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ORIGINAL ARTICLE

Deformation control through fixture layout design and clamping force optimization

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Abstract Workpiece deformation must be controlled in the numerical control machining process. Fixture layout and clamping force are two main aspects that influence the degree and distribution of machining deformation. In this paper, a multi-objective model was established to reduce the degree of deformation and to increase the distributing uniformity of deformation. The finite element method was employed to analyze the deformation. A genetic algorithm was developed to solve the optimization model. Finally, an example illustrated that a satisfactory result was obtained, which is far superior to the experiential one. The multi-objective model can reduce the machining deformation effectively and improve the distribution condition.

Keywords Fixture layout · Clamping force · Genetic algorithm · Finite element method

1 Introduction

Fixture design is an important procedure in manufacturing engineering. It is critical to machining accuracy. A workpiece should be constrained in a fixture during machining with fixture elements such as locators, clamps, and supports. The positions of locators, clamps and supports should be strategically designed and appropriate clamping forces should be applied. The fixture elements can be placed anywhere within the candidate regions on the workpiece surfaces. Clamping force must be large enough to hold the workpiece during machining. Typically, it relies heavily on the designer's experience to choose the positions of the fixture elements and to determine the clamping forces. Thus there is no assurance that the resultant solution is optimal or near optimal for a given workpiece. Consequently, the fixture layout and the clamping force optimization become two main aspects in fixture design. The positions of locators and clamps, and the values of clamping force should be properly selected and calculated so that the workpiece deformation due to clamping and cutting force is minimized and uniformed.

The objective of fixture design is to find an optimal layout or positions of the fixture elements around the workpiece and optimal clamping force. In this paper, a multi-objective optimization method is presented for the fixture layout design and clamping force optimization. The objective is two folded. One is to minimize the maximum elastic deformation of the machined surfaces, and another is to maximize the uniformity of deformation. The ANSYS software package is used to calculate the deformation of the workpiece under given clamping force and cutting force. A genetic algorithm is developed, and the direct search toolbox of MATLAB is employed to solve the optimization problem. Finally, a case study is given to illustrate the application of the proposed approach.

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2 Literature review

With the wide applications of optimization methods in industry, fixture design optimization has gained more interests in recent years. Fixture design optimization includes fixture layout optimization and clamping force optimization. King and Hutter presented a method for optimal fixture layout design using a rigid body model of the fixture-workpiece system [1]. DeMeter also used a rigid body model for the analysis and synthesis of optimal fixture layouts and minimum clamping force [2]. He presented a finite element method (FEM) based support layout optimization procedure with computationally attractive qualities [3]. Li and Melkote used a nonlinear programming method and a contact elasticity model to solve the layout optimization problem [4]. Two years later, they presented a method for determining the optimal clamping force for a multiple clamp fixture subjected to quasi-static machining force [5]. They also presented an optimal synthesis approach of fixture layout and clamping force that considers workpiece dynamics during machining [6]. A combined fixture layout and clamping force optimization procedure was presented. Other researchers [7, 8] used the FEM for fixture design and analysis. Cai et al. [9] extended the work of Menassa and DeVries [8] to include synthesis of fixture layout for sheet metal assembly. Qin et al. [10] established an elastic contact model between clamp and workpiece to optimize the clamping force with an objective to minimize the position error of the workpiece. Deng and Melkote [11] presented a model-based framework for determining the minimum required clamping force, which ensures the dynamic stability of a fixtured workpiece during machining.

Most of the above studies used nonlinear programming methods, which seldom gave global or near-global optimum solutions. All of the fixture layout optimization procedures must start with an initial feasible layout. In addition, solutions obtained from these models are very sensitive to the initial feasible fixture layout. The problem of fixture design optimization is nonlinear because there is no direct analytical relationship between the objective function and design variables, i.e. between the machined surface error and the fixture parameters (positions of locator and clamp, and clamping forces).

