Optimization of Modular Fixture Layout by Minimizing Work-piece Deformation

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Abstract

Machining fixtures are utilized to locate and restrain a workpiece during different manufacturing processes. The workpiece must be properly located and clamped in order to have it to be manufactured according to the prescribed dimensions and tolerance. The real motive of fixture design is to maximize locating accuracy and workpiece firmness while minimizing deformations. The purpose of this research 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 found by harmonic analysis.

1. Introduction

Fixture is any accessory which is used for positioning, clamping and holding up a workpiece in relevance to some other components like cutting tools, measurement devices or welding electrodes etc. while it is being machined. Fixturing elements are crucial part of manufacturing techniques as they play their role in many production and assembling environments. There are a lot of customary devices such as bench vices, chucks and collets etc. which are extensively used in factories for this purpose and are reserved in inventory for routine usage. Fixtures are usually made for a certain process to cater a definite part processing technique and are created exclusively. 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.

Previous FEA based researches in fixture design are discussed. A brief summary of each methodology is given below. Subrahmanyam et al. [1] described the procedure of identifying fixturing features from the design parameters and features involved in machining in a feature-based computer aided drawing system. An organized approach for calculation of forces and moments produced during drilling and milling machining processes were introduced. Amaral et al. [2] developed a technique for sculpting workpiece boundary conditions and external applied forces during a machining operation, analyzed contact area deflection of flexible fixture tool and performed automatic optimization of support locations, using finite element analysis (FEA). Selvakumar et al. [3] discussed the parameters which influence the deformation of the workpiece such as clamping forces, cutting forces, number of locators & clamps and positions of locators and clamps. They determined minimum clamping forces mandatory to secure the workpiece by applying balancing force moment method and then verified it through coulomb static friction law.

Siebenaler et al. [4] considered the effect of fixture body compliance on workpiece deformation in their study. Additionally the influence of some FEM parameters on the forecasting of accuracy was also studied. Kaya et al. [5] applied genetic algorithms (GAs) to the fixture layout optimization problem. The approach of genetic algorithm is coupled with finite element method which was running in batch mode to optimize fixture layout and to figure out the objective function values for each group. Vasundara et al. [6] dealt with forecasting the optimum fixture layout for minimizing the maximum elastic deformation of the part during machining using both Artificial Neural Networks (ANN) and Response Surface Methodology (RSM). The results of ANN and RSM are also compared by considering an example from the previous literature. Prabhakaran et al. [7] presented a fixture layout optimization scheme that used genetic algorithm (GA) and ant colony algorithm (ACA) discretely.

After reviewing the literature we decided to carry out the multi-faceted optimization simultaneously in order to have even lesser deformation. For that purpose we took a symmetrical workpiece upon which drilling and milling operation were to be performed. Then we determined the cutting forces and performed both optimizations.

2. Methology

2.1. Cutting forces determination

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.

2.2. Milling forces

The forces in a milling process includes an axial or thrust load along the axis of the end mill due to a downward push for maintaining the tool-workpiece contact, a transverse or tangential load due to the linear feeding of the workpiece, and a shear or radial force due to rotation of the tool.

To calculate the magnitude of these forces we will use the empirical relations for aluminium workpieces given in Eq. 2.1–2.3.

Tangential Force

$$F_x = K_t \times b \times t_c \text{ (N)} \dots\dots\dots (2.1)$$

Radial Force

$$F_y = K_r \times P_x \text{ (N)} \dots\dots\dots (2.2)$$

Thrust Force

where, t_c is undeformed chip thickness, which is given as

$$t_c = \frac{f}{N_t} \times N \quad \dots\dots\dots(2.4)$$

where, f is feed rate, N_t is number of teeth, N is rotational speed (rpm), V_c is cutting speed = πDN (m/min), D is tool diameter (mm), b is depth of cut (mm), K_t , K_r , K_c are empirical data constants.

