Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 5216966, 15 pages
https://doi.org/10.1155/2022/5216966

Research Article

Evolutionary Design of Machining Fixture Layout for Thin-Walled Structure

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Received 28 July 2022; Revised 5 October 2022; Accepted 19 October 2022; Published 26 October 2022

Academic Editor: Rui Pang

Fixture layout for machining thin-walled structures plays an important role in fixture performance. This work focuses on the optimization design of machining fixture layout including clamp layout and the layout of support heads. A universal optimization methodology that can automatically generate the optimal machining fixture layout is proposed. The optimization of fixture layout is implemented based on the criteria of minimizing maximum deflection of the thin-walled workpiece while remain relatively small torque caused by the clamping tables. An evolutionary algorithm is employed to solve the fixture layout optimization for the optimal solution. The optimal position of the support heads and the layout of clamping tables obtained from this work vary along with the change of cutting force. To validate the proposed optimization methodology, a fixture layout design for a typical thin-walled structure is optimized as an example. The case study demonstrates the application of the proposed approach in the fixture layout design for thin-walled structures, which is beneficial to design an optimal fixture layout.

1. Introduction

Thin-wall structures have been designed for a wide range of applications in the field of aerospace engineering and automotive industry, due to the fact that thin-walled structures exhibit high performances such as light-weight, high specific strength, and high structural efficiency. Although the thin-walled structures have those excellent performances, they also have some critical liminations such as low structural stiffness and large deflection during the manufacturing process [1–3]. Such limitations not only cause a big challenge in its fabrication but also influence product quality.

To overcome the limitations mentioned above, a lot of researchers pay attention to the machining fixture layout design for thin-walled structures. For instance, some researchers devote themselves to finding the mathematical modeling method of fixture layout optimization. De Meter [4] proposed a fast support layout optimization model to optimize the support layout. Based on error amplification factors, Wan et al. [5, 6] and his colleagues focused on the optimization of fixture layout. In their research, the global differential method is used to model the position error of the fixture-workpiece system. Ramachandran et al. [7] presented a drilling fixture layout optimization model for the engine bracket to minimize the deformation of the workpiece. In order to reduce the deflection of the workpiece and improve the distribution of the deformation induced by the machining tool, Chen et al. [8] proposed a multiobjective optimization model to design a fixture layout. By employing structural strain energy as an objective, Ahmad et al. [9, 10] determined the optimal fixture layout. Zhang et al. [11] established a mathematical model to obtain the optimal machining fixture layout. The effect of the clamp position on the deformation of the structural system was also analyzed in their work. Raghu and Melkote [12] analyzed the effect of the clamping sequence on the locating errors that were quantified with the deflection of the workpiece. To evaluate the deflection of the workpiece and design the optimized fixture layout, Lu et al. [13] established an elastic model considering friction and contact effects. Hunter Alarcón et al. [14] developed a fixture knowledge model, which was implemented based on a functional design approach. Li et al. [15] proposed a new optimization model. In this model, a novel region division strategy was used based on elasticity, and the optimal layout was determined by a genetic algorithm. Ju et al. [16] derived energy equations of the thin circular plates subject to vacuum clamping, and an optimization model for the vacuum fixture was developed based on the energy equations. Yacob et al. [17] established a mathematical model based on dual quaternion for part quality prediction given parts with form errors and fixtures with $N-2-1$ $(N>3)$ layout. To validate the presented method, a part with form errors produced in a two-stationed machining process with a 12-2-1 fixture layout was considered.

Instead of finding the mathematical modeling method for fixture layout optimization, other researchers prefer to study the algorithm of fixture layout optimization. Alshameri et al. [18] employed a declining neighborhood simulated annealing algorithm to optimize the fixture in a point-set domain. Using spatial coordinates, the genetic algorithm-based solution of the fixture layout optimization was investigated by Vallapuzha et al. [19]. Combining the genetic algorithm with the ant colony algorithm, Prabhaharan et al. [20] studied the optimal solution for fixture layout. Cai et al. [21] presented a locating principle named "$N-2-1$." In Cai's method, the parameter N can be determined via nonlinear programming and finite element analysis such that the deflection of the workpiece is minimized. Nasr et al. [22] investigated an automatic fixture modeling system for the prismatic workpiece. The CBR was used to determine a feasible fixture layout. Zhong et al. [23] employed sparse learning and semidefinite programming relaxation techniques to convert the fixture layout optimization into a convex semidefinite programming problem such that existing convex optimization algorithms can be efficiently used for the optimal solution. Other related investigations have been reported in the literature [24, 25].

Unlike previous fixture optimization, many excellent papers focused on the improvement of fixture schemes. For example, Marin et al. [26] proposed a novel approach to determine the optimal clamping forces and clamping position, and this approach is implemented based on the 3-2-1 location principle. By introducing multiconstraints, Wang et al. [27] optimized the fixture layout. In Wang's approach, the clamping and locating domain was discretized into a mesh of finite clamping or locating elements, and each element was assumed to be a potential fixture position. Peng et al. [28, 29] developed a virtual reality-based integrated system. Combining RBR and CBR, the machining fixture layout was determined in the virtual reality system. Zhou et al. [30] proposed a fixture design based on the characteristics of a workpiece for the fixture of aircraft structures. According to this method, the characteristic model of the structures was formulated to retrieve the previous cases and rulers of fixture design for facilitating this work. Ma et al. [31] presented a dynamic model for the thin-walled workpiece in which magnetorheological damping was applied to the fixture-workpiece system during the milling process. Landwehr et al. [32] developed an adaptive fixture system to reduce machining deflection induced by residual stresses, and the experimental study was conducted to validate the developed fixture system with a monolithic part made of Ti-6A1-4V. Based on passive Stewart platforms, a fixturing system was constructed by Gašpar et al. [33] to optimize its layout and reconfiguration, and the optimal solution was determined via nonlinear optimization. Hu [34] presented a digital twin-based decision-making methodology to generate reconfigurable fixturing schemes through integrating virtual and physical information. In addition, there are some researches from other domains, which can also provide some new methodology for fixture layout optimization such as the reliability evaluation framework based on the direct probability integral method (DPIM) [35], the self-informed adaptivity mechanism in evolutionary algorithms [36], generalized probability density evolution method (GPDEM) [37, 38], simple evolutionary algorithm [39].

To sum up, we can get Table 1 as follows.

The previous works of research did not focus on the clamping tables of rectangular thin-wall structures; therefore, there is no suitable solution to the number and layout of clamping tables. To overcome this drawback, this article presents a novel method of fixture layout optimization for clamping tables and provides some useful guides for the fixture layout design of thin-walled structures. For example, this optimization method has abilities to get the optimal number of clamping tables and find the optimal layout for the clamping tables and support heads. A kind of dynamic optimization method that the fixture layout could vary as the changes of cutting forces is presented in this article. Compared with the above literature, the unique innovations of this article are to develop an appropriate optimization methodology to obtain the optimal number of clamping tables and find the optimal layout of clamping tables and support heads simultaneously for the rectangular thin-walled structure. This work exploits an evolutionary algorithm to optimize the machining fixture layout for thin-walled structures. The optimization problems for clamp layout and the layout of support heads are established based on the assumption that the 2-1 fixture locating datum from the 3-2-1 fixturing method is determined. The contributions of this work include the following: (1) a layout optimization of the clamping table was introduced to avoid the contact between clamps and workpiece such that the effect of clamps on the workpiece deflection can be eliminated; (2) a machining fixture layout optimization was proposed, which was applicable to the dynamic fixture layout optimization. The remainder of this paper is organized into five sections as follows. In the next section, the problem statement is briefly introduced. Then, Section 3 presents the optimization design of the machining fixture layout including the clamp layout and the layout of support heads. For the purpose of verification, a fixture layout design for a typical thin-walled structure is implemented in Section 4. Finally, conclusions are drawn in Section 5.