Previous researchers had shown that genetic algorithm (GA) was a useful technique in solving such optimization problems. Wu and Chan [12] used the GA to determine the most statically stable fixture layout. Ishikawa and Aoyama [13] applied GA to determine the optimal clamping condition for an elastic workpiece. Vallapuzha et al. [14] used spatial coordinates to encode in the GA based optimization of fixture layout. They also presented the methodology and results of an extensive investigation into the relative effectiveness of the main competing fixture optimization methods, which showed that continuous GA yielded the best quality solutions [15]. Krishnakumar and Melkote [16] developed a fixture layout optimization technique that used GA to find the fixture layout that minimized the deformation of the machined surface due to clamping and cutting force over the entire tool path. Locator and clamp positions were specified with node numbers. Krishnakumar et al. [17] presented an iterative algorithm that minimized the workpiece elastic deformation for the entire cutting process by alternatively varying the fixture layout and clamping force. Lai et al. [18] set up an analysis model that treated locator and clamps as the same fixture layout elements for the flexible part deformation. Hamedi [19] discussed a hybrid learning system that used nonlinear FEA with a supportive combination of artificial neural network (ANN) and GA. The ANN was used to calculate workpiece maximum elastic deformation, the GA was used to determine the optimum clamping forces. Kumar [20] proposed to combine the GA and ANN to develop a fixture design system. Kaya [21] used the GA and FEM to find the optimal locators and clamping positions in 2D workpiece and took chip removal effects into account. Zhou et al. [22] presented a GA based method that optimized fixture layout and clamping force simultaneously. Some of the studies did not consider the optimization of the layout for entire tool path. Some of the studies used node numbers as design parameters. Some of the studies addressed fixture layout or clamping force optimization methods but not both simultaneously. And there were few studies taking friction and chip removal into account. The effects of chip removal and frictional contact cannot be neglected for achieving a more realistic and accurate workpiece-fixture layout verification analysis [23], so it is essential to take chip removal effects and friction effect into account to achieve a better machining accuracy.

In this paper, the friction and chip removal are taken into account to achieve the minimum degree of the maximum deformation of the machined surfaces under clamping and cutting force and to uniform the deformation. A multi-objective optimization model is established. An optimization process based on GA and FEM is presented to find the optimal fixture layout and clamping force. Finally, the result of the multi-objective optimization model is compared with the single objective optimization method and the experience method for a low rigidity workpiece.

3 A multi-objective optimization model for fixture design

A feasible fixture layout has to satisfy three constraints. First, the locators and clamps cannot apply tensile forces on the workpiece. Second, the Coulomb friction constraint must be satisfied at all fixture-workpiece contact points. The positions of fixture element-workpiece contact points must be in the candidate regions. For a problem involving p fixture element-workpiece contacts and n machining load

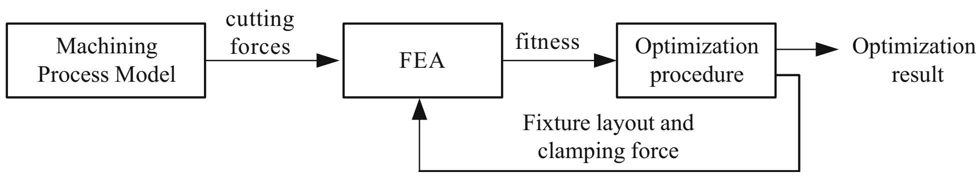

Fig. 1 Fixture layout and clamping force optimization process

steps, the optimization problem can be mathematically modeled as follows

$$\min\left(\max\left(|\Delta_1|,|\Delta_2|,\ldots,|\Delta_j|,\ldots,|\Delta_n|\right)+\sigma\right), j = 1,2,\ldots,n \tag{1}$$

Subject to

$$\mu|F_{ni}| \geq \sqrt{F_{\tau i}^2 + F_{\eta i}^2} \tag{2}$$

$$F_{ni} \geq 0 \tag{3}$$

$$pos(i) \in V(i), i = 1,2,\ldots,p \tag{4}$$

where Δ_j refers to the maximum elastic deformation at a machining region in the j-th step of the machining operation,

$$\sigma = \sqrt{\sum_{j=1}^{n}\left(\Delta j - \bar{\Delta}\right)^2 \Big/ n}$$

$\overline{\Delta}$	is the average of Δ_j
F_{ni}	is the normal force at the i-th contact point
μ	is the static coefficient of friction
$F_{\tau i}, F_{\eta i}$	are the tangential forces at the i-th contact point
$pos(i)$	is the i-th contact point
$V(i)$	is the candidate region of the i-th contact point.

The overall process is illustrated in Fig. 1 to design a feasible fixture layout and to optimize the clamping force. The maximal cutting force is calculated in cutting model and the force is sent to finite element analysis (FEA) model. Optimization procedure creates some fixture layout and clamping force which are sent to the FEA model too. In FEA block, machining deformation under the cutting force and the clamping force is calculated using finite element method under a certain fixture layout, and the deformation is then sent to optimization procedure to search for an optimal fixture scheme.

