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Optimization of machining fixture layout for thin-walled component using DOE and FEM

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Abstract: Machining fixtures are used to improve the productivity and quality of the finished components. It is essential to produce a component in specified accuracy and quality; this can be achieved by optimizing the precise fixture design based on workpiece geometry and machining parameters. In this work, optimum fixture layout is developed for thin-walled component. Taguchi and response surface methodology-based optimization procedures are established for identifying the optimum fixture layout. Finite element solver ANSYS is used for predicting the workpiece elastic deformation caused by machining and clamping forces.

Keywords: Fixture Layout, Workpiece deformation, Locator, Clamp, Optimization

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1. Introduction

A typical machining fixture consists of fixture body, locating elements and clamping elements. The number and position of these elements plays main role in the quality of the finished components. Li and Melkote (1999) used six point locating method is best suited for locating the prismatic rigid body workpiece, which will constrain all the possible degrees of freedom. Design of experiments (DOE) is a systematic method to determine the relationship between factors affecting a process and the output of that process. In DOE, Taguchi and Response Surface Methodology are considered here as optimization tools.

2. Literature review

There are several studies are carried out in related to fixture layout optimization problems for minimizing workpiece deformation and improving the quality of the finished workpiece. Li and Melkote (1999) proposed a fixture system for elastic model. Nonlinear programming method is used to minimize the workpiece rigid body motion. Li and Melkote (2001) presented clamping force optimization problem for rigid body workpiece. In this study workpiece dynamic machining force is considered. Krishnakumar and Melkote (2000) presented an optimum fixture layout using the genetic algorithm on machined surface due to clamping and machining forces over the entire tool path. Kulankara et al. (2002) has presented iterative fixture layout and clamping force optimization technique for a compliant workpiece using genetic algorithm. This technique minimizes the workpiece deformation for the complete machining process by analyzing different fixture layouts and clamping force.

Siebenaler and Melkote (2006) explore the influence of fixture elements in workpiece accuracy and deformation. The locator's tips are considered as planer and spherical. Finite Element Method (FEM) is used for predicting workpiece deformation. Experimental setup is conducted for measuring the locator's reaction for thin-walled component. Liu et al. (2006) presented an Optimization problem for low rigidity workpiece in peripheral milling. In this paper, a method is proposed to optimize the fixture layout by number and position of the fixture elements. Number of locators on the secondary locating plane is directly influence the workpiece deformation. According to Prabhaharan et al. (2007) among Genetic algorithm (GA) and Ant Colony Algorithm (ACA) for optimum fixture layout, it is concluded that ACA approach provides better solutions for minimizing the dimensional and form errors.

Padmanaban et al. (2009) presented ACA based continuous optimization technique for fixture layout. The workpiece dynamic condition is determined using FEM. The dynamic response is analyzed for all the ACA layouts. In this paper ACA-based continuous method and ACA-based discrete method are compared. Selvakumar et al. (2012) proposed a fixture layout optimization approach for rigid body component and hollow component using artificial neural network (ANN) and DOE and Selvakumar et al. (2013) used FEM for analyzing workpiece deformation. Vasundara et al. (2012) presented a technique for 2D workpiece fixture system in end milling operation for minimizing workpiece deformation. ANN and RSM based optimization techniques are followed. Mathematical equation is developed using RSM and the final deformations are compared with Fem.

Selvakumar et al. (2013) presented combined GA and ANN based fixture layout optimization process for rigid body workpiece. In this work, the results of GA are given as input for ANN. Wenbin Tang et al. (2016) presented location error analysis for workpiece fixture contact system. Two case studies are considered for analysis. 3DCS software is used for predicting the location error. Hussain Lal et al. (2015) used finite element analysis for experimental analysis of deformation of the aluminium 6060-T6 bracket. Real time investigation is conducted for aluminium bracket. Selvakumar et al. (2016) proposed an optimum fixture layout method for drilling of elastomer component. Taguchi method is used as optimization tools. Finally finite element method is used for calculating the workpiece deformation. Sundararaman et al. (2016) used combiner optimization procedure for thin wall component in end milling operation using Genetic algorithm and Particle swarm optimization. Quadratic model is created between the position of fixture elements and maximum workpiece deformation using RSM.

