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The Determination of Workpiece Fixturing Scheme Based on Gray Relation Analysis Method

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Abstract

The design of machining fixtures is a highly complex process that heavily relies on designer experience and his/her implicit knowledge to achieve a good design. The determination of fixturing scheme is an optimizing problem with multi-objective and multi-constraint. In order to evaluate the fixturing scheme objectively, a fixturing design scheme selection objective system is developed according to the feature of multi-level and multi-index of fixturing design scheme. With location accuracy, contact force, workpiece deformation and successive fixturing as the objective functions, the optimization selection of mathematical model of fixturing design scheme is established, then it is solved by gray relation analysis and analytic hierarchy process. The method provides a qualitative and quantitative combining analysis for a fixturing design scheme: (a) verifying whether a particular fixturing scheme is valid with respect to locating stability, deterministic workpiece location, clamping stability and total restraint and (b) determining the optimal fitness value based on integrate performances. An example is presented to demonstrate the effectiveness and the capabilities of the methodology. The study shows the gray relation analysis and the analytic hierarchy process can improve selecting quality for determination of fixturing design scheme.

Keywords: *Gray relation analysis, Locating accuracy, Contact force, Indexes system*

1. Introduction

The function of a fixture is to establish the required position and orientation of a workpiece with respect to the machining tool or cutter and to maintain its position during machining through a set of fixture elements in contact with the workpiece. Fixture design is a complicated, experience-based process which needs comprehensive qualitative knowledge about a number of design issues including location accuracy, contact deformation between the workpiece and the locators/clamps, *etc.*, and quantitative knowledge about location correctness, static equilibrium of workpiece due to external loads (clamping and cutting forces). So fixturing performance is crucial to product quality. It is necessary to establish applicable analytical systematic methodology to evaluate the effect of a few of fixture performance indexes on the product quality.

In the past, many researchers had worked on the fixture design and analysis. Qin *et al.*, [1, 2] firstly defined the concept of locating correctness. Moreover, a locating correctness based approach was proposed to determine locating scheme including locator number and positions. Asada and Andrek [3] developed a kinematic model of the locating scheme using Taylor

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expansion to verify the deterministic location. Location correctness is the firstly important rule of fixture design. Stability is one of the most important technical principles in fixturing design and analysis. Stability analysis in fixture design evaluates the workpiece's static equilibrium under the given fixturing condition and in the presence of machining forces. A kinematic modeling approach was used in selecting the configuration of fixturing locations and clamping positions such that the workpiece is totally constrained from any type of motion during a machining operation [3]. Utpal and Liao [4] developed a method to judge the effect of the magnitude and position of clamping forces on the workpiece stability. Chou *et al.*, [5] developed a mathematical approach based on screw theory to automate the fixture analysis and synthesize. A linear programming problem was formulated as a part of their analytic approach to derive the optimal clamping forces. Fuh *et al.*, [6] presented a systematic approach used in verification of the fixturing scheme. Mittal *et al.*, [7] proposed a dynamic model for the fixture-workpiece system, and used it to obtain the clamping forces required to maintain stability of workpiece under the given machining conditions.

Certainly, a good design fixture must still optimize a few performance indexes including location accuracy, workpiece deformation, contact forces, economic cost, and so on. Dan and Xiang *et al.*, [8] proposed a fixture layout design method which selected a set of locating points from a collection of discrete points for reduction of locating error. Wu and Lou *et al.*, [9] determined the locator layout aiming at minimizing locating error, based on hybrid method of empirical analysis with generic algorithm. Qin and Zhang *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. By assuming deformable in the contact zone, and rigid elsewhere, Li and Melkote *et al.*, [11] presented a method to minimize the effect of rigid body motion caused by local deformation in the contact zone between fixture and workpiece. Tseng [12] established the FBFA (Feature-Based Fixturing Analysis) procedure to determine the fixturing scheme for the intermediate steps in a sequential feature based machining.

Minimizing the maximum elastic deformation of the machined surfaces and maximizing the uniformity of deformation as the goal, Chen and Xue *et al.*, [13] presented a method to determine a fixture layout with FEA and GA. Diana *et al.*, [14] determined and evaluated the acceptable fixture designs based on multiple quality criteria and to select an optimal fixture with appropriate trade-offs among multiple performance requirements. Wang and Chen *et al.*, [15] presented a methodology of fixture layout optimisation, based on three performance indexes including the repeatability, immobility and stability of fixturing. Bansal and Nagarajan [16] developed a fixture planning model with consideration of uniqueness, stability, accessibility and tolerance minimization.