4 Fixture layout design and clamping force optimization

4.1 A genetic algorithm

Genetic algorithms (GA) are robust, stochastic and heuristic optimization methods based on biological reproduction processes. The basic idea behind GA is to simulate "survival of the fittest" phenomena. Each individual candidate in the population is assigned a fitness value through a fitness function tailored to the specific problem. The GA then conducts reproduction, crossover and mutation processes to eliminate unfit individuals and the population evolves to the next generation. Sufficient number of evolutions of the population based on these operators lead to an increase in the global fitness of the population and the fittest individual represents the best solution.

The GA procedure to optimize fixture design takes fixture layout and clamping force as design variables to generate strings which represent different layouts. The strings are compared to the chromosomes of natural evolution, and the string, which GA find optimal, is mapped to the optimal fixture design scheme. In this study, the genetic algorithm and direct search toolbox of MATLAB are employed.

The convergence of GA is controlled by the population size (P_s), the probability of crossover (P_c) and the probability of mutations (P_m). Only when no change in the best value of fitness function in a population, N_{chg}, reaches a pre-defined value $NC_{\max}$, or the number of generations, N, reaches the specified maximum number of evolutions, $N_{\max}$., did the GA stop.

There are five main factors in GA, encoding, fitness function, genetic operators, control parameters and constraints. In this paper, these factors are selected as what is listed in Table 1.

Since GA is likely to generate fixture design strings that do not completely restrain the fixture when subjected to machining loads. These solutions are considered infeasible and the penalty method is used to drive the GA to a feasible solution. A fixture design scheme is considered infeasible or unconstrained if the reactions at the locators are negative, in other words, it does not satisfy the constraints in equations (2) and (3). The penalty method essentially involves

Table 1 Selection of GA's parameters

Factors	Description
Encoding	Real
Scaling	Rank
Selection	Remainder
Crossover	Intermediate
Mutation	Uniform
Control parameter	Self-adapting

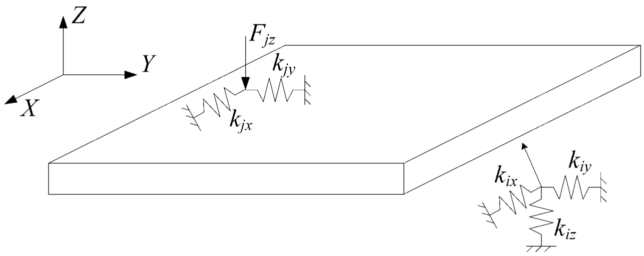

Fig. 2 Semi-elastic contact model taking friction into account

assigning a high objective function value to the scheme that is infeasible, thus driving it to the feasible region in successive iterations of GA. For constraint (4), when new individuals are generated by genetic operators or the initial generation is generated, it is necessary to check up whether they satisfy the conditions. The genuine candidate regions are those excluding invalid regions. In order to simplify the checking, polygons are used to represent the candidate regions and invalid regions. The vertex of the polygons are used for the checking. The "inpolygon" function in MATLAB could be used to help the checking.

4.2 Finite element analysis

The software package of ANSYS is used for FEA calculations in this study. The finite element model is a semi-elastic contact model considering friction effect, where the materials are assumed linearly elastic. As shown in Fig. 2, each locator or support is represented by three orthogonal springs that provide restrains in the X, Y and Z directions and each clamp is similar to locator but clamping force in normal direction. The spring in normal direction is called normal spring and the other two springs are called tangential springs.

The contact spring stiffness can be calculated according to the Herz contact theory [8] as follows

$$\begin{cases} k_{iz} = \left(\frac{16 R_i^* E_i^{*2}}{9} \right)^{\frac{1}{3}} f_{iz}^{\frac{1}{3}} \\ k_{iz} = k_{iy} = \frac{6}{E_i^*} \left(\frac{2-\nu_{fi}}{G_{fi}} + \frac{2-\nu_{wi}}{G_{wi}} \right)^{-1} \cdot k_{iz} \end{cases} \quad (5)$$