$$\ln K_t(t) = 7.28668 - [0.18688 \ln t_c(t)] - [0.08711 \ln V_c(t)] \dots\dots\dots(2.5)$$

$$\ln K_r(t) = 6.58305 - [0.35873 \ln t_c(t)] - [0.33895 \ln V_c(t)] \dots\dots\dots(2.6)$$

$$\ln K_c(t) = 5.98786 - [0.54912 \ln t_c(t)] - [0.48816 \ln V_c(t)] \dots\dots\dots(2.7)$$

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

$$f = 0.2032 \text{ mm/tooth}, N_t = 4, N = 660 \text{ rpm}, D = 25.4 \text{ mm}, b = 3.81 \text{ mm}, f = (660 \times 4)/60 = 44 \text{ Hz}$$

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

$$F_x = 254.6 \text{ N}, F_y = 886.3 \text{ N}, F_z = 442.1 \text{ N}$$

2.3. 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.

Now to calculate the magnitude of these forces we will again use the empirical relations for aluminium workpieces given in Eq. 2.8–2.9.

Tangential Force

$$F_a = M_p (D/20) \text{ in (N)} \dots\dots\dots (2.8)$$

Thrust Force

$$F_t = 4.6343 \times D^{0.97} \times h_{avg}^{0.83} \times h^{0.5} \text{ (N)} \dots\dots (2.9)$$

where, h_{avg} is chip thickness (mm)

where, a is advance in one revolution of the spindle (mm/rev), k is rake angle (rad) and N_f is number of flutes.

Drilling Torque

$$M_p = 0.001542 \times D^{2.0} \times h_{avg}^{0.8} \times h^{0.5} \text{ (Nm)} \dots\dots (2.11)$$

where, D is cutter diameter (mm), h is hardness of the material (N/mm²).

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

$a = 0.178$ mm/rev, $k = 20^\circ$, $h = 95$ (N/mm²), RPM = cutting speed $\times$ 4/Dia of cutter = 1702 rpm

$f = 1702 \times 2/60 = 56.7$ Hz, $D = 12$ mm

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

$$F_a = 7.26\text{N}, F_t = 279.2\text{N}$$

2.4. Optimization and Finite Element Analysis

The main theme of this research 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. The materials which we have selected for our study are Aluminium 6061-T6 for the workpiece and AISI 1144 Steel for fixtures. The properties of both the materials are given in the following Table 1:

Table 1
Workpiece and fixture material properties.

Material	Young's Modulus (GPa)	Density (kg/m ³)	Poisson's Ratio	Yield Strength (Pa)
Aluminium 6061-T6	70	2700	0.35	1.7×10^8
AISI 1144 Steel	200	7861	0.295	6.7×10^8

2.5. Fixture Layout Optimization

We can minimize part deflection and maximize its locating accuracy by optimizing the boundary conditions which includes the locator and clamp positions & clamping force magnitudes. The locators fulfill two purposeful desires: (1) Locate and stabilize the workpiece and (2) Minimize workpiece deformations by serving as supports. The optimization analysis tries to fulfill both functional

requirements using only one design parameter which is the identifying the position of the locators on the workpiece surface [10].

The fixture layout optimization analysis is executed using ANSYS which proposes two optimization techniques to cater an extensive range of optimization problems. (1) The sub-problem approximation method is an advanced zero-order method which can be easily adapted to solve most of the engineering problems. (2) The first order method is more sensitive to design parameters and is appropriate for problems which demands high accuracy. For both the methods, ANSYS executes a succession of analysis-evaluation-modification cycles.

The optimization variables are defined as; Design Variables (DVs) are independent quantities which are altered to attain the optimum design [11]. 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 [12]. A state variable can either have a maximum and minimum limit, or it may have only one of these limits. The state variable in our case is the Von Mises Stress which should be less than the yield strength of the workpiece material that is 170 MPa; so that the material does not deform plastically under any circumstances. Objective Function is the dependent variable that we are trying to minimize. It must be a function of the DVs i.e. altering the values of the DVs must bring a change in the objective function's value. In our case the objective function is the maximum deformation of the workpiece. These optimization variables are enlisted in the Table 2.