Table 1: The summary of the literature.

Objective of research	Literature
Finding the mathematic modeling method	(4)~(17)
Studying the algorithm	(18)~(25)
Improvement of fixture schemes	(26)~(39)

2. Problem Statement

2.1. Thin-Walled Structure. Without any loss in generality, a typical rectangular thin-walled structure is considered as shown in Figure 1, which consists of the side walls and sternums. To simplify our discussion, the coordinate frame is placed, and the dimension of the thin-walled structure is demonstrated in this figure. Due to its compliance, the thin-walled structure will produce large deflection during the machining process such that the thin-walled structures are not easy to be fabricated in reality. Although fixture layout is a critical factor, existing methodologies have limits to further improving the fixture performance. Here, we exploit the evolutionary algorithm to optimize the machining fixture layout including the clamp layout and the layout of support heads for thin-walled structures. To machine the thin-walled structures, a multipoint locating tooling is employed, which will be described in the next section.

2.2. Multipoint Locating Tooling. Compared with traditional fixtures, it has several advantages such as saving storage space, shortening the product development time, reducing the manufacturing cost. Its stiffness is suitable for the thin-walled structure. Figure 2 illustrates a multipoint locating tooling which is tooling that discretizes the support area into multiple support points, and the spatial position of each support point can be adjusted independently. As shown in Figure 2, the multipoint flexible locating tooling is mainly composed of a work platform, X-axis guide grooves, Y-axis sliders, and Z-axis locating telescopic rods as well as the support heads. The X-axis guide grooves allow the guide to move in X-direction on the work platform while Y-axis sliders can slide along the Y-direction. Each sliding block on the slider is constrained to be fixed in Z-direction. The motion in Z-axis can be achieved by adjusting Z-axis to locate telescopic rods. In this paper, only three support heads are used to fix the workpiece. This is because the thin-walled structure considered in Figure 2 does not include curved surfaces. However, there is still room for improvement such as enhancing its intelligentization, further reducing the deformation of this structure, and so on for this tooling. For example, the deformation must be further reduced to 0.05 mm while applied in actual engineering, and the intelligentization of this tooling should be further enhanced that can make support heads arrive at their destination on time and accurately.

2.3. Deflection Evaluation of the Thin-Walled Structure. Static analysis of thin-walled structure is critical to evaluate the structural performances, because such static analysis will be repeatedly implemented during the optimization process. In this work, the finite element analysis (FEA) will be used to investigate the stiffness properties of the thin-walled structure. Based on the finite element method, the stiffness matrix for the i^{th} finite element in the mesh of the thin-walled structure, $\mathbf{K}_i$, can be expressed as

$$\mathbf{K}_i = \iiint \mathbf{B}^{\mathrm{T}}\mathbf{D}\mathbf{B}\,\mathrm{d}V, \tag{1}$$

where B and D represent the deformation matrix in FEA and the constitutive matrix in solid mechanics, respectively. The scalar variable, V, represents the volume of the finite element. By assembling the stiffness matrix of all the finite elements, the stiffness matrix of the thin-walled structure can be calculated as

$$\mathbf{K}_{\mathrm{FE}} = \sum_{i=1}^{N_e} \mathbf{K}_i, \tag{2}$$

where N_e is the total number of the finite elements. The resultant FEA equilibrium equation for the thin-walled structure can be given as

$$\mathbf{K}_{\mathrm{FE}}\mathbf{U}_{\mathrm{FE}} = \mathbf{F}_{\mathrm{FE}}, \tag{3}$$

where U_{FE} and F_{FE} represent the nodal displacement vector and nodal load vector of the thin-walled structure, respectively. By solving the FEA equilibrium (3), the deflection of the thin-walled structure can be evaluated in the framework of finite element analysis.

3. Proposed Optimization Methodology

In this section, we will propose the optimization methodology for the machining fixture layout design of the thin-walled structure. As shown in Figure 3, the proposed optimization can be implemented by following three steps: (1) extract workpiece information, (2) implement the clamping tables optimization to determine the optimal number of clamp tables, (3) determine the optimal fixture layout via the genetic algorithm.

3.1. Clamping Table Optimization. The clamping table is designed to clamp the thin-walled workpiece during the machining process. Such a clamping table is introduced to avoid direct contact between clamps and the workpiece such that the effect of the clamps on the workpiece deflection can be eliminated. Hence, the clamp layout is a critical factor in fixture performance. In this work, the clamping table is designed in such a way that the clamping tables are arranged in a symmetrical configuration as shown in Figure 4. The number of the clamping tables can eventually be optimized in this optimization process.

To formulate the clamping table optimization problem, the maximum deflection of the thin-walled workpiece is taken into account. According to the characteristics of the thin-walled workpiece shown in Figure 4, the maximum deflection of the workpiece will occur on its sternum. This is because the side wall of the thin-walled workpiece is much

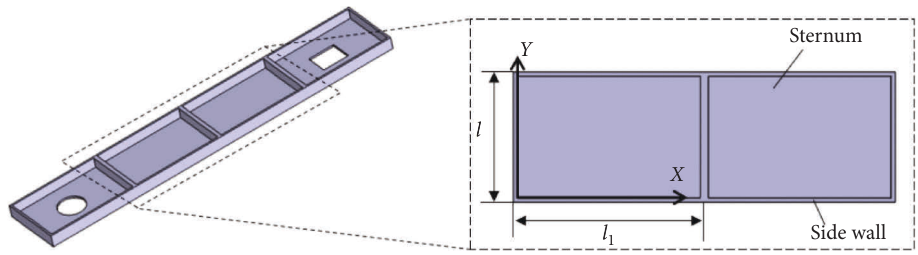


Figure 1: A typical rectangular thin-walled structure.

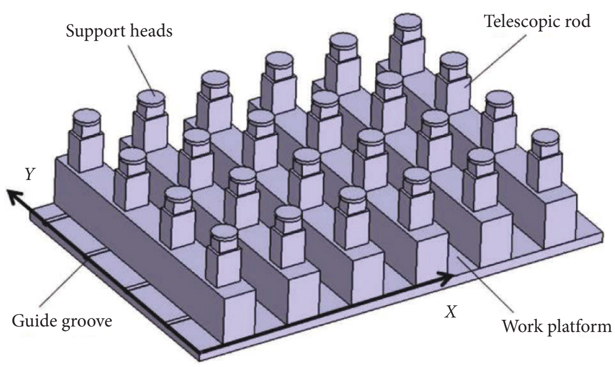


Figure 2: Illustration of multipoint locating tooling.

stiffer than its sternum. Based on thin plate theory, the maximum deflection of the sternum can be computed as [40]

$$w = \gamma \frac{Fl^2}{Eh^3}, \tag{4}$$

where l and h represent the width and thickness of the thin-walled workpiece, respectively. E represents Young's modulus. F represents a cutting force applied to the center of the sternum. γ represents a constant that depends on the aspect ratios of the thin-walled workpiece.