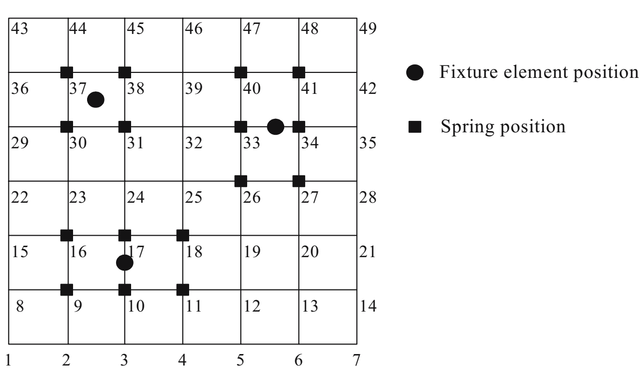

Fig. 3 Continuous interpolation

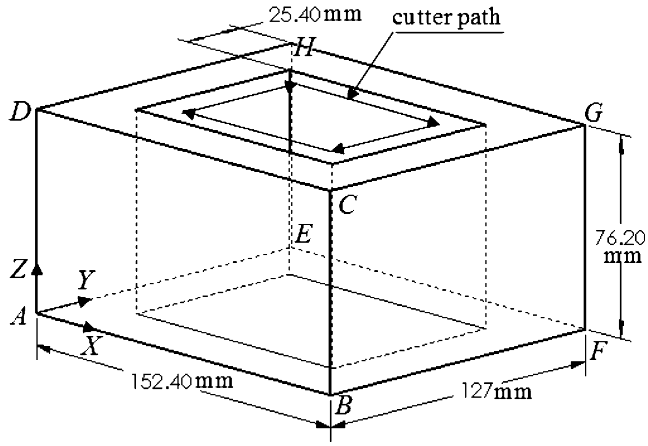

Fig. 4 A hollow workpiece

where

k_{iz}, k_{ix}, k_{iy}	are the tangential and normal contact stiffness,
$\frac{1}{R_i^*} = \frac{1}{R_{wi}} + \frac{1}{R_{fi}}$	is the nominal contact radius,
$\frac{1}{E_i^*} = \frac{1-V_{wi}^2}{E_{wi}} + \frac{1-V_{fi}^2}{E_{fi}}$	is the nominal contact elastic modulus,
R_{wi}, R_{fi}	are radius of the i-th workpiece and fixture element,
E_{wi}, E_{fi}	are Young's moduli for the i-th workpiece and fixture materials,
ν_{wi}, ν_{fi}	are Poisson ratios for the i-th workpiece and fixture materials,
G_{wi}, G_{fi}	are shear moduli for the i-th workpiece and fixture materials and f_{iz} is the reaction force at the i-th contact point in the Z direction.

Contact stiffness varies with the change of clamping force and fixture layout. A reasonable linear approximation of the contact stiffness can be obtained from a least-squares fit to the above equation.

The continuous interpolation, which is used to apply boundary conditions to the workpiece FEA model, is

Table 2 Machining parameters and conditions

Parameter	Description
Type of operation	End milling
Cutter diameter	25.4 mm
Number of flutes	4
Cutter RPM	500
Feed	0.1016 mm/tooth
Radial depth of cut	2.54 mm
Axial depth of cut	25.4 mm
Radial rake angle	10
Helix angle	30
Projection length	92.07 mm

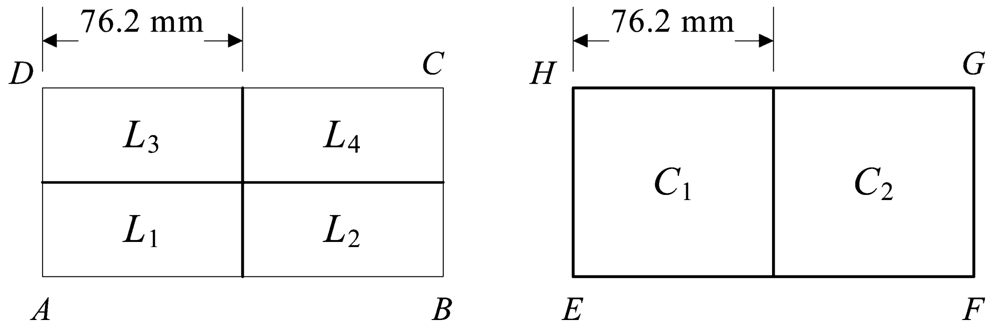

Fig. 5 Candidate regions for the locators and clamps

illustrated in Fig. 3. Three fixture element locations are shown as black circles. Each element location is surrounded by its four or six nearest neighboring nodes. These sets of nodes, which are illustrated by black squares, are {37, 38, 31 and 30}, {9, 10, 11, 18, 17 and 16} and {26, 27, 34, 41, 40 and 33}. A set of spring elements are attached to each of these nodes. For any set of nodes, the spring constant is