However, most of prior studies have two common limitations: (1) single object optimization, i.e., when the fixturing scheme is evaluated or optimized, the object function was established according to some fixturing performance, such as location accuracy, clamping forces, workpiece deformation, and so on. (2) Although some studies considered multi-objective optimization, they just considered individual contribution of each influential factor to the most appropriate scheme, neglected influence of intercoupling among all the factors on scheme performances.

While decision making system of multi-objective optimization is an organic entirety, each factor is correlative, and collectively influences system characteristic. It is difficulty to determine the influence degree, which is a gray information system. In order to select fixturing design scheme more objective, based on the idea of system decision making, this paper establishes a fixturing design scheme selection objective system according to multi-index, multi-level feature of fixturing design scheme. With location accuracy, contact forces, workpiece deformation and successive fixturing as the objective functions, the optimization selection of mathematical model of fixture design scheme is established, then it is solved by gray relation analysis and AHP. The method provides a qualitative and quantitative combining analysis for a fixture design scheme: (a) verifying whether a particular fixturing scheme is valid with respect to locating stability, deterministic workpiece location, clamping stability and total restraint and (b) determining the optimal fitness value based on integrate performances shown in Figure 1.

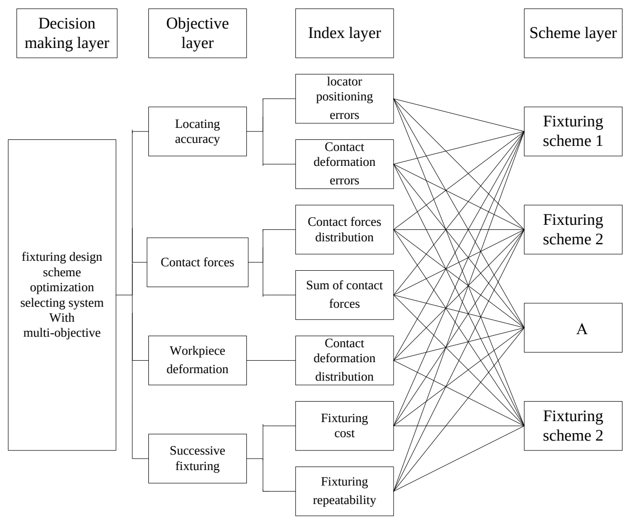

Figure 1. Decision making system of fixturing design scheme optimization Selecting

2. Two Basic Requirements for The Fixturing Scheme

2.1. Location correctness constraint

A workpiece has six DOFs (degree of freedom) in orthogonal coordinate system. In order to guarantee the design specification of the machining feature of the workpiece, some DOFs must be constrained to obtain the reasonable location of the workpiece with respect to the cutting tool. The essential constrained DOFs are named as the theoretical constrained DOFs. The relationship between the theoretical constrained DOFs and the design specification of the machining feature is represented as

$$\Delta \boldsymbol{r}_{\mathrm{p}}=\boldsymbol{E}_{\mathrm{p}}\cdot \boldsymbol{fr}_1 \tag{1}$$

where Δr_p is the machining error measuring the design specification. fr_1 is the theoretical constrained DOFs. E_p is the configuration matrix at the process point $r_p=[x_p, y_p, z_p]^{\mathrm{T}}$.

$$\boldsymbol{E}_{\mathrm{p}}=\begin{bmatrix} 1 & 0 & 0 & 0 & z_{\mathrm{p}} & -y_{\mathrm{p}} \\ 0 & 1 & 0 & -z_{\mathrm{p}} & 0 & x_{\mathrm{p}} \\ 0 & 0 & 1 & y_{\mathrm{p}} & -x_{\mathrm{p}} & 0 \end{bmatrix} \tag{2}$$