Using the maximum deflection obtained in (4), we can therefore formulate the following clamping table optimization problem:

$$\begin{aligned} &\text{Minimize } z_1 = w, \\ &\text{Subjected to : } w < \delta_{\max} l_2 < \frac{l_1}{N}, \end{aligned} \tag{5}$$

where $\delta_{\max}$ is the upper bound of the maximum deflection of the sternum. l_2 represents the length of a clamping table. The variable N represents the number of the clamping tables. This optimization model is to get an appropriate number of clamping tables. To avoid damage to the thin-walled structure while machining, the maximum deformation obtained in (4) is regarded as the objective function. Because the maximum deformation must be lower than the upper bound of the maximum deflection of the sternum, the first constraint is presented. The second constraint is introduced to ensure that the total length of all the clamping tables must be less than the length of the thin-walled workpiece l_1.

The clamping table optimization in (5) can be implemented by following these sequential steps:

The first step is to initialize the design variables in (5). The initial N is assigned with a value of 1. The maximum deflection of the thin-walled workpiece is computed in (4). The upper bound of the maximum deflection of the sternum is given.

Subsequently, in step 2, the length l_1 is divided by N, and the clamping table position can be determined by l_1/N.

Step 3 performs the evaluation of the objective function and constraints in (5). Once these two constraints, $w < \delta_{\max}$, $l_2 N < l_1$, are satisfied, the number of the clamping tables can be determined and is assigned as $N-1$. Otherwise, update the number of the clamping tables by $N = N + 1$ and go back to step 2.

The flowchart of the optimization scheme is illustrated in Figure 5.

By performing the optimization problem in (5), the clamping table layout can be determined, and the optimal layout is shown in Figure 6. It can be seen that the number of clamping tables is eventually determined to be 14.

3.2. The Optimization of Fixture Layout. In this section, three support heads are employed to fix the sternum of the thin-walled workpiece, as shown in Figure 7. These support heads marked by SH1, SH2, and SH3 can move freely in the XY plane as shown in Figure 1. The layout of support heads is critical to fixture performance. To minimize the deflection of the thin-walled workpiece during the machining process, the evolutionary algorithm is employed to optimize the fixture layout in this section.

For this optimization process, the following optimization problem for fixture layout can therefore be formulated:

$$\begin{aligned} &\text{Minimize } z_2 = U_{\max} + \sum_{i=1}^{14} \chi_i F_{clai} r, \\ &\text{Subjected to : } \frac{\max(F_{clai} r)}{\alpha l_1 l^2} \le \sigma_s \frac{\max(F_{szi})}{A} \le \sigma_s U_{\max} \le \delta'_{\max} \\ &d_{ij} \ge 20\text{mm}, i, j = 1, 2, 3 \\ &0 < x_i < 2l_1, 0 < y_i < 2l, i = 1, 2, 3, \end{aligned} \tag{6}$$

where $U_{\max}$ represents the maximum deflection of the thin-walled workpiece. χ_i represents the status of the i^{th} clamping table. For the clamping table to be clamped, χ_i is assigned with a value of 1. Conversely, χ_i is assigned as zero. F_{clai}

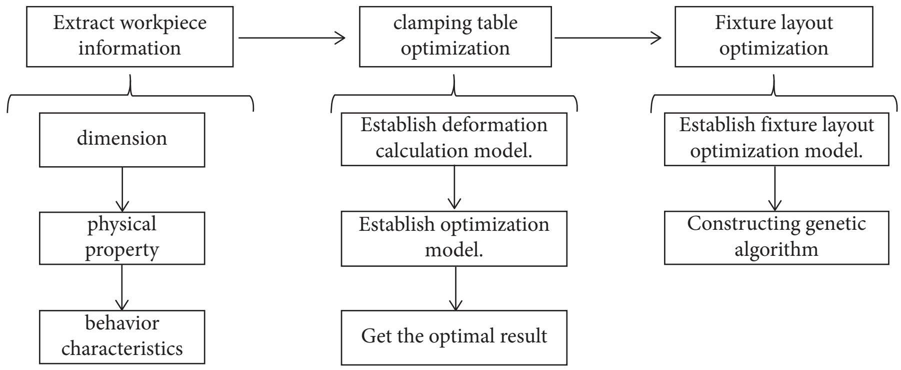


Figure 3: The process of optimization methodology.

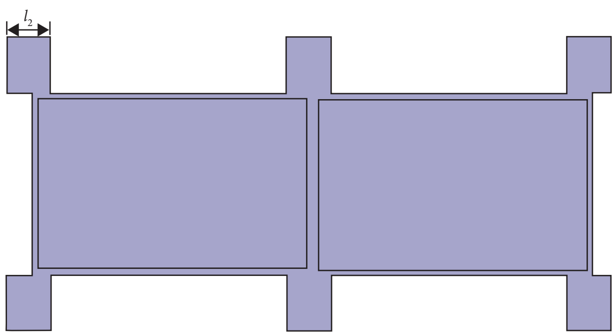


Figure 4: Initial configuration of the clamping tables.

represents the force applied to the i^{th} clamping table. α is a constant that depends on the ratio of short edge and long edge for the rectangular section between the workpiece and clamping tables. $\delta'_{\max}$ is the upper bound of the maximum deflection of the sternum. r represents the distance between the top surface and the center of the clamping table. σ_s represents the material yield stress. F_{szi} represents the applied force in Z-axis for the i^{th} support head. A represents the contact area between the support heads and sternum of the thin-walled workpiece. x_i and y_i are the coordinates of the i^{th} support head. d_{ij} is the distance between any two support heads.

From the fitness function in (6), we can learn that the greater sum of the clamping moment, $\sum_{i=1}^{14}\chi_i F_{clai} r$, the greater value of the fitness function; that is, this solution may have more possibility to be eliminated. Therefore, the fitness function can not only minimize the maximum deflection of the thin-walled workpiece while remain relatively small torque caused by the clamping tables.

The first two constraint equations are used to ensure that the stresses induced by the clamping table and the support head have to be less than the material yield stress. The fourth row of the constraint equation is introduced to avoid the conflict between these three support heads. The design domain is shown in the fifth row.

3.3. The Optimization for Fixture Layout Based on GA. The optimization problem of fixture layout is solved by the genetic algorithm (GA) for the optimal solution. The advantage of employing GA is that such an evolutionary

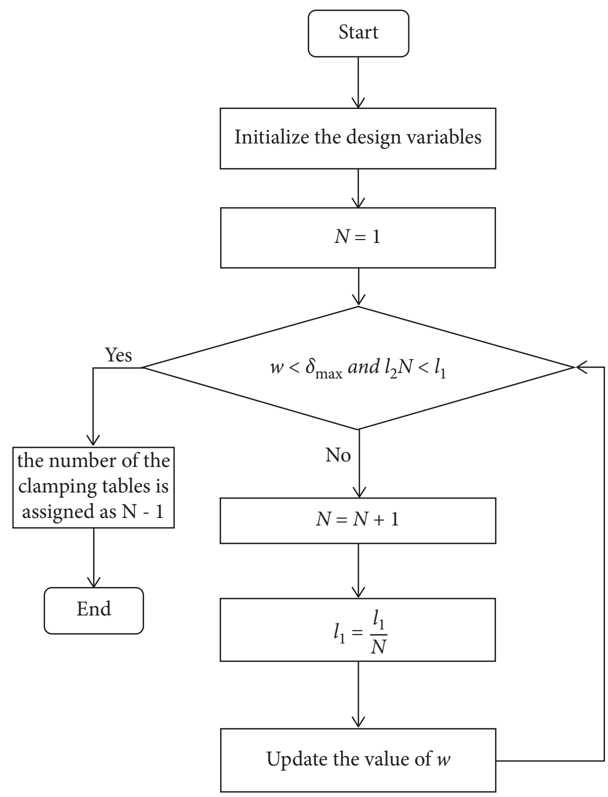


Figure 5: Flowchart of the optimization scheme.

algorithm inspired by the biological reproduction process is robust, stochastic, and heuristic so that it has a high chance to figure out the optimal solution [41]. In this section, the chromosome in GA is defined to represent the design variables, as illustrated in Figure 8. Each chromosome has 20 bits where the first fourteen bits are binary genes and the last six bits are decimal genes. The binary gene is used to represent the status of the clamping tables while the positions of three support heads are indicated by the decimal gene.

