International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 7 (2018) pp. 4675-4681

Force and Deformation Analysis for Determination of Optimum Fixture Configuration

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Abstract

An important aspect in the design of a good fixture is that of imparting sufficient rigidity to the entire work piece surface that are to be machined. Rigidity refers to the ability of the system to withstand applied loads with minimal deformation. A good fixture must able to completely restrain the work piece to counter any possible cutting forces and couples in machining stages.

The present study aims at implementing finite element analysis and finite element optimization techniques to determine the optimum fixture configuration for drilling through a deformable work piece. The 3-2-1 locating principle has been used and in order to simulate real time conditions contact elements have been used at the interfaces of the work piece and the fixturing elements. The desired fixturing characteristics are optimized with respect to the objective function. Excessive clamp forces and improper location may cause large elastic deformations in the work piece. Hence the lateral deflection of the work piece is chosen as the objective function. ANSYS software is used to carry out the Finite Element Analysis and optimization. Three case studies have been taken to illustrate the method. Comparison has been made between the initial and optimum fixture configuration.

Keywords: Optimization, Fixture, Finite Element Method, ANSYS, Force

INTRODUCTION

Fixtures are essentially work holding devices, which locate and restrain a work piece while some operation is being performed on it. These operations include machining, welding, assembly, inspection etc. Nowadays various analyses are being done in order to develop an accurate fixture structure for reducing dimensional variations in the final product. Some of the analysis includes geometric, kinematic, force and deformation analysis. Usually force analysis is concerned with checking whether the forces applied by the fixtures are sufficient to maintain static equilibrium in the presence of cutting forces. Deformation analysis considers that a part may deform elastically and/or plastically under the influence of cutting and clamping forces so that desired tolerances will not be achieved. Fixtures are used to locate and constrain a work piece during a machining operation, minimizing work piece and fixture tooling deflections due to clamping and cutting forces are critical to ensuring accuracy of the machining operation.

Traditionally, machining fixtures are designed and manufactured through trial-and-error, which prove to be both expensive and time-consuming to the manufacturing process. To ensure a work piece is manufactured according to specified dimensions and tolerances, it must be appropriately located and clamped, making it imperative to develop tools that will eliminate costly and time-consuming trial-and-error designs. Proper work piece location and fixture design are crucial to product quality in terms of precision, accuracy and finish of the machined part. Theoretically, the 3-2-1 locating principle can satisfactorily locate all prismatic shaped work pieces. This method provides the maximum rigidity with the minimum number of fixture elements. To position a part from a kinematic point of view means constraining the six degrees of freedom of a free moving body (three translations and three rotations). Three supports are positioned below the part to establish the location of the work piece on its vertical axis. Locators are placed on two peripheral edges and intended to establish the location of the work piece on the x and y horizontal axes. Properly locating the work piece in the fixture is vital to the overall accuracy and repeatability of the manufacturing process. Locators should be positioned as far apart as possible and should be placed on machined surfaces wherever possible. Supports are usually placed to encompass the center of gravity of a work piece and positioned as far apart as possible to maintain its stability. The primary responsibility of a clamp in fixture is to secure the part against the locators and supports. Clamps should not be expected to resist the cutting forces generated in the machining operation. Mass production methods demand a fast and easy method of positioning work for accurate operations on it.

Afzeri *et al* [1], studied the automatic mechanism using pin type fixture for holding a workpiece during machining process. The hybrid optimization algorithm is introduced to obtain the optimum configuration of pin type fixture. Combination between Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) algorithms is enable to determine optimum clamping respect to minimum workpiece deformation. Spherical type pin fixture with array arrangement in two opposite side conforms geometry of workpiece through to two supporting action. Deformation as effect of clamping force and friction slip are predicted by simulation of pin-workpiece clamping model and analyzed by Finite Element methods. Guohua Qin *et al* [2] considering the great impacts of the application sequence of multiclamps on the workpiece machining accuracy, this paper analyzes and optimizes clamping sequence. A new methodology that takes into account the varying contact forces and friction force during clamping is presented for the first time. A new analysis model is established to capture the effect of clamping sequence on contact force distributions and workpiece machining accuracy. S. Selvakumar *et al* [3], discussed 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. Finally, the deformation of the workpiece for the optimum clamping forces is determined by Harmonic analysis using FEM software. Li B *et al*. [4] studied 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. Mohsen Hamedi *et al*. [5] 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.