Wang et al. (2016) proposed a positioning analysis of rigid body workpiece by using N-2-1 locating scheme. In this study, six point locating method and N-2-1 locating methods are considered for analysis. In positioning variation analysis, rigid body workpiece and fixture elements are considered. Sabareeswaran et al. (2018) demonstrate a optimization procedure for 2D workpiece - fixture system in end milling operation using genetic algorithm and particle swarm optimization. The natural frequency of the workpiece during material removal is modeled using FEM. PSO provided optimum layout with minimum natural frequency. Crichigno Filho et al. (2019) conducted experimental study on analysis of workpiece location accuracy for 3-2-1 locating system. In this study, three types of locating elements are used, flexible locator, rigid locator and spherical locator. Orientation errors as a function of locator's types are analyzed. Khatu et al. (2022) developed a generic approach for designing a fixture for Wire-Cut EDM Machine. Liu et al. (2022) proposed a dynamic parameter based operational model analysis for thin walled

components in milling operation. To fit the harmonics with multiple fundamental frequencies a revised least-squares (LS) method is proposed. Agarwal and Desai (2021) analyzed geometric tolerance of thin wall components during milling operation and proposed Equivalent Radial Depth of Cut (RDOC) concept to derive component configurations.

The above literatures are focused on fixture layout design using different locating principles and optimization techniques. Results are verified using case studies. Based on the above studies the following points are shortened,

- Several studies on rigid-body model or workpiece-elastic contact model, and elastic deformation is not considered in many of the works.
- Many researchers are considered finite-element method for predicting the workpiece deformations.
- Most of the works solid rigid body models are considered and thin-walled components are rarely considered.
- Many studies do not consider the dynamic machining forces on workpiece.
- Many researchers used six point locating method (3-2-1) to locate the rigid body workpiece.
- Most researchers have optimized the fixture layout using Genetic Algorithm, ANN, and PSO.

3. Methodology

In this research work, Siebenaler and Melkote (2006) workpiece geometry and machining parameters are considered for study. Workpiece geometry conditions and workpiece deformation for various fixture layouts suggested by Taguchi and RSM methods are modeled and predicted using ANSYS work bench. Finally, by comparing the deformation of Taguchi and RSM layouts, optimum fixture layout is achieved. Figure 1 represents the workflow of the proposed work.

4. Selection of fixturing scheme and parameters

The workpiece fixture system presented by Siebenaler and Melkote (2006) is considered for the fixture layout optimization problem described in this work. Table 1 represents the workpiece property and machining parameters. Figure 2 shows the workpiece geometry.

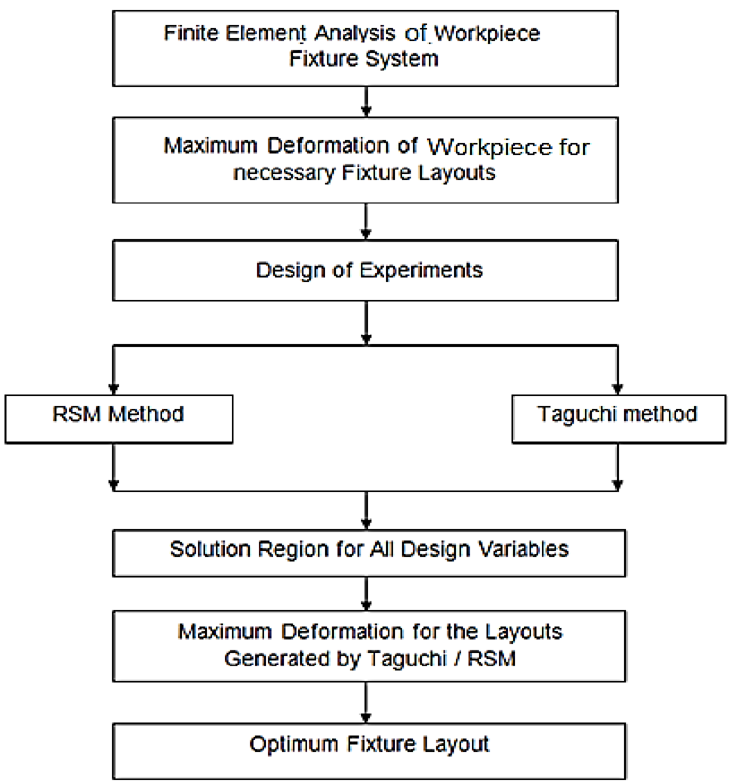


Figure 1. Process chart for fixture layout optimization.