The objective function and constraints should be initialized as (6). During the whole process, the individuals of the population unsatisfying with the constraints will be eliminated.

In addition, the changes of p_c and p_m have an impact on the iteration number and convergence value of the above

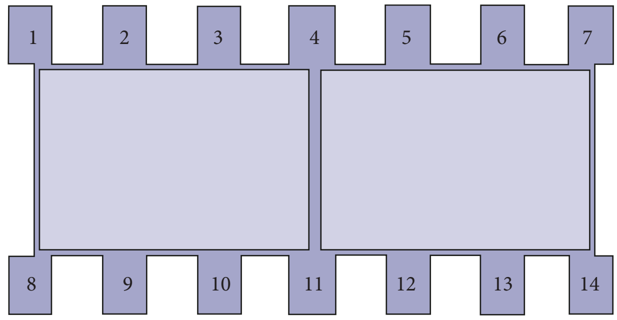
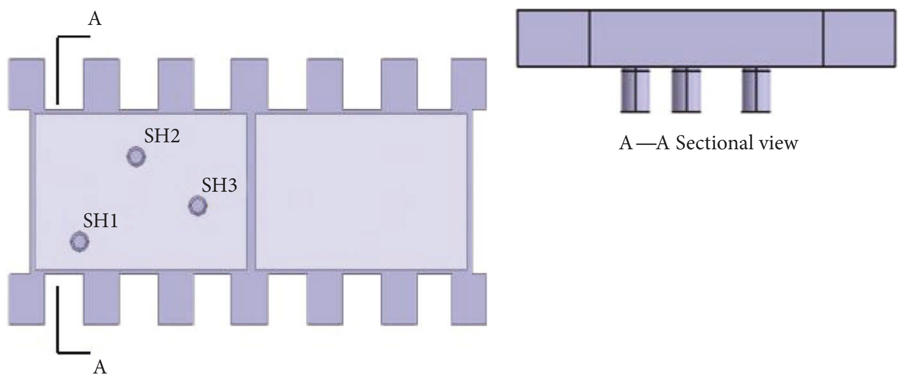


Figure 6: The optimal solution for the clamping table layout.



(a) (b)

Figure 7: Illustration of the thin-walled workpiece with three support heads. (a) Front view. (b) Sectional view.

1	0	0	1	0	1	1	0	0	0	0	1	1	1	6 support heads coordinates

Figure 8: Illustration of the chromosomes in genetic algorithm.

objective function. As shown in Figure 9 and Table 2, the convergence of the genetic algorithm is tested based on different parameter combinations, and the results are as follows.

It can be seen from Figure 9 that the number of iterations required for large p_c and p_m values is reduced, but the convergence effect is reduced. Therefore, it is necessary to select a group of appropriate parameter values in the calculation process.

Combined with references and sufficient algorithm experiments [20, 40, 41], sufficient tests have been carried out under different parameter combinations, and the ranges of parameters p_m, p_c, and G are 0.1–0.3, 0.65–0.85, and 40–100, respectively. Considering the operation efficiency and solution accuracy, the optimal parameter combination is obtained as shown in Table 3.

4. Case Study

To verify the proposed optimization methodology, a typical thin-walled workpiece shown in Figure 1 is considered in this section. Table 4 lists the values of parameters used in the case study. To simplify our discussion, three machining positions marked by MP1, MP2, and MP3 are investigated, and two cutting forces are applied to each machining position, as shown in Figure 10 and Table 5.

In this table, the value of $\delta_{\max}$ can be determined by literature [40], and the value of $\delta'_{\max}$ can be determined by literature [41].

Two groups of cutting forces with different sizes and directions are applied separately to the machining positions at the following 3 points as shown in Figure 10.

Select two different groups of cutting forces, as shown in Table 5.

Using the two groups of cutting forces to solve this problem, with many times of iterations, the pictures of convergence for the objective function and optimal fixture layout are shown as follows.

4.1. Case 1. Using the proposed optimization model in (6), the optimal fixture layout for the thin-walled structure eventually emerges after 50 generations, and each generation in this evolutionary process has 100 candidate solutions. Figure 11 shows the convergence plot for the best fitness in case #1 where the machining position is at MP1 as shown in Figure 10. It can be seen from Figure 11 that this optimization process has managed to converge since the best fitness value finally converges to 0.196 mm.

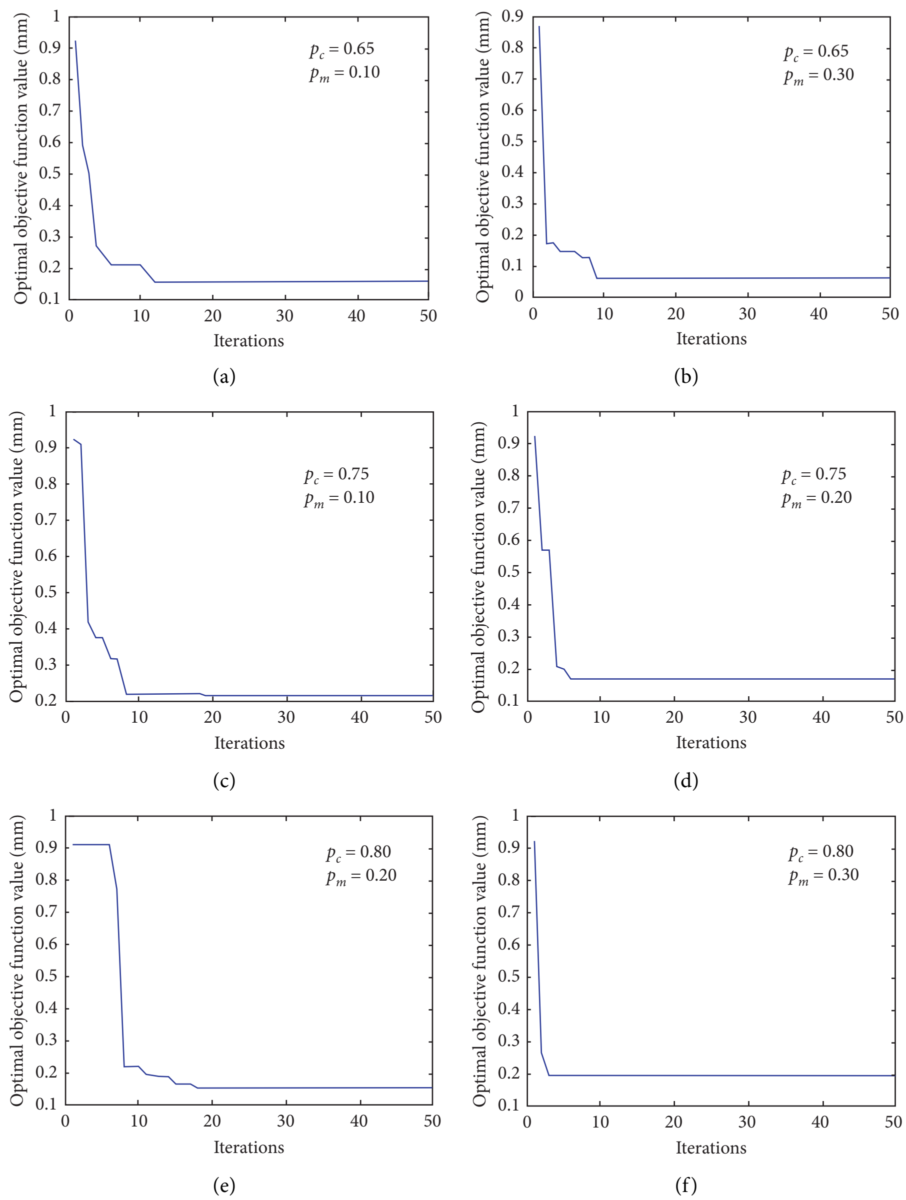


Figure 9: The convergence of the genetic algorithm.