The present study aims at optimizing the position of locators and clamps in a prismatic work piece fixture setup and also the required clamping forces so as to minimize the deflection of the work pieces and the stresses developed due to drilling and clamping forces. Force and deformation analysis is to be carried out to determine the optimal configuration. The finite element technique has been used for determining the deflection and induced stresses of the work piece under various drilling conditions.

CONTACT THEORY

In the present work, as the fixturing elements are relatively harder compared to the work piece, the contact between work piece and fixturing elements has been modeled as a rigid to flexible contact. The contacting surfaces of the work piece have been meshed with eight noded quadrilateral surface-to-surface contact elements and that of locators and clamps have been meshed using surface-to-surface triangular target elements. There are two types of surface-to-surface contact elements namely flexible to rigid contact and contact between rigid bodies. In the case of flexible to rigid surface contact the rigid surface is referred to as the 'target surface' and is modeled with target elements. The surface of the deformable body is referred to as the 'contact surfaces' and is meshed with contact elements. Contact problems are highly nonlinear and require significant computer time to solve. Contact problems present two significant difficulties. First, we have run the problem depending on the loads, material, boundary conditions and other factors. Surfaces could come into contact with each other in a largely unpredictable and abrupt manner. Second, most contact problems need to account for friction. There are several friction laws and models to choose from, and all are nonlinear. Frictional response can be chaotic, making solution convergence difficult. The node-to-node contact elements are typically used to model point to point contact applications, and in order to use node-to-node contacts, we need to know the location of contact beforehand. These types of contact problems usually involve small relative sliding between contacting surfaces.

Solid (3-D) 8 Noded Element

SOLID185 is used for the 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials.

Tetrahedral 10 Noded Structural Solid Element

SOLID187 element is a higher order 3-D, 10-node element. SOLID187 has a quadratic displacement behavior and is well suited to modeling irregular meshes (such as those produced from various CAD/CAM systems).The element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials.

DESIGN OPTIMIZATION

Design optimization is a technique that seeks to determine an optimum design by "optimum design," we mean one that meets all specified requirements but with a minimum expense of certain factors such as weight, surface area, volume, stress, cost, etc. In other words, the optimum design is usually one that is as effective as possible. Virtually any aspect of design can be optimized namely dimensions (such as thickness), shape (such as fillet radii), placement of supports, cost of fabrication, natural frequency, material property, and so on. The ANSYS program offers two optimization methods to accommodate a wide range of optimization problems viz. The sub-problem approximation method which is an advanced zero-order method that can be efficiently applied to most engineering problems and The first order, which is based on design sensitivities and requires high computation time.

For both the sub-problem approximation and first order methods, the program performs a series of analysis-evaluation-modification cycles. That is, an analysis of the initial design is performed, the results are evaluated against specified design criteria, and the design modified as necessary. This process is repeated until all specified criteria are met. It is important that the model must be created parametrically and results also retrieved parametrically. It is not necessary to create all dimensions of model parametrically, but the dimensions to be optimized must be defined parametrically. Initial analysis is carried out with arbitrarily initialized design parameters and is used to create analysis file and this file is used by the optimizer for each optimization loop with changed value of design parameters. At the end of each loop, a check for convergence is made. Convergence of the problem is said to occur if the current, previous, or best design is feasible and any one of the following conditions is satisfied. The change in objective function from the best feasible design to the current design is less than the objective function tolerance. The change in objective function between the last two designs is less than the objective function tolerance. The changes in all design variables from the current design to the best feasible design are less than their respective tolerances. The change in all design variables between the last two designs is less than their respective tolerances.

Drilling Fixture Optimization

The step involved in the determination of optimal drilling fixture configuration includes (a) **O**ptimization of bottom locator positions (b) Optimization of vertical and horizontal clamp positions (c) Optimization of clamp pressure.