It is well known that the theoretical constrained DOFs are eliminated by a feasible locating scheme. Here, an arbitrary locating scheme is assumed to consist of k locators, as shown in Figure 2 $n_i=[n_{ix}, n_{iy}, n_{iz}]^{\mathrm{T}}$ (i=1, 2, …, k) is the unit normal vector of the workpiece surface at the ith contact point r_i=[x_i, y_i, z_i]^T. Thus, its practical constrained DOFs of the workpiece whose formulation can be rewritten as

$$Jfr_2 = 0 \tag{3}$$

where fr_2 is the practical constrained DOFs. J is the locating Jacobin matrix, and its expression can be concluded as

$$\boldsymbol{J} = \begin{bmatrix} -\boldsymbol{n}_1 & -\boldsymbol{n}_2 & \dots & -\boldsymbol{n}_k \\ -\boldsymbol{n}_1 \times \boldsymbol{r}_1 & -\boldsymbol{n}_2 \times \boldsymbol{r}_2 & \dots & -\boldsymbol{n}_k \times \boldsymbol{r}_k \end{bmatrix}^T \tag{4}$$

The correctness of the designed locator layout depends on the logic relationship between fr_1 and fr_2. There are four possible logic relations shown in Figure 3. While only the included relation is correct for the location requirement.

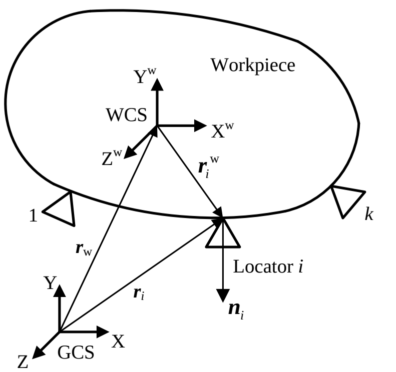

Figure 2. Fixture locating scheme

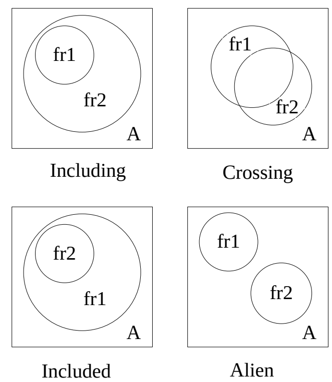

Figure 3. The logic relations between *fr1* and *fr2*

2.2 Static equilibrium constraint

Workpiece stability is one of the most important technical principles in fixture design and analysis. Stability analysis in fixture design evaluates the workpiece's static equilibrium under the given fixturing condition and in the presence of machining forces. The clamped workpiece should always contact the fixture locators, otherwise the contact status between the workpiece and the fixture locators would change, resulting in an unstable fixture performance. The workpiece–fixture system must be in static equilibrium for a stable fixture configuration to be realized. These constraints can be expressed in vector form as follows:

$$\sum \boldsymbol{F}=\boldsymbol{0} \tag{5}$$

$$\sum \boldsymbol{M}=\boldsymbol{0} \tag{6}$$

In the above equations F represents the vector sum of all forces applied to the workpiece and M represents the vector sum of all moments acting on the workpiece.

3. Quality Performance Indexes

3.1 Locating accuracy index

An essential aspect of fixture performance is the positioning accuracy of workpiece provided by the locators. In general the workpiece positional error is due to the geometric variability of the part and the locator set-up errors. The locator positional variability depends on the dimensioning and tolerance scheme of the fixture assembly and its components. In this paper we will focus on the workpiece positional errors due to the locator positioning errors.

The positioning errors of locators are characterized by their positioning inaccuracy. The norm of the locator positioning error is related with the localization error of the workpiece as follows:

$$\|\Delta s\| = \Delta r^T \left(J^T J \right) \Delta r \tag{7}$$

where $\Delta s = [\Delta s_1, \Delta s_2, \ldots \Delta s_n]^T$ and $\Delta r = [\Delta x, \Delta y, \Delta z, \Delta \alpha, \Delta \beta, \Delta \gamma]^T$ represent the locator positioning errors and the localization error of the workpiece, respectively. In general, the locator positioning errors is given. In order to obtain the minimal localization error of the workpiece, it is necessary to maximize the determinant of the information $M=J^TJ$, i.e., max det(J^TJ).

3.2 Contact Forces Distribution Index

Another significant issue in designing a fixture is that the total forces acting on the workpiece should be distributed as uniformly as possible among the locator contacts. If p_{avg} represents the mean reactive force in response to the clamp action, then we define the dispersion of the locator contact forces as

$$d = \sqrt{\sum_{i=1}^{n} \left(p_{ci}^{n} - p_{avg}^{n} \right)^2 \Big/ n}, \quad where \quad p_{avg}^{n} = \sum_{i=1}^{n} p_{ci}^{n} \Big/ n \tag{8}$$

Therefore, minimizing the defined dispersion represents an objective for a balanced force-closure, min(d).