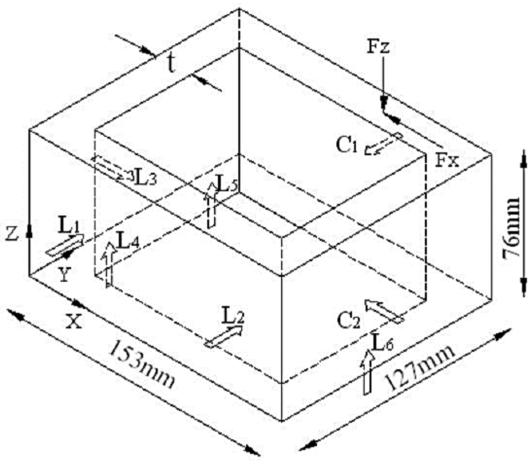


Figure 2. Workpiece geometry.

Table 1. Workpiece properties and machining parameters.

Material	Aluminium 6061 T6
Poission Ratio	0.33
Youngs modulus	70Gpa
Density	2795kg/m^3
Dimension in (X, Y and Z Axis)	127x76 x 153
Machining Forces in N	F_Z=900 N, and F_y= 1322.6N
Clamping Forces in N	C_1= 600 N, and C_2= 1100 N,

Fixture layout with six locators and two clamps consist 24 coordinate values. For each fixture elements two coordinates' values are considered as constant and remaining one is treated as variable. Hence, the number of design variables is eight. The boundary conditions for all the fixture elements are presented in Table 2. Locators are applied as displacement constraints and clamping forces are applied at clamps. There are six locating elements and three clamping elements are considered for analysis. Figure 3 shows the static condition of the workpiece-fixture system.

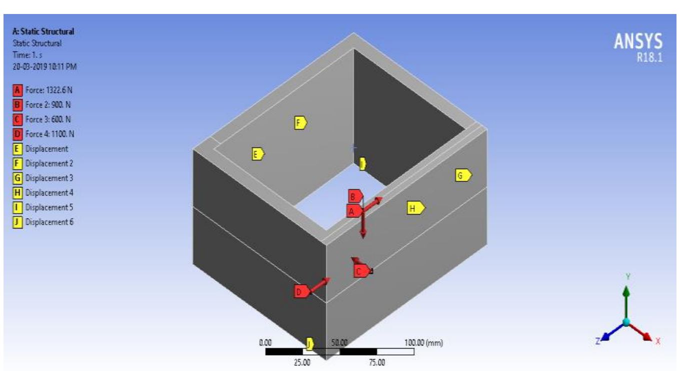


Figure 3. Structural analysis of workpiece-fixture system.

Table 2. Boundary values of locators and clamps.

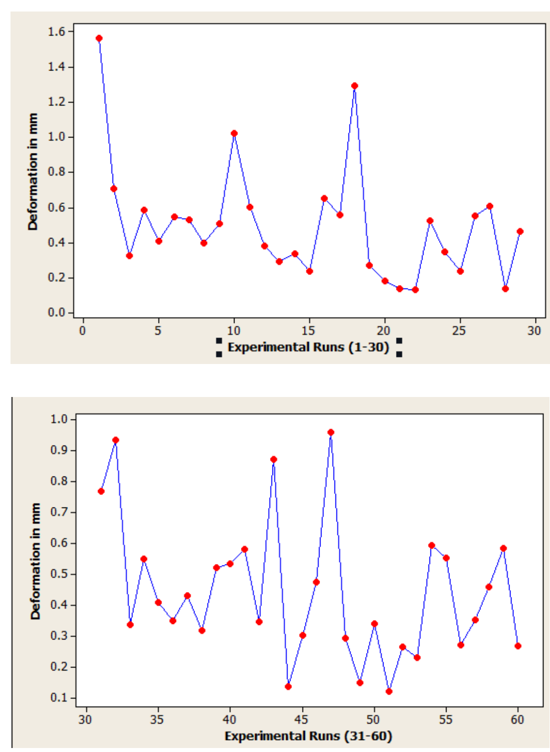
Elements	Boundary Conditions in mm	
	Constant	Variable
L_1	X=0, Y=38	Z =10 to 60
L_2	X=0, Y=38	Z = 70 to 43
L_3	Z=0, Y=38	X =10 to 117
L_4	Z=5, Y=0	X = 10 to 50
L_5	Z=5, Y=0	X = 70 to 117
L_6	Z=148, Y =0	X = 10 to 117
C_1	X=127, Y=38	Z = 10 to 117
C_2	Z=153, Y=38	X = 10 to 117