$$k_{ij} = \frac{d_{ij}}{\sum\limits_{k \in \eta_i} d_{ik}} k_i \tag{6}$$

where

- k_{ij} is the spring stiffness at the j-th node surrounding the i-th fixture element,
- d_{ij} is the distance between the i-th fixture element and the j-th node surrounding it,
- k_i is the spring stiffness at the i-th fixture element location.
- η_i is the number of nodes surrounding the i-th fixture element location.

For each machining load step, appropriate boundary conditions have to be applied to the finite element model of the workpiece. In this work, the normal springs are constrained in the three directions (X, Y, Z) and the tangential springs are constrained in the tangential directions (X, Y). Clamping forces are applied in the normal direction (Z) at the clamp nodes. The entire tool path is simulated for each fixture design scheme generated by the GA by applying the peak X, Y, Z cutting forces sequentially to the element surfaces over which the cutter passes [23].

In this work, chip removal from the tool path is taken into account. The removal of the material during machining alters the geometry, so does the structural stiffness of the workpiece. Thus, it is necessary to consider chip removal affects. The FEA model is analyzed with respect to tool movement and chip removal using the element death technique. In order to calculate the fitness value for a given fixture design scheme, displacements are stored for each load step. Then the maximum displacement is selected as fitness value for this fixture design scheme.

The interaction between GA procedure and ANSYS is implemented as follows. Both the positions of locators and clamps, and the clamping force are extracted from real strings. These parameters are written to a text file. The input batch file of ANSYS could read these parameters and calculate the deformation of machined surfaces. Thus the fitness values in GA procedure can also be written to a text file for current fixture design scheme.

It is costly to compute the fitness value when there are a large number of nodes in an FEM model. Thus it is necessary to speed up the computation for GA procedure. As the generation goes by, chromosomes in the population are getting similar. In this work, calculated fitness values are stored in a SQL Server database with the chromosomes and fitness values. GA procedure first checks if current chromosome's fitness value has been calculated before, if not, fixture design scheme are sent to ANSYS, otherwise fitness values are directly taken from the database.

The meshing of workpiece FEA model keeps same in every calculating time. The difference among every calculating model is the boundary conditions. Thus, the meshed workpiece FEA model could be used repeatedly by the "resume" command in ANSYS.

5 Case study

An example of milling fixture design optimization problem for a low rigidity workpiece displayed in previous research papers [16, 18, 22] is presented in the following sections.

Table 3 Bound of design variables

	Minimum		Maximum	
	X /mm	Z /mm	X /mm	Z /mm
L_1	0	0	76.2	38.1
L_2	76.2	0	152.4	38.1
L_3	0	38.1	76.2	76.2
L_4	76.2	38.1	152.4	76.2
C_1	0	0	76.2	76.2
C_2	76.2	0	152.4	76.2
F_1 /N	0		6673.2	
F_2 /N	0		6673.2	

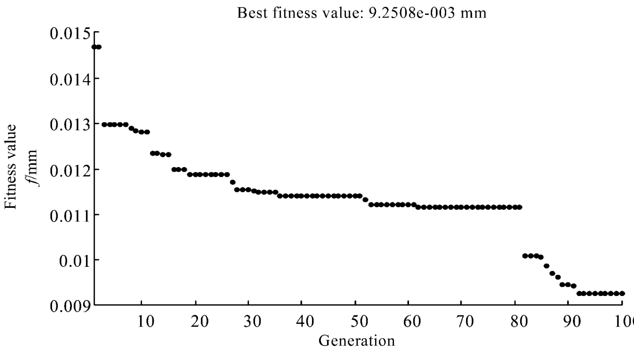

Fig. 6 Convergence of GA for fixture layout and clamping force optimization procedure