Table 2: Different combinations of parameters.

No	p_c	p_m	
1	0.65	0.1	0.3
2	0.75	0.1	0.2
3	0.80	0.2	0.3

Table 3: The optimal combination of parameters.

p_m	p_c	G
0.1	0.85	50

Table 4: The simulation parameters.

Parameters	Value	Parameters	Value
l (mm)	130	$h(mm)$	4
l_1 (mm)	195	$\delta'_{\max}(mm)$	0.13
l_2 (mm)	30	γ	0.0754
$\delta_{\max}$ (mm)	0.028	α	0.231
r (mm)	20	μ	0.334
σ_s (MPa)	361	G	50
A (mm^2)	400π	Population size	100
F (N)	500	p_c	0.85
E (MPa)	7.1×10^5	p_m	0.1

The optimal fixture layout of three support heads and fourteen clamping tables is illustrated in Figure 12(a), and the displacement contour of the thin-walled structure is shown in Figure 12(b). In Figure 12(a), three support heads highlighted in red color are denoted by SH1, SH2, and SH3, respectively. It can be seen that one of these support heads, SH2, is placed in the machining position, MP1.This is because the large deflection of the thin-walled structure will be

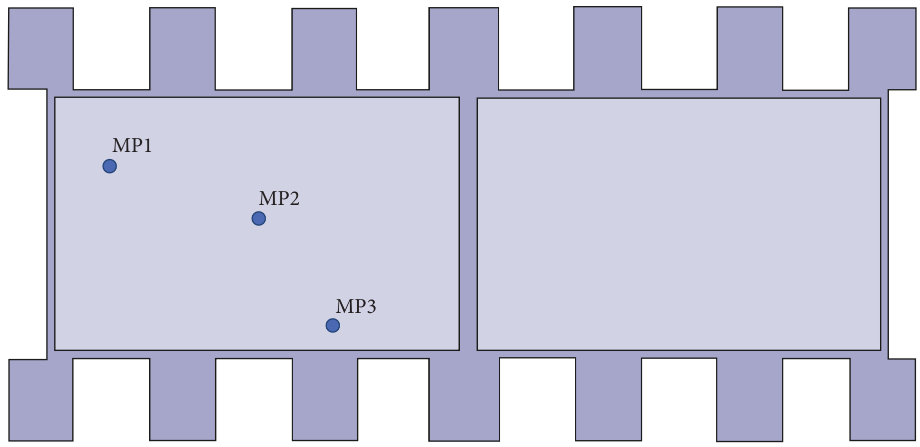


Figure 10: The picture of machining positions: MP is the machining position.

Table 5: The cutting forces.

Case	Cutting force (N)		
	F_x	F_y	F_z
1	180	480	−85
2	275	400	138

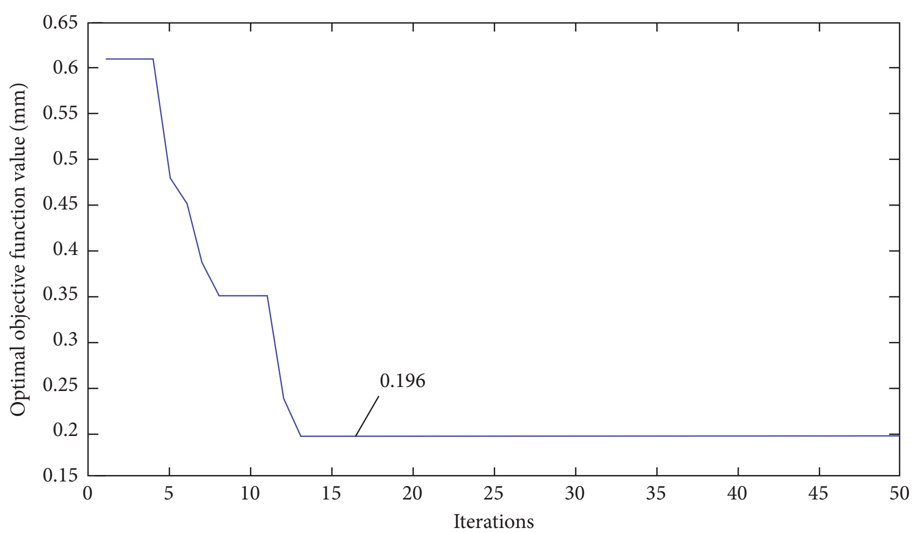


Figure 11: The convergence plot for best fitness in case #1 where the machining position is at MP1 as shown in Figure 10.

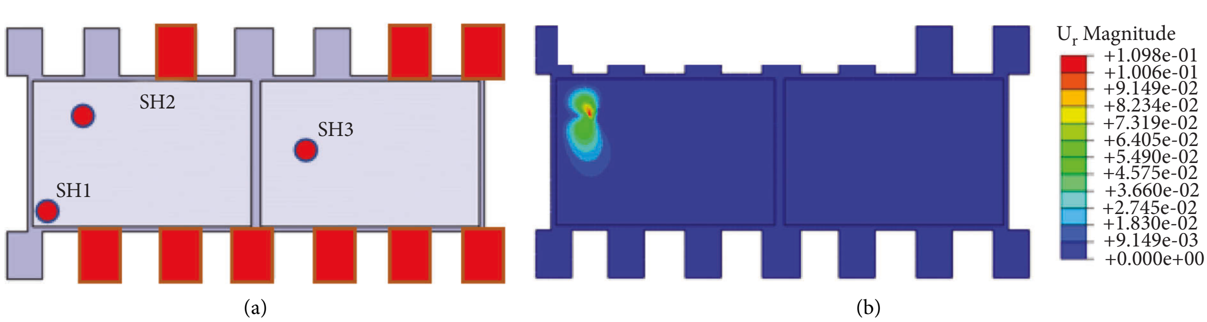


Figure 12: The optimal solution obtained in case #1 where the machining position is at MP1 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