3.3 Workpiece deformation index

A machining fixture consists of n fixture contact elements (*i.e.*, locators and clamps) with spherical, which is shown in Figure 4. The workpiece and fixture material are linearly elastic in the contact region, and perfectly rigid elsewhere. The workpiece-fixture system is under stable condition.

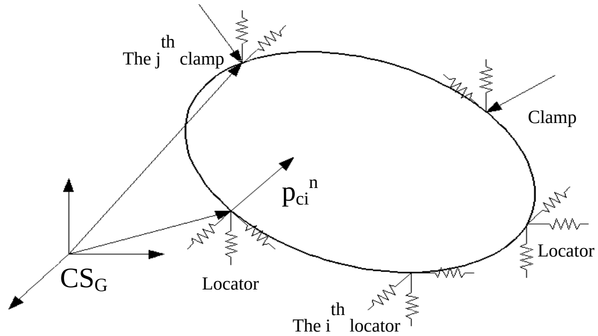

Figure 4. A workpiece constrained by the fixture elements

Contact deformation in the normal direction, owing to normal contact pressure, can be obtained by approximating the closed-form solution to the problem of a circular region of radius R_i subjected to uniform normal pressure. This involves replacing a square region of length 2 R_i by its inscribed circular area of radius R_i. Applying this approximation, the average normal deformation for this problem, δ_{navg}^{ni}, is given by:

$$\delta_{avg}^{ni} = 0.54 \frac{\left(1-\nu_w^2\right)}{E_w R_i} p_{ci}^n \tag{9}$$

where P^n_{ci} is the normal force, E_w is the Young's modulus of the workpiece material and v_w is its Poisson's ratio. It is assumed here that the effect of tangential force on normal deformation is negligible.

Similarly, the average deformation in the tangential direction due to a tangential force Q_{ci}:

$$\delta_{avg}^{ti} = \frac{\left(1+\nu_w\right)\left(2-\nu_w\right)}{4E_w R_i} Q_{ci} \tag{10}$$

To a candidate fixture layout, it is possible to minimize the maximum of workpiece deformation resulting from the contact forces. The index can be mathematically presented as follow:

$$\min\left(\max(\left|\delta_{avg}^{n1}\right|,\left|\delta_{avg}^{t1}\right|,\left|\delta_{avg}^{n2}\right|,\left|\delta_{avg}^{t2}\right|,......,\left|\delta_{avg}^{nn}\right|,\left|\delta_{avg}^{tn}\right|)\right) \tag{11}$$

$$d = \sqrt{\sum_{i=1}^{2n}\left(\delta_{avg}^{i} - \Delta\delta_{avg}\right)^2 \Big/ 2n}, \quad where \quad \Delta\delta_{avg} = \sum_{i=1}^{2n}\delta_{avg}^{i} \Big/ 2n \tag{12}$$

3.4 Successive Fixturing Index

The purpose of a fixture is to locate and hold a workpiece such that the cutting operations can be performed. To complete the machining of a part, the orientation and the position of the part may need to be changed at certain intermediate steps such that the different faces of the part can be machined. Therefore, different fixturing parameters are needed to hold the different intermediate workpieces in order to complete the machining of the part. Since the setup time often adds a great amount of the production lead time, it is desired to keep the change of fixturing parameters at a minimum level. In practice, the fixture elements are classified into several major groups: base plate group, element group locating element group, clamping element group, supporting element group, standard element group, connecting elements group, and so on, according to their different functions. With regard to some physical fixture element, its adjustment includes three measures: being removed, being replaced by the other element belonging to the same group, be moved about the position. The different adjustment has a variational effect on the setup time. The movement of fixture element is the easiest, while the removing of the fixture element may be the most complicate, because it maybe deal with the construction of the fixture.

4. The Gray Relation Analysis of Fixturing Scheme

The problem of the optimal selecting of the candidate fixture scheme is actually a gray determination problem with multi-objective, quantitative and qualitative analysis. On the premise of meeting the basic design requirements, there are a few candidate schemes. The designer needs to determine the most optimal scheme which is the best on the integrative performances.

The gray relation, which is the basic concept in the gray system, is defined as the uncertain relationship among things, the interior factors of system or effect of factors on primary actions. The gray system regards that it is impossible to be strictly irrelevant for the two arbitrary action sequences in the system. Consequently, the gray system theory estimates the microcosmic or macroscopical geometrical adjacent grades among the action sequences of system with relation analysis method. The gray relation analysis is the quantitative analysis for the dynamic development of the action sequences.