The design variables are the positions of the clamps, locators and the clamp pressure. The state variables include static stability, positive reaction forces at the locators, non-interference with drilling process and undesirable stresses at regions away from drill zone. The objective functions should capture the variable that directly or indirectly reduces the form error as well as the position error that occurs in the machined feature. The Steps involved in optimization is shown in figure 1.

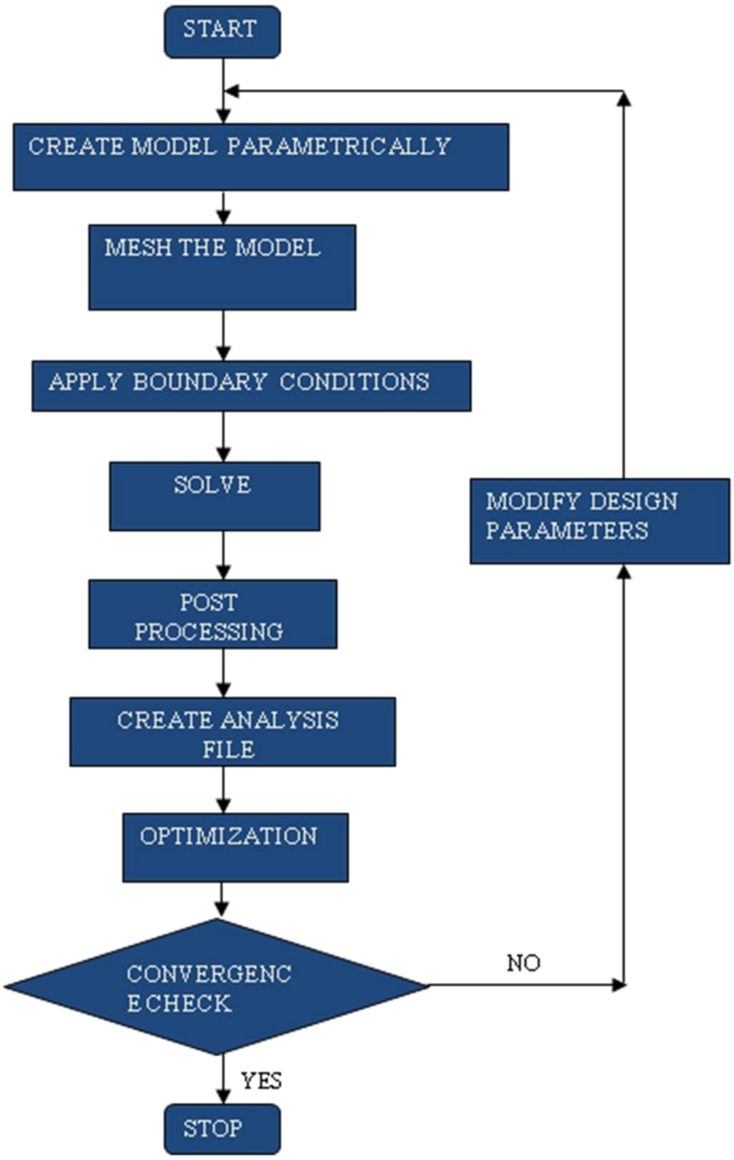

Figure 1: Schematic view of flow chart shows **s**teps involved in optimization

Static Stability

In order to achieve static stability of the work piece before clamping it is ensured that the center of gravity of the work piece falls within the triangle formed by the Three base locators

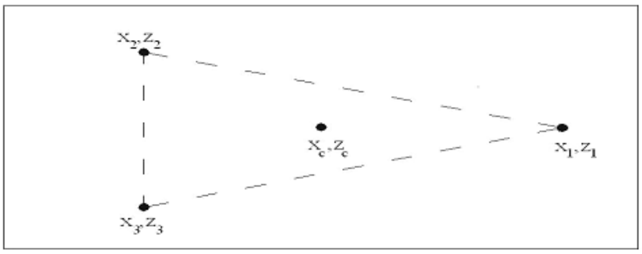

Figure 2: Check for static stability

In figure 2, if (Xc, Zc) represents the position of center of gravity of the work piece in the x-z plane and (X1, Z1), (X2, Z2) and (X3, Z3) are the positions of the three base locators. The equation to the sides of the triangle obtained by joining the three locating pins are given by