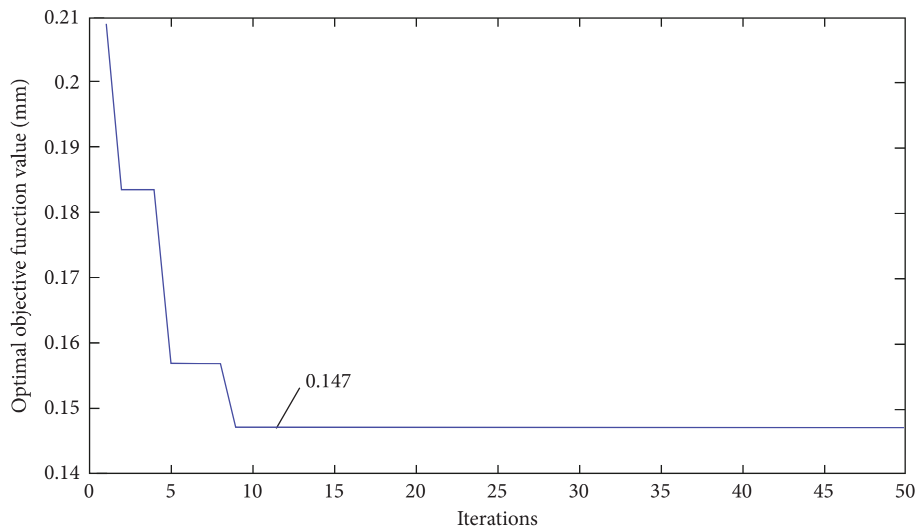
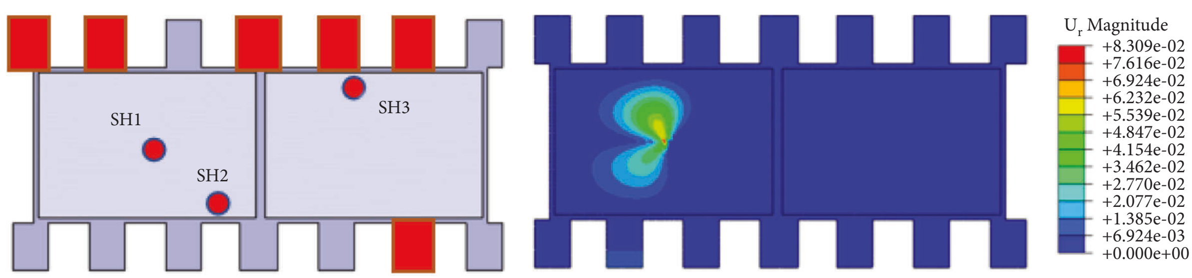


Figure 13: The convergence plot for best fitness in case #1 where the machining position is at MP2 as shown in Figure 10.



(a) (b)

Figure 14: The optimal solution obtained in case #1 where the machining position is at MP2 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

produced at the machining position, MP1. Once one of three support heads is allocated at MP1, the large deflection of the thin-walled structure will be reduced. The fixture layout of three support heads is rational, which can be explained by means of the displacement contour of the thin-walled structure as shown in Figure 12(b). In addition, there are nine clamping tables to be fixed to the ground, which are highlighted in red color as shown in Figure 12(a). It can be noted that the fixed clamping tables are mainly allocated on the bottom right of the thin-walled workpiece. This is because such a configuration can avoid the thin-walled workpiece to flip over.

Figure 13 shows the convergence plot for the best fitness in case #1 where the machining position is at MP2 as shown in Figure 10. It can be seen from Figure 13 that this optimization process has managed to converge since the best fitness value finally converges to 0.147 mm.

In Figure 14(a), it can be noted that the fixture layout is different from Figure 12(a) due to the variation of the cutting forces' position. Similarly, to reduce the large deflection of the thin-wall structure caused at MP2, one of these support heads, i.e., SH1, is placed in MP2. Moreover, there are six clamping tables to be fixed to the ground as shown in Figure 14(a). We can get the information that the fixed clamping tables are mainly allocated on the top right of the thin-walled workpiece. Such configuration can also avoid the thin-walled workpiece to flip over. Therefore, the fixture layout is rational, which can be explained by means of the displacement contour of the thin-walled structure as shown in Figure 14(b).

Figure 15 shows the convergence plot for the best fitness in case #1 where the machining position is at MP3 as shown in Figure 10. It can be seen from Figure 15 that this optimization process has managed to converge since the best fitness value finally converges to 0.139 mm.

In Figure 16(a), compared to the previous two examples, this fixture layout is still distinct because of the different positions of cutting forces. The support head, SH2, is placed to MP3 for decreasing the deformation of the workpiece during machining, and there are seven clamping tables are fixed to provide more stability for machining. For the machining point near the center of the workpiece, the red clamping tables are allocated on the left and right sides of the thin-walled workpiece. The displacement contour shown in Figure 16(b) has verified the rationality of this layout.

4.2. Case 2. Loading the cutting forces in case #2 to the thin-walled workpiece, we can get the results as follows.

The convergence plot for the best fitness is shown in Figure 17 where the machining position is at MP1. It can be

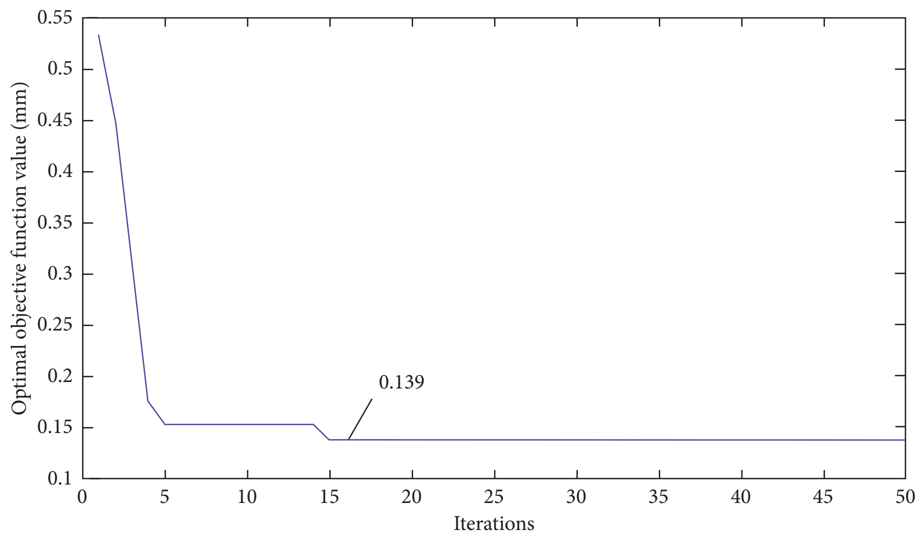


Figure 15: The convergence plot for best fitness in case #1 where the machining position is at MP3 as shown in Figure 10.

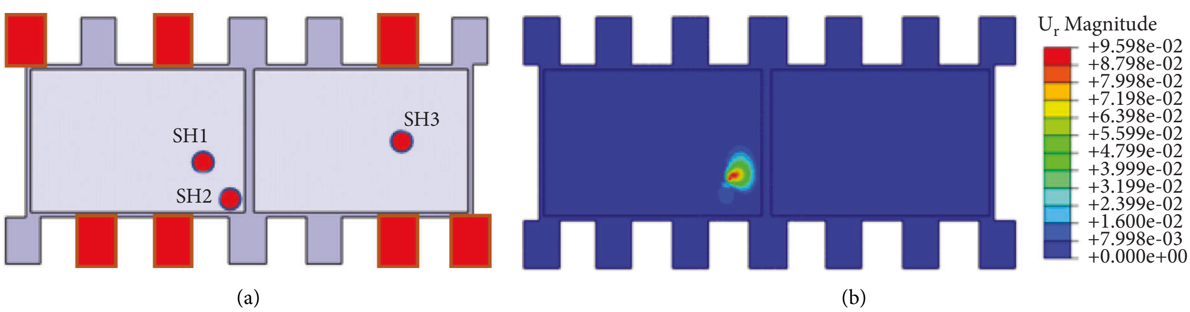


Figure 16: The optimal solution obtained in case #1 where the machining position is at MP3 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