From the vector viewpoint, a design scheme Fi defined by m objectives can be described as

$$F_i = \left(f_{i1}, f_{i2}, ..., f_{im} \right) \tag{13}$$

When the *m* objective values are determined, the scheme fitness is also determined. And then, the optimal selection is transformed to compare the fitness of these objectives. The sub-objective value of the candidate scheme constitutes the comparative sequences in the gray relation analysis.

It is assumed that one scheme collection of the gray system is made up of *n* schemes in the candidate fixturing design schemes, and every scheme has *m* indexes collection. According to different properties, these indexes are divided into some gray sub-systems. And these indexes are necessary to meet these requirements:

$$\mathrm{F} = \bigcup_{j=1}^{n} f_j, \quad f_j \cap f_k = \Phi \qquad j \neq k \tag{14}$$

Where, ∪, ∩ denote the sum and intersection, respectively. Φ denotes null collection.

In the gray system, m factors of n schemes can be described as:

$$X = \left(x_{ij} \right)_{n \times m} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{15}$$

To be convenient for gray relation analysis, all the evaluation indexes will be normalized, the method is as followed:

(1) If the function value is bigger, the index will be better (benefit mode);

$$f_{ij} = \frac{f_{ij} - \min\left(f_{ij}\right)}{\max\left(f_{ij}\right) - \min\left(f_{ij}\right)} \tag{16}$$

(2) If the function value is smaller, the index will be better (cost mode);

$$f_{ij} = \frac{\max\left(f_{ij}\right) - f_{ij}}{\max\left(f_{ij}\right) - \min\left(f_{ij}\right)} \tag{17}$$

Using the normalization, the equation (15) can be transformed to

$$R = \left(r_{ij}\right) = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} \tag{18}$$

For comparing with all the candidate schemes, it is necessary to construct a reference sequence. Since the optimization selecting of the scheme has relativity of compare, an imaginary perfect scheme is defined. All its indexes are the corresponding greatest value among the schemes, i.e. the reference sequence of the perfect scheme is as followed:

$$R_0 = \left(r_{01}, r_{02}, ..., r_{0m}\right) \qquad there\,\mathrm{int}\,o : r_{0j} = \begin{cases} \vee_j f_{ij}(benefit) \\ \wedge_j f_{ij}(\cos t) \end{cases} \tag{19}$$

Every candidate scheme will be compared with the above imaginary one, and the relationship coefficients of all the candidate schemes are obtained.

$$\xi_{ij} = \frac{\min_{i\in n}\min_{j\in m}\left|f_{0j} - f_{ij}\right| + \rho \max_{i\in n}\max_{j\in m}\left|f_{0j} - f_{ij}\right|}{\left|f_{0j} - f_{ij}\right| + \rho \max_{i\in n}\max_{j\in m}\left|f_{0j} - f_{ij}\right|} \tag{20}$$

Where $\rho \in [0, 1]$ is differentiation coefficient. Let it be 0.5 in general.

The above equation means in respect of the *j*th objective of the *i*th candidate scheme, it is possible to reach degree of perfect scheme after considering possible effect of various objectives of all the candidate schemes on the *i*th candidate scheme. The total systematic gray relation coefficient matrix of all the candidate schemes is given.

$$\Xi = \left(\xi_{ij}\right)_{n\times m} = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1m} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ \xi_{n1} & \xi_{n2} & \cdots & \xi_{nm} \end{bmatrix} \tag{21}$$

5. Case Study

5.1 Workpiece and fixture element properties

The geometry and features of the workpiece are shown in Figure 5. In this case, the aluminum workpiece surface (E_w=72 GPa, v_w=0.3) contacts with a spherical tip referring to Eq. (9) and assuming a fixture element diameter of 12 mm,The material of the employed fixture elements is alloy steel with a Poisson ration of 0.3 and Young's modulus of 220 Gpa.