(Xc - X1)(Z2 - Z1) - (Zc – Z1)(X2 - X1)

(Xc - X2)(Z3 - Z2) - (Zc – Z2)(X3 - X2)

(Xc - X3)(Z1 - Z3) - (Zc – Z3)(X1 - X3)

If (Xc,Zc) lies within the triangle formed by the three base pins then the products (A x B) and (B x C) should be positive where A,B,C are defined by

A = (Xc - X1) (Z2 - Z1) - (Zc – Z1)(X2 - X1)

B = (Xc - X2) (Z3 - Z2) - (Zc – Z2)(X3 - X2)

C = (Xc - X3)(Z1 - Z3) - (Zc – Z3)(X1 - X3)

Interference Checks

The optimization process shifts the positions of the base locators for each optimization loop. During this process we need to check whether the interference occurs between the base locators and the holes to be drilled between the locator pins and the existing through pockets and holes and between two locator pins themselves. In the present analysis it is ensured that the distance between the centers of any locating pins and the drilled hole. For this purpose the following constraints have to be satisfied with respect to the figure 3

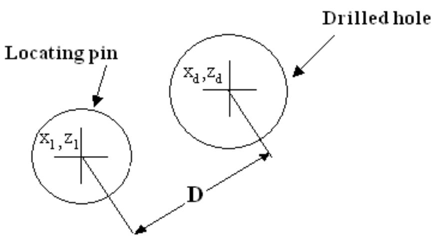

Figure 3 Interference between vertical locator and drilled hole

$$(Xd - X1)^2 + (Zd - Z1)^2 > 1.5R$$

$$(Xd - X2)^2 + (Zd- Z2)^2 > 1.5R$$

$$(Xd - X3)^2 + (Zd - Z3)^2 > 1.5R$$

Where R= sum of the radii of the locating pin and drilled hole Xd and Zd are the coordinates of the center of the drilled hole (X1 , Z 1) ,(X2 , Z2) , (X3 Z3) and (X3, Z3) are the coordinates of the centers of the base locating pins.

Reaction Force Prediction

For various positions of the base and side locators the normal reaction forces are summed up for each locator. This normal component of the reaction should always be directed towards the work piece. If it is not so loss of contact at that locator is indicated. As such a situation is not desirable the total reaction force is monitored continuously. This information can then be used to check for force equilibrium. This is one of the state variables, which is to be considered during the optimization runs.

Optimization Parameters

Before going in for the optimization run, the objective function, the design variables and the state variables have to be defined. In the case of drilling fixture optimization a three-stage optimization has been done. Each stage has its own set of parameters to be defined. The objective function could be that of minimizing the deflection, or stress under the clamps or any other parameter which is of interest to the problem under study. Design variables may be the coordinates of base locators or clamp positions or clamping pressures. State variables could include the parameters for checking for stability or interference or stress under the clamps.

Optimization

Having defined the optimization parameters, the optimization is to be performed. When any of the state variables fail the required checks, an infeasible solution results. A feasible solution is one that satisfies all state variables and the best among the feasible solutions is the optimal solution. The optimal solution is one that minimizes the objective function and also satisfies all the state variables. For the present case study, prismatic work piece of dimensions 150 x 75 x 10mm was considered as shown in figure 4