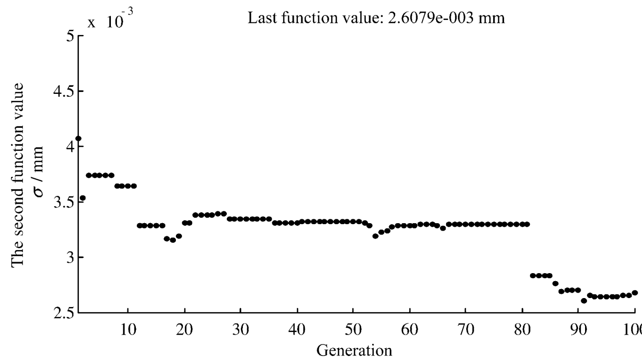

Fig. 8 Convergence of the second function values

5.1 Workpiece geometry and properties

The geometry and features of the workpiece are shown in Fig. 4. The material of the hollow workpiece is aluminum 390 with a Poisson ration of 0.3 and Young's modulus of 71 Gpa. The outline dimensions are 152.4 mm×127 mm×76.2 mm. The one third top inner wall of the workpiece is undergoing an end-milling process and its cutter path is also shown in Fig. 4. The material of the employed fixture elements is alloy steel with a Poisson ration of 0.3 and Young's modulus of 220 Gpa.

5.2 Simulating and machining operation

A peripheral end milling operation is carried out on the example workpiece. The machining parameters of the operation are given in Table 2. Based on these parameters, the maximum values of cutting forces that are calculated and applied as element surface loads on the inner wall of the workpiece at the cutter position are 330.94 N (tangential), 398.11 N (radial) and 22.84 N (axial). The entire tool path is discretized into 26 load steps and cutting force directions are determined by the cutter position.

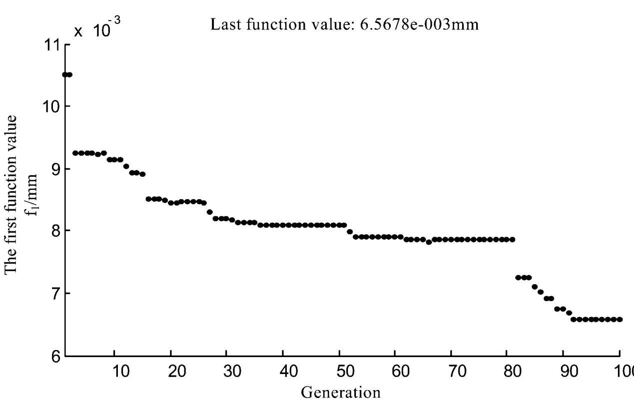

Fig. 7 Convergence of the first function values

5.3 Fixture design plan

The fixture plan for holding the workpiece in the machining operation is shown in Fig. 5. Generally, the 3–2–1 locator principle is used in fixture design. The base controls 3 degrees. One side controls two degrees, and another orthogonal side controls one degree. Here, it uses four locators (L1, L2, L3 and L4) on the Y=0 mm face to locate the workpiece controlling two degrees, and two clamps (C1, C2) on the opposite face where Y=127 mm, to hold it. On the orthogonal side, one locator is needed to control the remaining degree, which is neglected in the optimal model. The coordinate bounds for the locating/clamping regions are given in Table 3.

Since there is no simple rule-of-thumb procedure for determining the clamping force, a large value of the clamping force of 6673.2 N was initially assumed to act at each clamp, and the normal and tangential contact stiffness obtained from a least-squares fit to Eq. (5) are 4.43×10^7 N/m and 5.47×10^7 N/m separately.

5.4 Genetic control parameters and penalty function

The control parameters of the GA are determined empirically. For this example, the following parameter values are

Table 4 Result of the multi-objective optimization model

	Multi-objective optimization	
	X /mm	Z /mm
L_1	17.102	30.641
L_2	108.169	25.855
L_3	21.315	56.948
L_4	127.846	60.202
C_1	22.989	62.659
C_2	117.615	25.360
F_1/N	167.614	
F_2/N	382.435	
f_1/mm	0.006568	
σ/mm	0.002683	

Table 5 Comparison of the results of various fixture design schemes

	Experimental optimization		Single objective optimization	
	X/*mm*	Z/*mm*	*X*/mm	*Z*/mm
L_1	12.700	12.700	16.720	34.070
L_2	139.7	12.700	145.360	17.070
L_3	12.700	63.500	18.400	57.120
L_4	139.700	63.500	146.260	58.590
C_1	12.700	38.100	5.830	56.010
C_2	139.700	38.100	104.400	22.740
F_1/N	2482		444.88	
F_2/N	2482		1256.13	
f_1/mm	0.031012		0.013178	
σ/mm	0.014377		0.005696	

used: P_s=30, P_c=0.85, P_m=0.01, $N_{\max}$=100 and N_{cmax}= 20. The penalty function for f_1 and σ is

$$\phi(f_v) = f_v + 50$$

Here f_v can be represented by f_1 or σ. When N_{chg} reaches 6 the probability of crossover and mutation will be change into 0.6 and 0.1 separately.