Table 2
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
	($VONMISES < \text{Yield Strength}$)
Objective Function	Maximum Displacement
	(D_{MAX})

Now in order to start our analysis we have to prescribe the upper and lower for the design variables which are given in the Table 3.

Table 3
Lower and upper limits for the design variables.

Variable Name	Lower Limit (mm)			Upper Limit (mm)		
	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.

2.6. Clamping Forces Optimization

The clamping forces are being optimized through balancing force-moment method [12]. 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 Fig. 3.

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

$$\Sigma F_X = 0 \quad \Sigma F_Y = 0 \quad \Sigma F_Z = 0$$

$$-C_1 + R_1 + R_2 - F_X = 0 \quad -C_3 + R_4 + R_5 + R_6 - F_Y = 0 \quad -C_2 + R_3 - F_Z = 0$$

$$-C_1 + R_1 + R_2 = 886.3 \dots (3.1)$$

$$-C_3 + R_4 + R_5 + R_6 = 442.1 \dots (3.2)$$

$$-C_2 + R_3 = 254.6 \dots (3.3)$$

$$\Sigma M_{L_1} = 0$$

$$C_1 \times 49.7 + C_2 \times 63.5 + C_3 \times 54.8 - R_2 \times 85.3 + R_3 \times 63.5 + R_4 \times 110.1 + R_5 \times 110.1 + R_6 \times 11.5 = -51630.5 \dots (3.4)$$

$$\Sigma M_{L_2} = 0$$

$$C_1 \times 35.6 + C_2 \times 63.5 + C_3 \times 60.3 - R_1 \times 85.3 + R_3 \times 63.5 + R_4 \times 110.1 + R_5 \times 110.1 + R_6 \times 11.5 = 23909.9 \dots (3.5)$$

$$\Sigma M_{L_3} = 0$$

$$C_1 \times 55.7 + C_2 \times 0 + C_3 \times 60.3 + R_1 \times 110.1 + R_2 \times 20.1 - R_4 \times 11.5 - R_5 \times 110.1 + R_6 \times 38.1 = -46713.1 \dots (3.6)$$

$$\Sigma M_{L_4} = 0$$

$$C_1 \times 16.9 + C_2 \times 115.5 + C_3 \times 55.3 + R_1 \times 110.1 + R_2 \times 110.1 + R_3 \times 11.5 - R_5 \times 98.6 + R_6 \times 38.1 = 18569.7 \dots (3.7)$$

$$\Sigma M_{L_5} = 0$$

$$C_1 \times 16.9 - C_2 \times 16.9 - C_3 \times 49.8 - R_1 \times 19.05 - R_2 \times 110.1 + R_3 \times 110.1 + R_4 \times 98.6 + R_6 \times 98.6 = 11809.7 \dots (3.8)$$

$$\Sigma M_{L_6} = 0$$

$$C_1 \times 115.5 + C_2 \times 63.5 + C_3 \times 3.2 + R_1 \times 11.5 + R_2 \times 11.5 + R_3 \times 63.5 + R_4 \times 52 + R_5 \times 63.5 = -78008.5 \dots (3.9)$$

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 101.6 mm, 34.29 mm, 127 mm are:

$$C_1 = 810.1 \text{ N} \quad C_2 = 376.8 \text{ N} \quad C_3 = 341.3 \text{ N}$$

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 101.6 mm, 34.29 mm, 101.6mm:

$$C_1 = 722.5\text{N } C_2 = 70.9\text{N } C_3 = 1456.5\text{N}$$

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

$$C_1 = 902.3\text{N } C_2 = 489.2\text{N } C_3 = 1792.6\text{N}$$

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

$$C_1 = 1103.1\text{N } C_2 = 565.1\text{N } C_3 = 1507.2\text{N}$$

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

$$C_1 = 875.2\text{N } C_2 = 301.7\text{N } C_3 = 1628.9\text{N}$$

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

$$C_1 = 395.1\text{N } C_2 = 266.8\text{N } C_3 = 242.1\text{N}$$

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

$$C_1 = 340.7\text{N } C_2 = 298.1\text{N } C_3 = 199.5\text{N}$$

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

$$C_1 = 321.1\text{N } C_2 = 210.1\text{N } C_3 = 187.6\text{N}$$

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

$$C_1 = 410.8\text{N } C_2 = 303.3\text{N } C_3 = 180.1\text{N}$$

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

$$C_1 = 450.6\text{N } C_2 = 321.6\text{N } C_3 = 171.2\text{N}$$

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

$$C_1 = 1103.1\text{N } C_2 = 565.1\text{N } C_3 = 1792.6\text{N}$$

Reactions at the locators corresponding to these clamping forces are:

$$R_1 = 455.9\text{N} \quad R_2 = 109.9\text{N} \quad R_3 = 528.1\text{N}$$

$$R_4 = 1000.6\text{N} \quad R_5 = 891.5\text{N} \quad R_6 = 768.7\text{N}$$

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.

3. Simulation And Results

3.1. Optimized fixture layout

As we initially provided a fixture layout keeping in view the symmetry of the workpiece; it served the purpose for initializing the optimization and also as a basis for the comparison that how much deformation we were able to reduce in the process [13]. Table 4 provides the comparison between initial and optimized fixture layouts.

Table 4
Initial & optimized locator and clamp locations.

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

Positions of L_1 and L_2 are changed and they are moved towards the edges of the face upon which they are being applied. L_3 is not moved and it follows the symmetry. Positions of L_4 , L_5 and L_6 are changed as well and the area covered by the triangle formed by these locators is increased. C_1 is slightly shifted towards the right side of the face on which it is acting. The position of C_2 is unchanged. The location of C_3 is slightly shifted closer to the drilling point.

3.2. Deformations at Initial & Optimized Fixture Layouts

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 [14]. The analysis for the deformation at initial and optimized fixture layout is shown in Figs. 5 and 6 respectively.

As we can see that the deformation is reduced from 0.0522 mm to 0.0392 mm so the optimized fixture layout has decreased deformation quite significantly.

3.3. Optimized clamping forces

We assumed all the three clamping forces to be 3000N initially while performing fixture layout optimization as they were not known yet. Once the optimized fixture layout was determined we applied the balancing force-moment method to the FBD of the workpiece and calculated the clamping forces at each load step which were found to be less than the initially assumed value [14, 15].

3.4. Deformations at different load steps

So in order to see the effect of machining forces acting upon different locations of the workpiece. We performed harmonic analysis of the workpiece at each load step and also did the same for the optimized clamping forces as shown in Fig. 7 and Fig. 8.

The deformations under all the scenarios are given in Table 5

Table 5
Deformation values during different analysis.

Scenario	Deformation Value (mm)
Load Step 1	0.00798
Load Step 2	0.00711
Load Step 3	0.02670
Load Step 4	0.00820
Load Step 5	0.00903
Load Step 6	0.00233
Load Step 7	0.00311
Load Step 8	0.00135
Load Step 9	0.00276
Load Step 10	0.00149
Initial Fixture Layout	0.05220
Optimized Fixture Layout	0.03920
Optimized Clamping Forces	0.02730

3.5. Deformation Sequence

IFL > OFL > OCF > All Load Steps

This sequence of values makes absolute sense as initially no optimization was performed so we had absolute maximum deformation and then as fixture layout was optimized the deformation reduced. There was a further decrease when we optimized the clamping forces as well. As the optimized clamping forces are the maximum forces taken from the load steps so the deformation at OCF are greater than the deformations at all the load steps.

4. Conclusion

Multi-objective optimization of the workpiece upon which drilling and milling operations were performed is done through an FEA package i.e. ANSYS. The objective of the research i.e. minimizing workpiece deformation is achieved. The analysis performed during the study indicates that the application of machining forces at different locations along with the chip removal effect has an effect on the workpiece deformation. Moreover, the pre-loading of workpiece by the clamping forces induces most of the

deformation as the deformation increases only slightly upon loading the workpiece with machining forces.