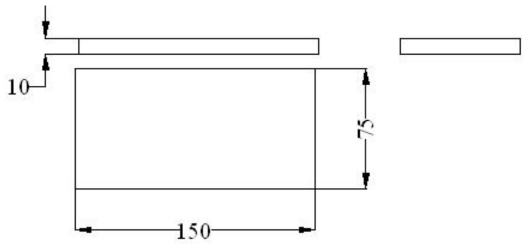

Figure 4: Schematic view work piece

Material properties, Elastic modulus = 2E+05 (N/mm^2), Poisson ratio = 0.3, The desired machined feature is a drilled hole of diameter 10 mm at the center of the work piece whose coordinates are (75, 10, and 37.5). The origin is at the top left corner of the bottom plane. In all the cases, mild steel plate with an elastic modulus of 2E+05 (N/mm^2) and a Poisson ratio of .3 is considered as the work piece To obtain optimum positions of locator and clamps and clamping pressure for a drilling fixture by deformation analysis of work piece using finite element analysis. The optimization has been done in three stages as there would be problems of convergence if all the parameters were optimized simultaneously. The following shows the effect of the optimum values of the fixture parameters that are determined at each stage on overall fixture work piece system: (a) Optimum locating position – Minimize deflection of the work piece (b) Optimum clamping position - Minimize deflection of the work piece (c) Optimum locating position - Minimize the stresses on the work piece. The following are the some of the assumptions made for the analysis (a) Work piece is considered to be a deformable body (b) Fixturing elements are considered to be rigid (c) Contact between fixturing elements (locator and clamp) and work piece has been modeled using surface to surface contact elements (d) Coulomb friction employed between contact surfaces (e) The deformations taking place in the work piece, outside the drilled hole, are elastic and completely recoverable on removal of cutting forces.

Drilling Force Calculation

Axial thrust Fa = 10 C2 d x's y' N, Torque T = 10 C1 d x s y N-mm

d = Diameter of the drill bit, mm, s = Feed, mm/rev

Table 1: Material Composite for Drilling force calculation

Material	C1	x	y	C2	x'	y'
Steel	34	1.9	0.8	85	1.0	0.7

To drill a 10mm hole in a steel work piece for a feed of 0.25 mm/rev, the calculated axial force = 3250 N and Torque = 9000 N-mm

The 3-2-1 locating principle has been used for the work piece location and to obtain complete restraint three clamping forces are applied. A Three stage optimization was carried out to determine the optimum fixture configuration. (a) Optimization of vertical locator positions. (b) Optimization of clamp and horizontal locator positions (c) Optimization of clamp pressure. The desired machined feature is a drilled hole of diameter 10 mm at the center of the work piece whose coordinates are (75, 10, and 37.5).

BOUNDARY CONDITIONS: Axial thrust = 3250 N, Torque = 900 N mm

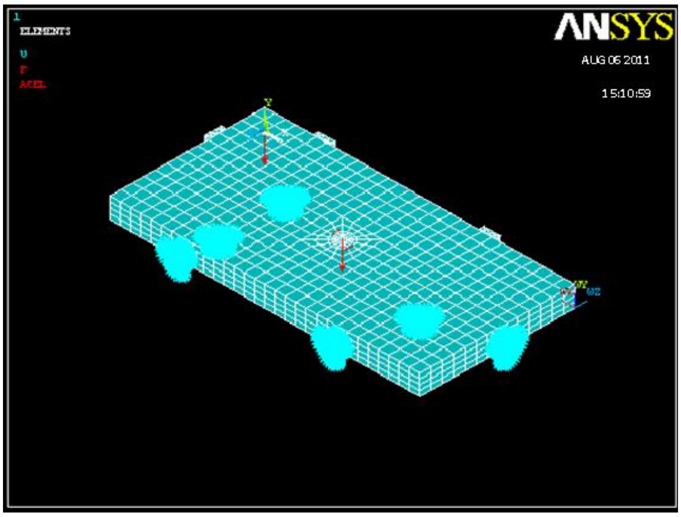

Figure 5: FEM model with applied boundary conditions

In the step, an initial analysis is carried out with arbitrarily initialized design parameters and state variables that satisfy stability and interference checks. It is imported to note that the design variables are to be parametrically defined. The locating pins and clamps are defined as separate volumes, which are in contact with the work piece. This initial run is used to create the analysis file, which will be used in the subsequent optimization runs. Figure 5 shows FEM model with applied boundary conditions and figure 6 shows deformed shape of the work piece