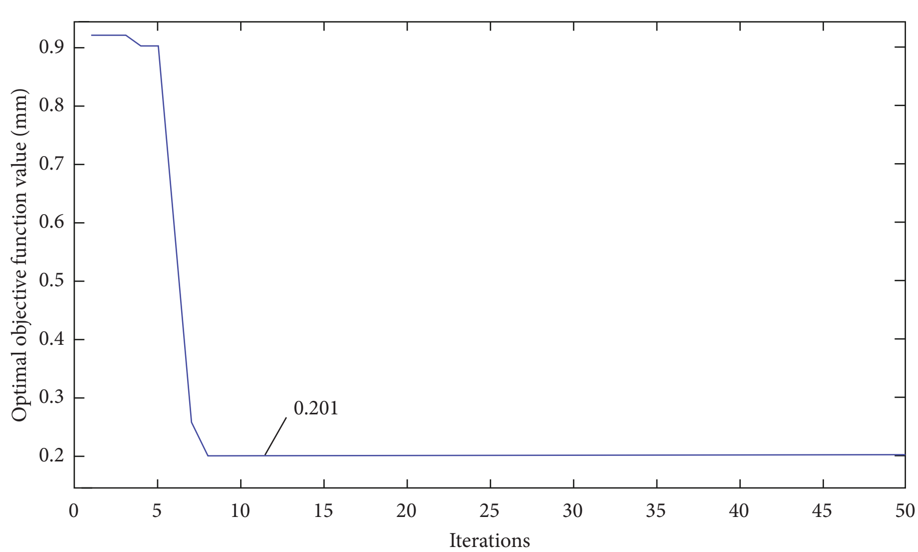


Figure 17: The convergence plot for best fitness in case #2 where the machining position is at MP1 as shown in Figure 10.

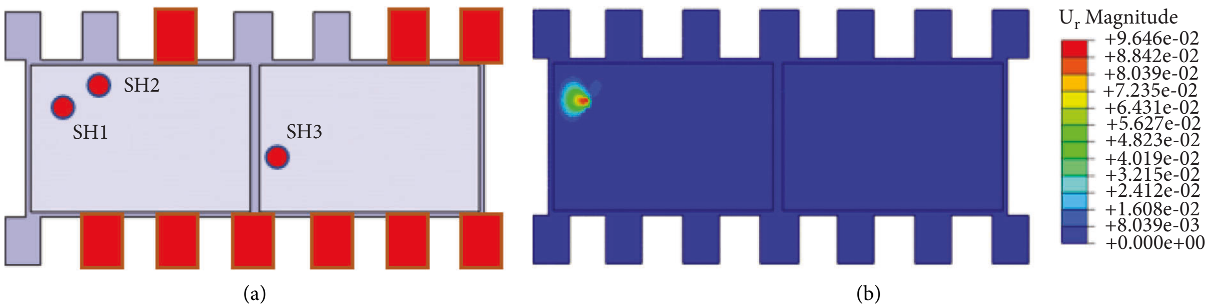


FIGURE 18: The optimal solution obtained in case #2 where the machining position is at MP1 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

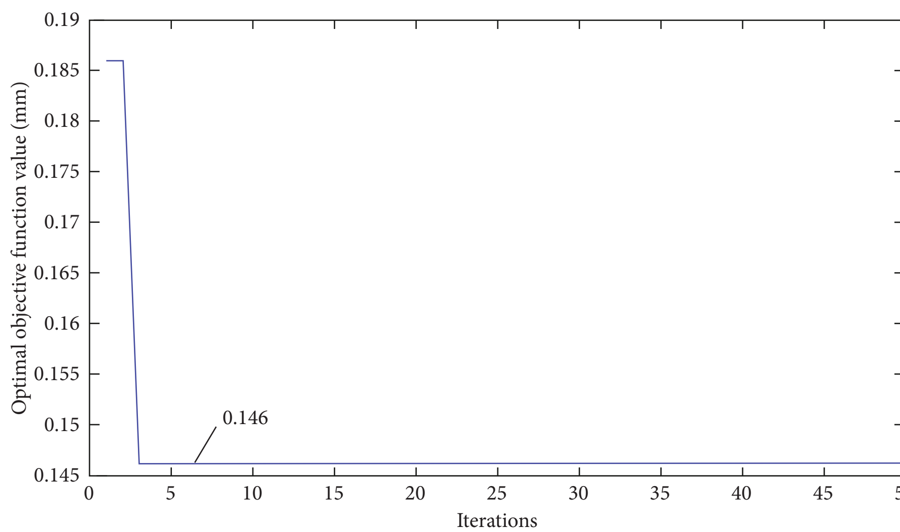


FIGURE 19: The convergence plot for best fitness in case #2 where the machining position is at MP2 as shown in Figure 10.

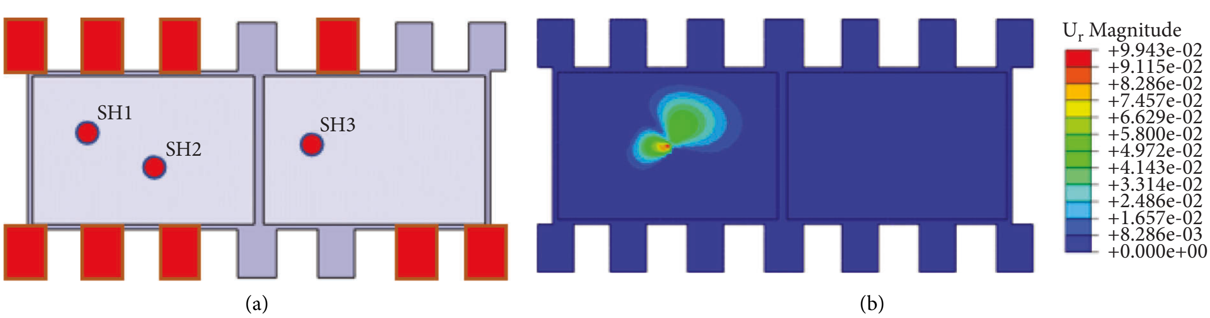


FIGURE 20: The optimal solution obtained in case #2 where the machining position is at MP2 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

noted from this figure that this optimization process has managed to converge since the best fitness value finally converges to 0.201 mm.

In Figure 18(a), the support head, SH1, is placed to MP1 for decreasing the deformation of the workpiece during machining. It can be seen from Figure 18(a) that the layout of support heads is different from that of case #1. This is because the values of cutting forces have changed. However, the layout of the red clamping tables is similar to that of case #1, and the reason is still unclear and needs further investigation. Therefore, the fixture layout is rational, which can be explained by means of the displacement contour of the thin-walled structure as shown in Figure 18(b).

The convergence plot for the best fitness is shown in Figure 19 where the machining position is at MP2. It can be noted from this figure that this optimization process has managed to converge since the best fitness value finally converges to 0.146 mm.

In Figure 20(a), the support head, SH2, is located in MP2 for reducing the deflection of the workpiece during machining. It can be seen from Figure 20(a) that the fixture layout is different from that of case #1. This is because the

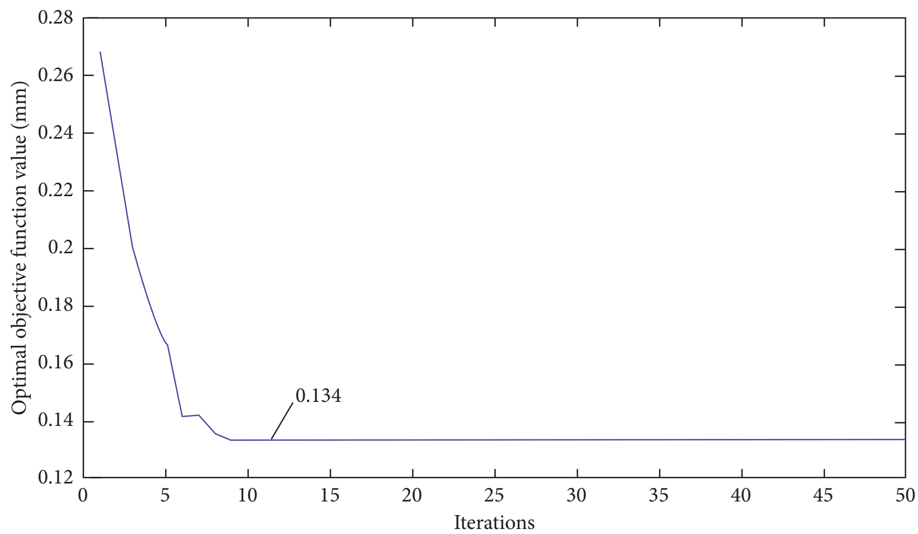


Figure 21: The convergence plot for best fitness in case #2 where the machining position is at MP3 as shown in Figure 10.