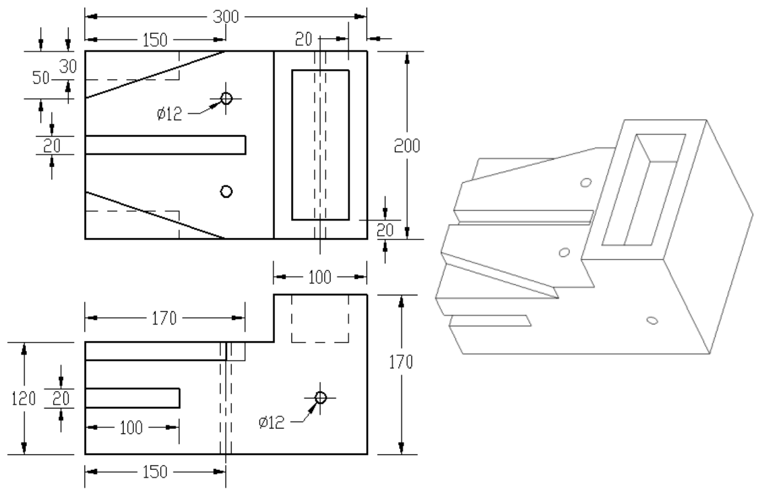

Figure 5. The feature and geometry of workpiece

A peripheral end milling operation is carried out on the illustrated workpiece. The cutting parameters of the operation are given in Table 1 [13]. 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).

Table1. The cutting parameters and condition

College Parameter	Description
Type of operation	End milling
Cutter diameter	25.4 mm
Number of flutes	4
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°

5.2 Candidate fixturing design schemes

The fixturing schemes for holding the workpiece in the machining operation are shown in Figure 6. 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. For example, here, scheme (a) uses four locators (L1, L2 and L3) on the bottom surface to locate the workpiece controlling three DOFs, two locators (L4 and L5) are placed on the right surface to constrain two DOFs and one locator (L6) is placed on the front face to constrain two DOFs. Two clamps (C1, C2) are placed on the left side of the back surface and on the top side of the left surface, respectively. The positions of fixture elements of four candidate fixturing schemes are shown in Table 2.

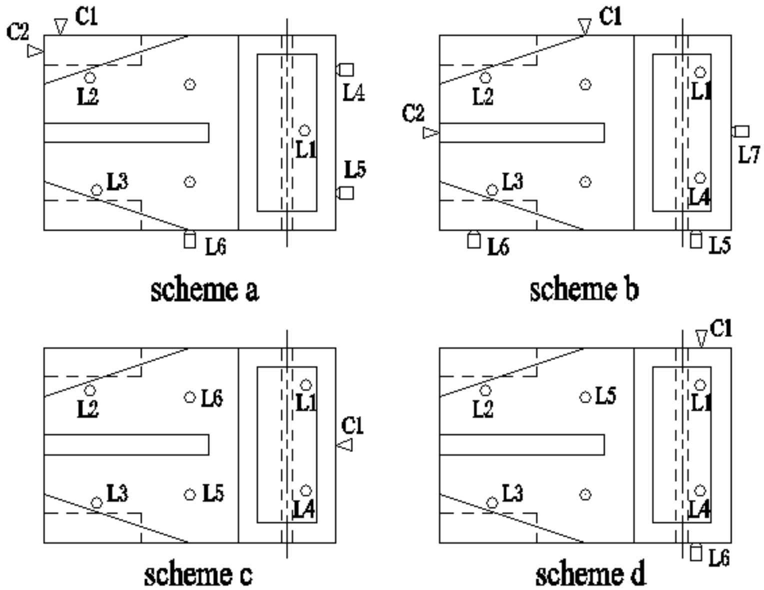

Figure 6. Four candidate fixturing schemes

Table 2. The positions of fixture elements of four candidate fixturing schemes

	Scheme a	Scheme b	Scheme c	Scheme d
L1	(270,100,0)	(270,170,0)	(270,170,0)	(270,170,0)
L2	(55,35,0)	(55,35,0)	(55,35,0)	(55,35,0)
L3	(55,165,0)	(55,165,0)	(55,165,0)	(55,165,0)
L4	(300,170,85)	(270,30,0)	(270,30,0)	(270,30,0)
L5	(300,30,85)	(270,0,60)	(150,50,20)	(150,150,20)
L6	(150,0,60)	(30,0,60)	(150,150,20)	(270,0,60)
L7	-	(300,100,60)	-	-
C1	(10,200,80)	(150,200,60)	(300,100,60)	(270,200,60)
C2	(0,290,80)	(0,100,60)	-	-

Using finite element analysis (FEA), the force and deformation indexes can be obtained; and the Successive fixturing index can be obtained by process planning and cost calculation. The initial values of all the performance indexes are shown in Table 3.