5.5 Optimization result

The convergence behavior for the successive optimization steps is shown in Fig. 6, and the convergence behaviors of corresponding functions (1) and (2) are shown in Fig. 7 and Fig. 8. The optimal design scheme is given in Table 4.

5.6 Comparison of the results

The design variables and objective function values of fixture plans obtained from single objective optimization and from that designed by experience are shown in Table 5. The single objective optimization result in the paper [22] is quoted for comparison. The single objective optimization method has its preponderance comparing with that designed by experience in this example case. The maximum

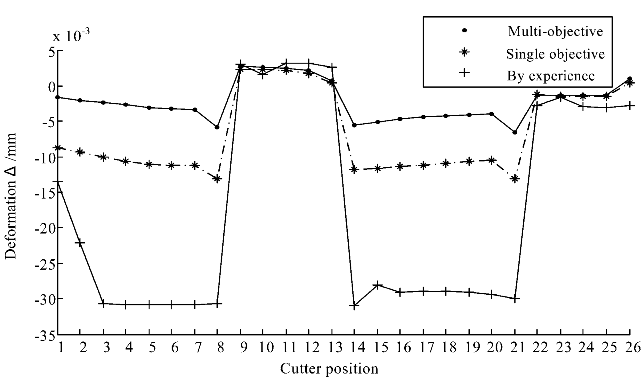

Fig. 9 Distribution of the deformation along cutter path

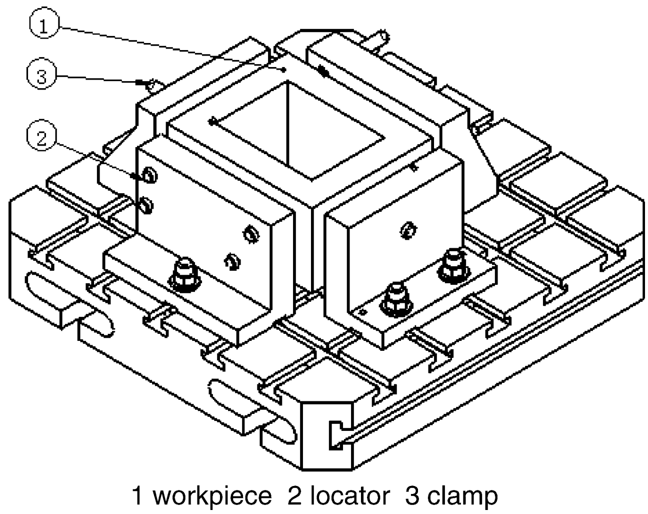

Fig. 10 A real case fixture configuration

deformation has reduced by 57.5%, the uniformity of the deformation has enhanced by 60.4% and the maximum clamping force value has degraded by 49.4%. What could be drawn from the comparison between the multi-objective optimization method and the single objective optimization method is that the maximum deformation has reduced by 50.2%, the uniformity of the deformation has enhanced by 52.9% and the maximum clamping force value has degraded by 69.6%.The deformation distribution of the machined surfaces along cutter path is shown in Fig. 9. Obviously, the deformation from that of multi-objective optimization method distributes most uniformly in the deformations among three methods.

With the result of comparison, we are sure to apply the optimal locators distribution and the optimal clamping force to reduce the deformation of workpiece. Figure 10 shows the configuration of a real-case fixture.

6 Conclusions

This paper presented a fixture layout design and clamping force optimization procedure based on the GA and FEM. The optimization procedure is multi-objective: minimizing the maximum deformation of the machined surfaces and maximizing the uniformity of the deformation. The ANSYS software package has been used for FEM calculation of fitness values. The combination of GA and FEM is proven to be a powerful approach for fixture design optimization problems.

In this study, both friction effects and chip removal effects are considered. In order to reduce the computation time, a database is established for the chromosomes and fitness values, and the meshed workpiece FEA model is repeatedly used in the optimization process.

The traditional fixture design methods are single objective optimization method or by experience. The results of this study show that the multi-objective optimization method is more effective in minimizing the deformation and uniforming the deformation than other two methods. It is meaningful for machining deformation control in NC machining.

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