5. Optimization of fixture layout using DOE

Design of Experiments (DOE) based optimization technique is considered for the fixture layout optimization problem. In DOE, Response Surface Methodology and Taguchi method is considered for analysis. The optimum fixture layout is identified by comparing the better fixture layouts of RSM and Taguchi.

5.1. Respond surface methodology

In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. Fraction factorial method and eight factors are considered. 91 runs are carried out using Minitab Software and the deformation of corresponding fixture layouts are Calculated. The workpiece deformations for 91 different fixture layouts are shown in Figure 4.



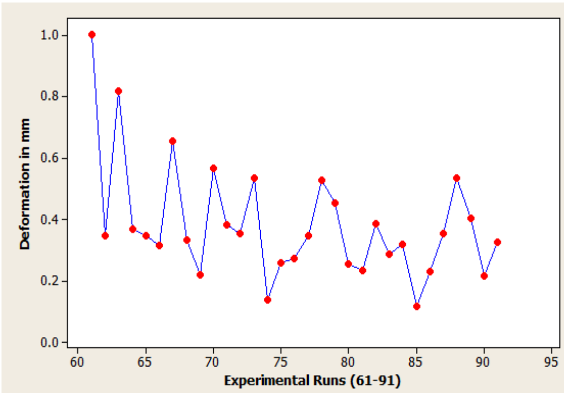


Figure 4. Workpiece deformation using RSM (a) 1-30 runs, (b) 31-60 runs, and (c) 61-91 runs.

5.5.1. Optimum Layout using RSM

RSM provides 91 different layouts for the given boundary conditions. The optimum fixture layout suggested by response surface methodology is represented in Table 3. Maximum workpiece deformation for the optimum fixture layout by RSM is 0.11736 mm which is shown in Figure 5.

Table 3. Optimum fixture layout using RSM.

Elements	Position in mm
L_1	44
L_2	85
L_3	113
L_4	17
L_5	74
L_6	111
C_1	111
C_2	112

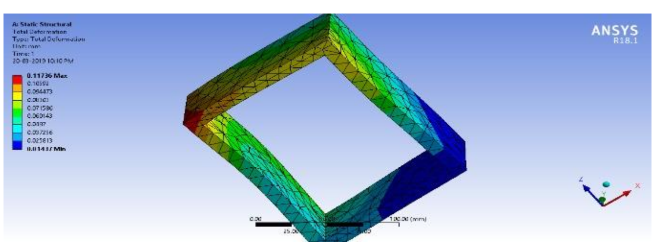


Figure 5. Workpiece deformation for RSM based optimum layout.

5.2. Taguchi method

The Taguchi method is a structural approach for determining the best combination of inputs to produce a robust design of experiments. L27 orthogonal array is used, 8 factors and 3 levels are considered. Figure 6 represents the workpiece deformation using Taguchi method. (a) 27 fixture layouts in first iteration, (b) 27 fixture layouts in second iteration, and (c) 27 fixture layouts in third iteration.

