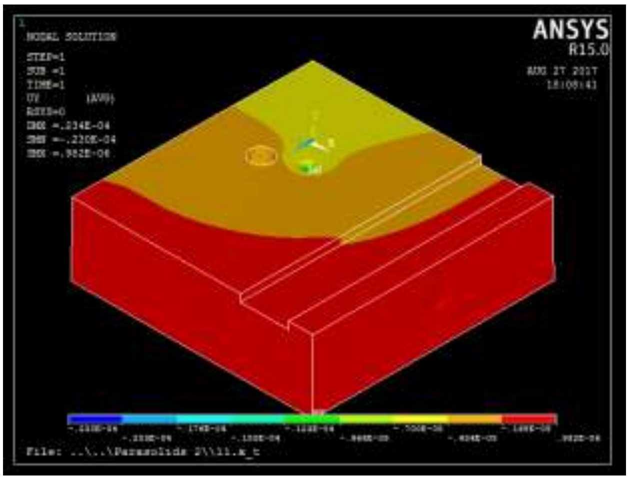

FIGURE 8. MAXIMUM DEFORMATION AT OCF

TABLE V
DEFORMATIONS AT MACHINING LOAD STEPS

Load Steps	Deformation (mm)
Load Step No. 1	0.00798
Load Step No. 2	0.00711
Load Step No. 3	0.02670
Load Step No. 4	0.00820
Load Step No. 5	0.00903
Load Step No. 6	0.00233
Load Step No. 7	0.00311
Load Step No. 8	0.00135
Load Step No. 9	0.00276
Load Step No. 10	0.00149

E. DEFORMATION COMPARISON

TABLE VI shows the deformation comparison before and after the multi-objective optimization. This deformation trend is quite justified as in the beginning with no optimization; we observed highest maximum deformation.

TABLE VI
WORKPIECE DEFORMATION COMPARISON AFTER BOTH THE OPTIMIZATIONS

	Deformation (mm)
Initial Fixture Layout (IFL)	0.05220
Optimized Fixture Layout (OFL)	0.03920
Optimized Clamping Forces (OCF)	0.02730

IFL > OFL > OCF

The deformation reduced afterwards because of fixture layout optimization. Then a further drop in deformation was observed as soon as the clamping forces were optimized.

V. CONCLUSIONS

Multi-objective optimization i.e. fixture layout & clamping forces is carried out on a workpiece that is going through drilling as well as milling operations. The primary objective of this study i.e. workpiece deformation minimization is accomplished. The optimization analysis highlights the following aspects:

- ❖ The machining forces' consideration at several workpiece locations coupled with chip removal phenomenon directly influences the workpiece deformation.
- ❖ Most of the deformation is caused due to the workpiece pre-loading i.e. the clamping forces. As only a slight increase in the deformation is observed upon inclusion of machining forces.

VI. RECOMMENDATIONS

After performing the simulation and optimization analysis it is suggested that the Pakistani manufacturing industry should also adapt this approach for fixture optimization in order to achieve better production and cost reduction due to the fact that through this procedure all the experimental trial and error speculation would be avoided.

In future this work can be extended by considering the following factors:

- ❖ Number of load steps in which our machining operations were discretized can increased in order to have more reliable results. It might help us in further optimization of clamping forces.
- ❖ The effect of mesh density can be considered and the results for different scenarios can be compared.
- ❖ Number of locators and clamps can be optimized as well in order to have a further reduction in the maximum workpiece deformation.
- ❖ The study can involve the analysis by using different materials if there is a constraint that the deformation cannot exceed a certain value and then choose the suitable material.

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