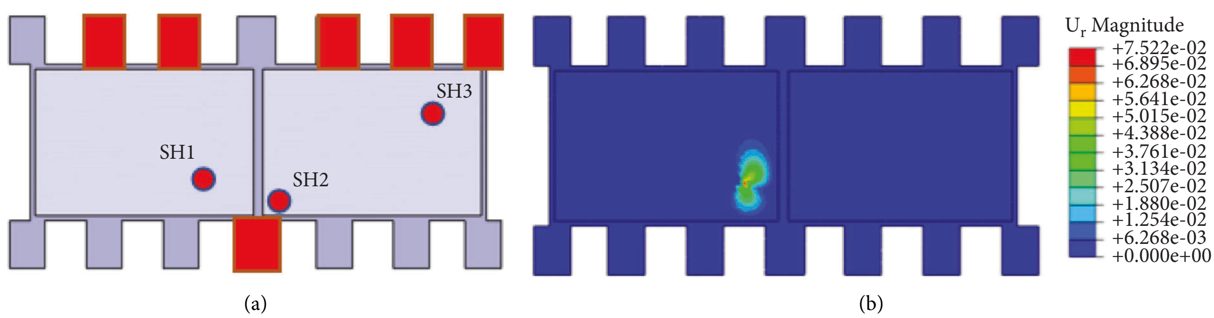


Figure 22: The optimal solution obtained in case #2 where the machining position is at MP3 as shown in Figure 10. (a) The optimal fixture layout. (b) The displacement contour of the thin-walled structure.

values of cutting forces have changed. Although compared to case #1, this layout of red clamping tables has changed, it can still provide sufficient stability to the thin-wall workpiece. Figure 20(b) can also validate the fixture layout.

The convergence plot for the best fitness is shown in Figure 21 where the machining position is at MP2. It can be noted from this figure that this optimization process has managed to converge since the best fitness value finally converges to 0.134 mm.

In Figure 22(a), the support head, SH1, is located in MP3 for reducing the deflection of the workpiece during machining. It can be seen from Figure 22(a) that the fixture layout is also different from that of case #1 in that the values of cutting forces have changed. Compared to case #1, this layout of red clamping tables has also changed, and similarly, it still provides sufficient stability to the thin-wall workpiece. Therefore, the fixture layout is rational, which can be explained by means of the displacement contour of the thin-walled structure as shown in Figure 22(b).

To sum up, the fixture layout can be summarized in Tables 6 and 7.

From the aforementioned results, we can see that the maximum deformation is lower than 0.12 mm. According to the result of these researches [1, 4, 25, 40–44], we can learn that the maximum deformation of the workpiece with the aluminum materials is in the range of 0.02 to 2 mm when the eternal load is in the range of 200 N to 1500 N. For example, [1] uses sheet metal with a thickness of 3 mm and similar material properties to this article to research the fixture layout. Finally, its maximum deformation is in the range of 0.7 to 1.9 mm. In literature [4], the workpiece with a thickness of 8 mm that is made of 7075-T6 aluminum is used to research its fixture layout. Similarly, its maximum deformation is in the range of 0.04 to 0.3 mm. Some other researches can also get similar results. Therefore, the results of this article are rational.

In addition, comparing the researches [1, 20, 40, 41, 44], we can also see that the results of the genetic algorithm are greater than others. Those researches employ the whale algorithm, genetic algorithm, ant colony algorithm, and nonlinear programming algorithm, respectively. Where the literature [1] uses the whale algorithm to solve the fixture layout optimization, the literature [20] uses the ant colony algorithm to solve the fixture layout optimization; the literature [40, 41] uses the genetic algorithm to solve the fixture layout optimization; the literature [44] uses the nonlinear programming algorithm to solve the fixture layout optimization. The optimization method in this article needs to optimize both the clamping tables and support heads; that is, it involves the combined use of discrete variables and

Table 6: The layout of support heads.

Case	Position	Support head 1		Support head 2		Support head 3		Objective function (mm)
		X	Y	X	Y	X	Y	
1	MP1	1.882	0.587	43.126	90.869	224.303	54.819	0.196
	MP2	101.699	55.172	149.250	12.431	272.199	116.322	0.147
	MP3	144.313	35.982	177.346	0.0526	312.869	41.979	0.139
2	MP1	37.299	82.865	58.191	9.407	189.579	48.041	0.201
	MP2	49.4967	75.632	98.110	48.708	219.720	16.013	0.146
	MP3	141.292	32.618	200.014	0.2172	325.356	71.484	0.134

Table 7: The layout of clamping tables.

Case	Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	MP1	0	0	1	0	0	1	1	0	1	1	1	1	1	1
	MP2	1	1	0	1	1	1	0	0	0	0	0	0	1	0
	MP3	1	0	1	0	0	1	0	0	1	1	0	0	1	1
2	MP1	0	0	1	0	0	1	1	0	1	1	1	1	1	1
	MP2	1	1	1	0	1	0	0	1	1	1	0	0	1	1
	MP3	0	1	1	0	1	1	1	0	0	0	1	0	0	0

continuous variables. The hybrid coding of genetic algorithm binary and real numbers can solve this problem conveniently. In the meanwhile, the genetic algorithm has the advantages of low time-space complexity and easy implementation. Therefore, the genetic algorithm is chosen for this article [42–44].

5. Conclusions

In this paper, the optimization design of the machining fixture layout for thin-walled structures is investigated. A universal optimization methodology is proposed, and an evolutionary algorithm is employed to automatically generate the optimal machining fixture layout including the clamp layout and the layout of support heads. The proposed optimization methodology can not only eliminate the effect of clamps on the workpiece deflection but also provide a dynamic fixture layout for a thin-walled structure. The results from the two cases show that the maximum deformation is lower than 0.12 mm, and they are rational. Case analyses show that this methodology can greatly resolve the fixture layout optimization of rectangular thin-walled structures. Its innovation is to present a kind of optimization method for clamping tables and develop a novel fixture layout optimization method for rectangular thin-walled structures, which is associated with the clamping tables.

However, the methodology cannot be applied to practical engineering temporarily, because there are still some shortcomings. First, this methodology is not experimentally verified, because there is currently no lab facility that can implement both dynamic layouts of clamping tables and support heads in this area of research. Second, the number of clamping tables and the time complexity of the program should be further reduced. Finally, the finite element model is a little simple that the real situation of cutting is not considered in this finite element model, which leads to a gap between theoretical research and practical application. In future research, this methodology should not only resolve the aforementioned shortcomings but also further reduce the deformation of the thin-walled structure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Shanxi Postgraduate Innovation Project Funding, China (2021Y578); Central and Local Science and Technology Development Fund Project (provincial and ministerial level fund project): Research on Digital Automatic Docking Assembly Technology of General Aviation Aircraft Large Parts, China (YDZX20201400001519).

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