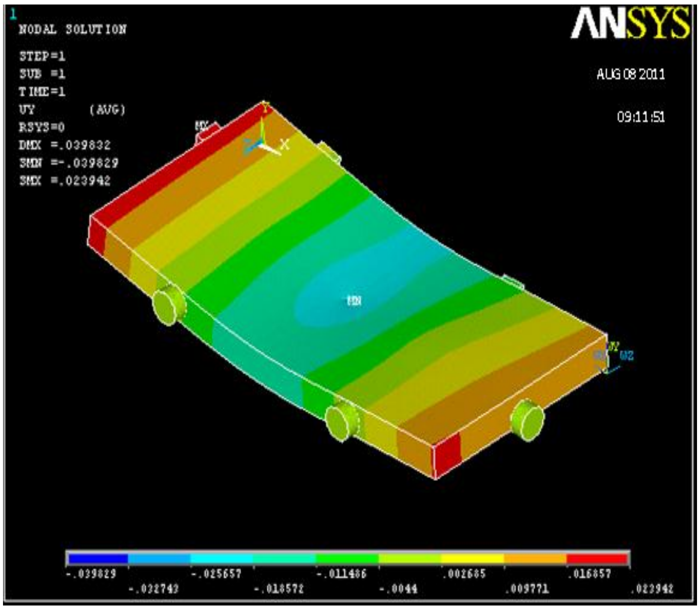

Figure 6: Deformed shape of the work piece

Optimization Stages

STAGE1: Base Locating Points Optimization

Design variables: Position of locators {(X1, Z1), (X2, Z2), (X3, Z3)}

Objective function: Minimize: Deflection (DMAX)

State variables: (a) The locators should not lie under the drilling region (b) The stress developed should be within the limit (c) The C.G of work piece should lie inside the triangle formed by the 3 locators (d) Reaction at the locators should always be towards the work piece.

STAGE2: Clamping and Side Locating Point Optimization

Design variables: Positions of side locators (L1, L2, L3) and Positions of the clamps (C1, C2, C3)

Objective function: Minimize: Deflection (DMAX)

State variables: (a) Stress (SMAX) should be within the limit i.e. less than yield stress at all points except at the drilling zone (b) Reaction at the locators should always be positive, i.e. it should be directed towards the work piece.

STAGE 3: Clamping Pressure Optimization

Design variable: Clamping pressure (P)

Objective function: Minimize: Stress (Smax)

State variable: (a) Reaction at the locators should always be towards the work piece (b) Maximum lateral deflection should not increase.

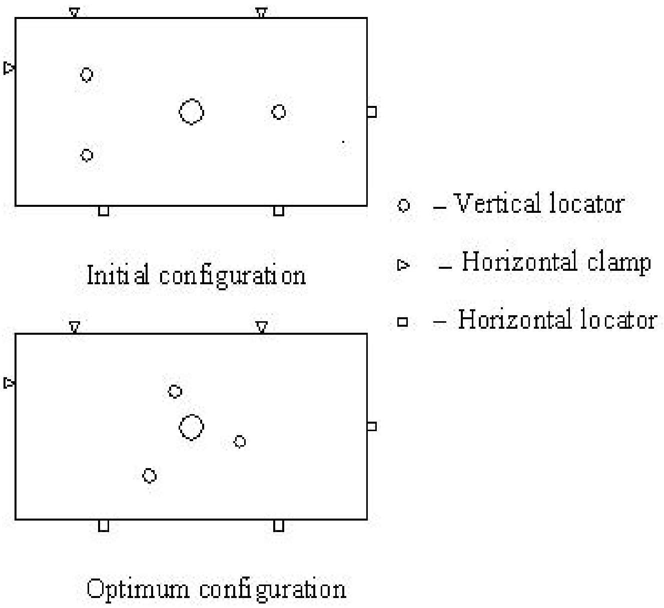

Figure 7: Schematic view of optimum configuration

RESULTS AND DISCUSSION

The table 2 lists the parameters obtained for all the positions of the base locators during stage I optimization run. Infeasible solutions are obtained when any of the state variables fall outside the specified range