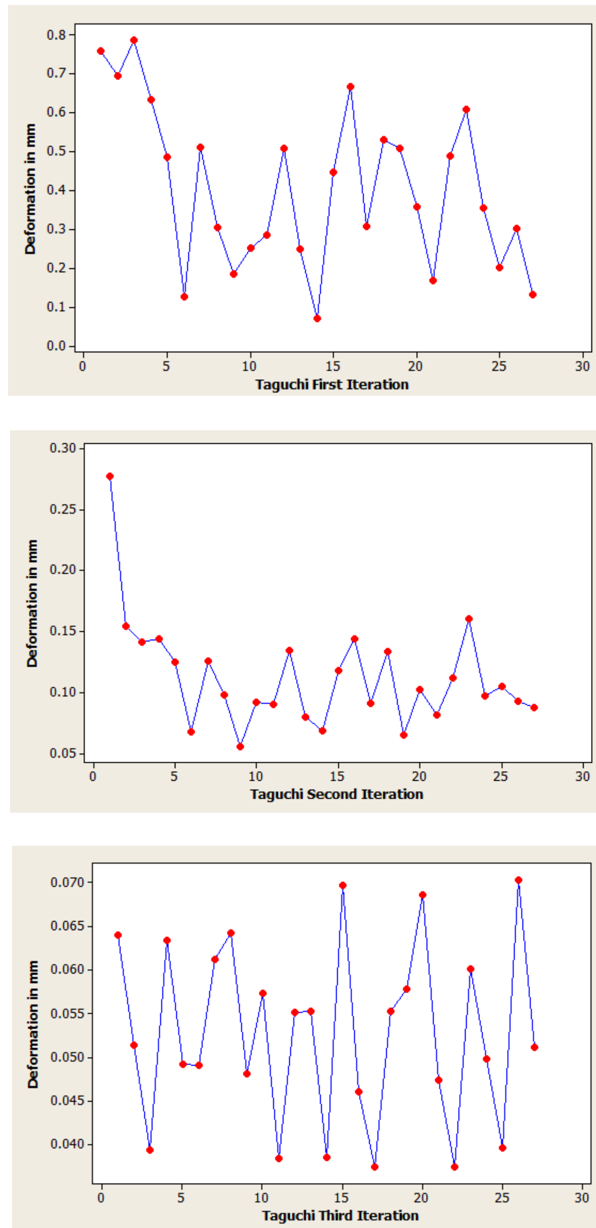


Figure 6. Workpiece deformation using Taguchi (a) first iteration, (b) second iteration, and (c) third iteration.

5.3. Optimum layout using Taguchi method

Finally, the optimum fixture layout by the Taguchi is obtained at third iteration. Table 4 represents the optimum layout by the Taguchi method. The maximum workpiece deformation for optimum layout is 0.03747 mm which is shown in Figure 7.

Table 4. Optimum layout using Taguchi method.

Elements	Position in mm
L_1	31.5
L_2	116
L_3	110
L_4	22
L_5	93.5
L_6	115.5
C_1	40.5
C_2	103.5

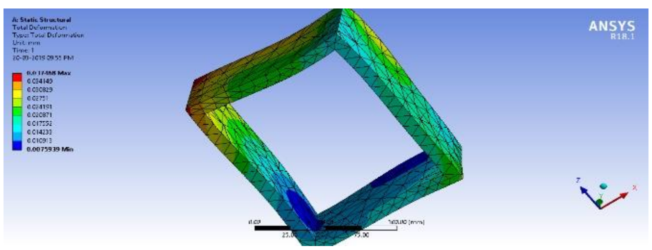


Figure 7. Optimum layout using Taguchi method.

5.4. Comparison of results

The optimum fixture layout of Response Surface Methodology and Taguchi method are compared in Table 5. Taguchi method is providing the minimum deformation than the RSM.

Table 5. Comparison of results.

Fixture Elements	Optimum layout	
	RSM	Taguchi
L_1	44	31.5
L_2	85	116
L_3	113	110
L_4	17	22
L_5	74	93.5
L_6	111	115.5
C_1	111	40.5
C_2	112	103.5
Deformation in mm	0.11736	0.03746

6. Conclusion

In this work, an active effort is made to improve the quality of the finished component by model the workpiece- fixture interaction system to minimize the workpiece deformation using RSM and Taguchi methods. The productivity and quality of the component is improved through the optimum fixture layout by achieving minimum workpiece deformation because of machining and clamping forces. In this work DOE based optimization procedure to solve the fixture design problem is briefly explained. The following conclusions are made from this work.

- Taguchi based optimization procedure provides better rigidity for rigid body workpiece.
- Better quality of the component can be accomplished by minimizing the workpiece Eleatic deformation.
- DOE based optimization procedure is better suited for fixture layout optimization problems. Comparing with GA, ANN and mathematical based optimization procedures.

Conflict of interest

The authors do not have any type of conflict of interest to declare.

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