Table 3. The initial values of all the performance indexes

Performance index		Scheme a	Scheme b	Scheme c	Scheme d
Locating accuracy	Locator position error/mm	0.3012	0.2767	0.2531	0.2885
	Contact deformation error/mm	0.76×10-3	0.57×10-3	0.51×10-3	0.62×10-3
Contact forces	Sum of all contact forces/N	4251.89	3551.89	3751.89	3551.89
	Contact forces distribution/N	245.3	219.4	235.9	232.7
Workpiece deformation	Contact deformation distribution/mm	0.093×10-3	0.063×10-3	0.071×10-3	0.089×10-3
Successive fixturing	Fixturing cost	85	102	82	77
	Fixturing repeatability	0.9	0.8	0.6	0.7

5.3 Optimal selection of fixturing design scheme

The initial values of all the performance indexes of the four schemes are be normalized according to Eq. (16) and Eq. (17). The AHP (analytic hierarchy process) method is used to determine weight coefficients of all the performance indexes. The processed values are shown in Table 4.

Table 4. The normalized values of all the performance indexes

Performance index		Scheme a	Scheme b	Scheme c	Scheme d
Locating accuracy	Locator position error/mm	0	0.51	1	0.26
	Contact deformation error/mm	0	0.76	1	0.56
Contact forces	Sum of all contact forces/N	0	1	0.71	1
	Contact forces distribution/N	0	1	0.36	0.49
Workpiece deformation	Contact deformation distribution/mm	0	1	0.73	0.13
Successive fixturing	Fixturing cost	0.68	0	0.8	1
	Fixturing repeatability	0.9	0.8	0.6	0.7

According to Section 4, we can obtain the gray relation coefficients of the candidate schemes shown in Figure 6. It is known from Figure 4 that the locating accuracy performance, the contact forces performance and the workpiece deformation of scheme a are the worst; the contact forces performance and the successive fixturing performance of scheme c are the worse; the locating accuracy performance and the workpiece deformation performance are the worse. The ideal indexes *F* is (1, 1, 1, 0.85), the degree of association of the four schemes relative the ideal scheme ξ is (0.39, 0.80, 0.73, 0.63). Consequently, scheme b is the most appropriate among the four schemes, in other words, scheme b is the most close to the ideal scheme, shown in Figure7.

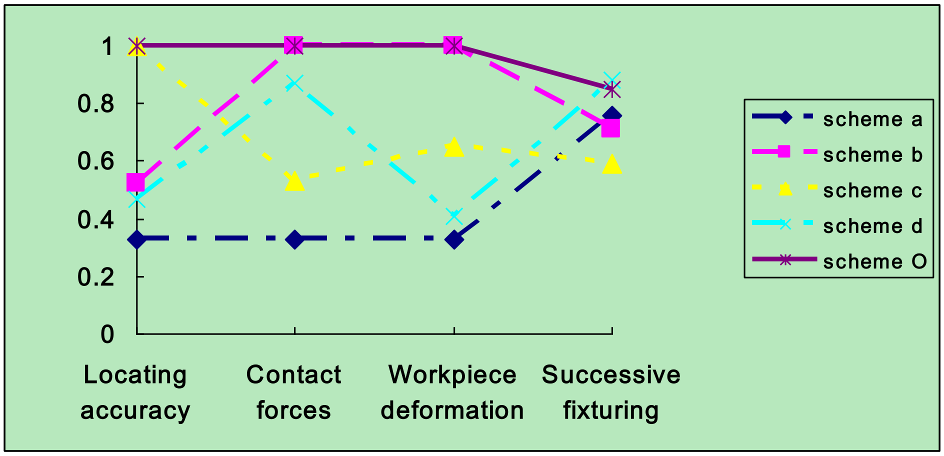

Figure 7. The gray relation coefficient of four candidate schemes

6. Conclusion

This paper has presented a fixturing scheme optimization selecting method based on gray correlation analysis method. The goal of the method is firstly to determine the feasible fixturing layout that satisfies deterministic localization and stability requirements. Secondly, the sets of acceptable fixturing designs are evaluated based on four performance indexes, an appropriate (or sub-appropriate) fixture scheme is selected by gray relation analysis and AHP. The performance measures considered in this work are location accuracy, locator contact forces, contact deformation and successive fixturing. These objectives cover the most critical considerations of a fixturing design. The optimal selection of multi-objective can roundly evaluate the fixturing scheme and avoid subjectivity of designer. It can also be the basis of optimisation of fixturing scheme.

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