Table 2: Base locator position for each optimization set

SET	X1 (mm)	Z1 (mm)	X2 (mm)	Z2 (mm)	X3 (mm)	Z3 (mm)	DMAX (mm)
1	30.00	20.00	30.00	52.50	112.50	37.50	0.03982
2	61.60	22.77	36.34	53.08	109.57	42.81	0.02563
3	53.23	16.19	34.10	40.03	109.14	59.53	0.03281
4	49.74	17.57	57.46	49.98	106.27	51.19	0.02686
5	35.23	15.37	39.92	56.47	97.49	42.64	0.02743
#6	57.64	27.03	20.32	50.54	101.09	17.68	0.02921
7	63.62	22.15	41.31	53.87	105.58	42.81	0.02456
8	67.57	22.23	58.14	56.86	95.90	43.10	0.02148
#9	69.50	25.95	56.36	57.61	90.78	20.18	0.02183
*10	67.87	23.39	57.00	57.22	95.51	43.55	0.02130

* Optimum set # infeasible sets

The table 3 lists the parameters obtained for all the positions of the side locators and the clamps during the stage II optimization run.

Table 3: Side locator and clamp positions for each optimization set

SET	L1 (mm)	L2 (mm)	L3 (mm)	C1 (mm)	C2 (mm)	C3 (mm)	DMAX (mm)
*1	37.50	112.50	37.50	20.00	105.00	25.00	0.021294
2	56.60	110.15	31.34	48.08	110.43	31.01	0.021333
3	56.63	85.18	35.80	27.62	96.40	32.98	0.021331
4	48.23	88.85	29.10	16.18	110.86	10.58	0.021334
5	44.74	93.30	52.46	40.50	113.73	20.77	0.021297
6	56.00	91.50	51.74	49.25	107.51	61.51	0.021349
7	30.23	86.21	34.92	56.36	122.51	31.22	0.021309
8	52.64	123.91	15.32	41.86	118.91	61.72	0.021364

* Optimum set

The table 4 lists the parameters obtained for all the clamping pressure during the stage III optimization run.

Table 4: Clamping pressure for each optimization set

SET	P (N/mm^2)	S (N/mm^2)
1	20.00	39.87
2	84.73	42.96
3	45.77	40.40
*4	18.65	39.84

*Optimum set

The initial and optimum fixture configuration obtained through the optimization run in ANSYS is shown in figure 8

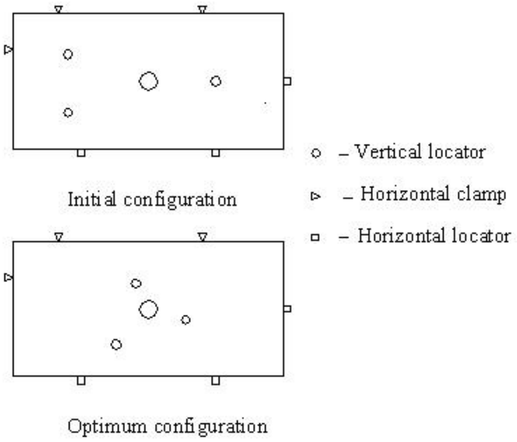

Figure 8: Initial and optimum fixture configuration for case

CONCLUSION

This project has presented a methodology that could be adopted to develop an optimum fixture configuration for drilling through deformable work pieces. The basis for this work is that drilling causes deflection of flexible work pieces in the transverse direction.

Several features of the analysis package used (ANSYS) have been utilized to simulate the actual situation that exists during the machining of a work piece held in a fixture. Contact forces between fixture elements and work piece have been considered by the use of contact and target elements. Friction between the contacting surfaces has also been accounted for. Care has been taken to ensure static stability of the fixtured work piece and that there is no interference between drill bit and fixture elements and between fixture elements themselves. In order to prevent the work piece from loosing contact with the fixture elements it is ensured that the reactions are always directed towards the work piece.

The drilling process involves removal of material and this leads to reduction in stiffness of the work piece. This reduction in stiffness and hence increased deflection has been considered by the use of elements that could be activated or deactivated at different points of time. Comparison between shape and size of the drilled hole between initial and optimum suggest that the optimum fixturing model developed herein can lead to appreciable control over the drilling process, resulting in, marked improvement in quality and accuracy of drilling. Using this approach of optimization technique the lead-time of the product development can be reduced considerably.

From the different case studies undertaken it is obvious that the method adopted could lead to reduction in cutting force induced errors in the machined features by optimizing fixture parameters. The experimental study has indicated that the model requires further refinement and the inclusion of certain dynamic characteristics that occur during drilling process is strongly recommended.

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