5. Declarations

Availability of data and materials

Not applicable

Competing interests

There are no conflicts to declare.

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Authors' contributions

Awais Ali: Conceptualization, Methodology, Writing - Original Draft. **Awais Ahmed Khan:** Supervision, Writing - Review & Editing. **Muhammad Qasim:** Writing - Review & Editing, Investigation. **Muhammad Waqas:** Resources, Validation. **Muhammad Ammar:** Supervision, Writing - Review & Editing, Funding acquisition. **Muhammad Yasar Javaid:** Validation, Investigation.

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References

1. Subrahmanyam SR (2002) Fixturing features selection in feature-based systems. *Computers in Industry* 48 (2):99-108
2. Amaral N, Rencis JJ, Rong YK (2005) Development of a finite element analysis tool for fixture design integrity verification and optimisation. *The International Journal of Advanced Manufacturing Technology* 25 (5-6):409-419
3. Selvakumar S, Arulshri K, Padmanaban K, Sasikumar K (2010) Clamping force optimization for minimum deformation of workpiece by dynamic analysis of workpiece-fixture system. *World Applied Sciences Journal* 11 (7):840-846
4. Siebenaler SP, Melkote SN (2006) Prediction of workpiece deformation in a fixture system using the finite element method. *International Journal of Machine Tools and Manufacture* 46 (1):51-58

5. Kaya N (2006) Machining fixture locating and clamping position optimization using genetic algorithms. *Computers in Industry* 57 (2):112-120
6. Vasundara M, Padmanaban K, Sabareeswaran M, RajGanesh M (2012) Machining fixture layout design for milling operation using FEA, ANN and RSM. *Procedia engineering* 38:1693-1703
7. Prabhakaran G, Padmanaban K, Krishnakumar R (2007) Machining fixture layout optimization using FEM and evolutionary techniques. *The International Journal of Advanced Manufacturing Technology* 32 (11-12):1090
8. Shih AJ, Luo J, Lewis MA, Strenkowski JS (2004) Chip morphology and forces in end milling of elastomers. *Journal of Manufacturing Science and Engineering* 126 (1):124-130
9. Esim E, Yıldırım Ş (2017) Drilling performance analysis of drill column machine using proposed neural networks. *Neural Computing and Applications* 28 (1):79-90
10. Das G, Das P (2015) Cutting Forces in Drilling Operation: Measurement and Modeling for Medium-scale Manufacturing Firms. *International Journal of Computer Applications* 121 (8)
11. Selvakumar S, Arulshri K, Padmanaban K, Sasikumar K (2013) Design and optimization of machining fixture layout using ANN and DOE. *The International Journal of Advanced Manufacturing Technology* 65 (9-12):1573-1586
12. Vasundara M, Padmanaban K (2014) Recent developments on machining fixture layout design, analysis, and optimization using finite element method and evolutionary techniques. *The International Journal of Advanced Manufacturing Technology* 70 (1-4):79-96
13. Wang Y, Chen X, Gindy N Deformation analysis of fixturing for workpiece with complex geometry. In: *Key Engineering Materials*, 2005. Trans Tech Publ, pp 631-636
14. Dong Z, Jiao L, Wang X, Liang Z, Liu Z, Yi J (2016) FEA-based prediction of machined surface errors for dynamic fixture-workpiece system during milling process. *The International Journal of Advanced Manufacturing Technology* 85 (1-4):299-315
15. Deng H, Melkote SN (2006) Determination of minimum clamping forces for dynamically stable fixturing. *International Journal of Machine Tools and Manufacture* 46 (7-8):847-857

Figures

Figure 1

Force components in end milling [8].

Figure 2

Force Components in drilling [9].

Figure 3

Workpiece model.

Figure 5

Maximum Workpiece Deformation at IFL.

Figure 6

Maximum Workpiece Deformation at OFL.

Figure 7

Maximum Deformation at Load.

Figure 8

Maximum Deformation at OCF.