Adaptive Machining Scheme for Multi-Hole Part with Multi-Position Accuracy Requirements

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Research Article

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Adaptive Machining Scheme for multi-hole part with multi-position accuracy requirements

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Abstract:

The machining of multi-hole parts often has complex correlated position accuracy requirements. When some position accuracies do not meet the requirements, several hole axes need to be adjusted. Previous methods usually correct all deviated axes to their theoretical locations. However, the correction workload is too large and inefficient. This paper proposes an efficient and adaptive hole position correction model for multi-hole part. First, the method establishes the topological relationship of the holes and faces on the part according to the position accuracy requirements of the multi-hole part. Then, the goal is to minimize the number of holes that need to be corrected. In this model, the parallelism of holes, perpendicularity, and other constraints are considered. The simulation and experimental results show that the use of this model can effectively reduce the number of holes that need to be corrected during the compensation of the position error between holes. It improves the efficiency in the subsequent compensation process significantly.

Keywords: Multi-hole part, Boring and milling, Adaptive processing, Verticality, Parallelism

1. Introduction

Multi-hole part plays an important role in the mechanical connection of the assembly process and the transmission of structural parts, such as gearboxes. The position accuracy between holes matters in evaluating the machining quality of holes and it will have an important influence on assembly accuracy, part performance and life[1]. Therefore, when processing multi-hole part, how to ensure the position accuracy between holes in processing is a problem that needs to be paid attention to.

The traditional hole processing method is usually manual, and the processing quality mainly depends on the workers' experience. Manual drilling has been gradually replaced by CNC equipment due to the higher precision and stability of CNC machining equipment [2]. However, on some occasions with high precision requirements, CNC still cannot meet the machining position accuracy of the hole due to the equipment accuracy limitation. The current research on improving accuracy of holes can be divided into two categories according to different drilling equipment. One type is based on a special drilling mechanism, such as a robot. This kind of method usually first designs the corresponding drilling fine-tuning compensation mechanism, and then designs the corresponding motion control and compensation algorithm according to the structural characteristics of the compensation mechanism, to control the action of the compensation mechanism and realize the hole position error compensation[3-5]. The other type is mainly processing equipment with CNC machine tools as holes. This type of equipment only needs to design the corresponding compensation algorithm to directly change the NC codes when performing hole processing, without the need to design a special hardware mechanism[6, 7].

However, the limitation of previous research is that when selecting methods to improve accuracy, the focus is to study the deviation of the actual position of the single hole from its theoretical position, and to make the hole as close to its theoretical position as possible through correction. There are usually complex positional requirements between holes and holes, holes and surfaces in multi-hole parts. To ensure its position accuracy requirements, it is necessary to correct the position of each hole to make it as close to its theoretical position as possible. However, this method requires a heavy correction workload, because the position tolerance allows the position of the hole to change within a certain range. Therefore, when correcting the hole position, it is unnecessary to correct all the holes to make it meet the accuracy requirements. In order to solve this problem, the method proposed in this paper reduces the workload of correction by reducing the number of holes that need to be corrected. First, the accuracy requirements' topological relationship between hole and hole is established according to the position accuracy requirements of the hole and surface of the part. A model with the minimum number of holes to be corrected as the goal and the position accuracy requirement as the constraint is established, and the correction scheme of holes is obtained through this model. The experimental results show that when the accuracy of a certain item or several positions in the set of holes does not meet the accuracy requirements, using this method to correct the axis direction of the hole in the Set of holes can reduce the number of holes that need to be corrected, and make the position accuracy of each hole meet the requirements, reducing the workload of subsequent processing and correction.

2. Related work

The equipment for machining holes mainly includes two types: robot and NC machine tool. Yuan et al. used the double eccentric discs-spherical pair structure[8] as the end axis correction mechanism of the robot drilling, and designed a drilling axis correction algorithm based on this mechanism and the deviation of the drilling axis. This algorithm can ensure that the axis deviation of the robot drilling does not exceed ±0.5°, which effectively ensures the perpendicularity of the hole to the end face[9]. Shen et al. optimized the rigidity of the robot drilling system before processing and proposed a compensation method for the hole position error during processing, which effectively improves the robot drilling accuracy[10]. In addition, position correction strategies of holes based on interpolation methods such as kriging[11], co-kriging[12], and Shepard[13] can also effectively improve hole machining accuracy.

Similar to the special drilling mechanism, corresponding improvements in hardware and software can also be made for CNC machine tools. Gao et al. added a piezoelectric actuator to the boring bar servo system to realize the online compensation for the precision boring machining error of the aspect ratio hole. The experiment proved that this method can significantly reduce the roundness error of the hole[14]. Chiu et al. designed a boring bar servo system with online compensation for machining errors. Forecasting compensatory control (FCC) was implemented in the boring bar servo system to predict machining errors, which is used for high-length-to-radius ratio precision boring machining error online compensation[15]. The flexibility and accuracy of the control of multi-axis CNC machine tools determine that the correction amount of the machining hole error can be directly calculated through the corresponding algorithm. According to the obtained correction amount, the machine correction processing code can realize the compensation of the hole machining error. Zhang et al. proposed a compensation method for online measurement of surface normal and adaptive correction of the direction of drilling tools based on easily deformable curved parts. The compensation method is based on the kinematics transformation of a five-axis machine tool and is realized by numerical control compensation[16]. Li et al. proposed a compensation method to improve the hole position accuracy of the shell parts in the vertical machining center. According to the error of the distance between holes measured by the coordinate measuring machine, the method compensates the hole distance by modifying the processing program and proves its validity[17]. Qi et al. proposed a rapid correction method to correct the coordinate of the assembly hole based on the online detection of the position of the pre-assembly hole. This method can effectively reduce the influence of the workpiece attitude deviation[18].

The rest of the article will be arranged: The second part mainly describes the establishment of the form and position error model; The third part mainly focuses on the theoretical analysis of the algorithm; the fourth part mainly describes the development of the experimental process and the analysis of the experimental results; The last part summarizes the conclusions.

3. Theory and analysis

3.1 Detection of hole’s position error

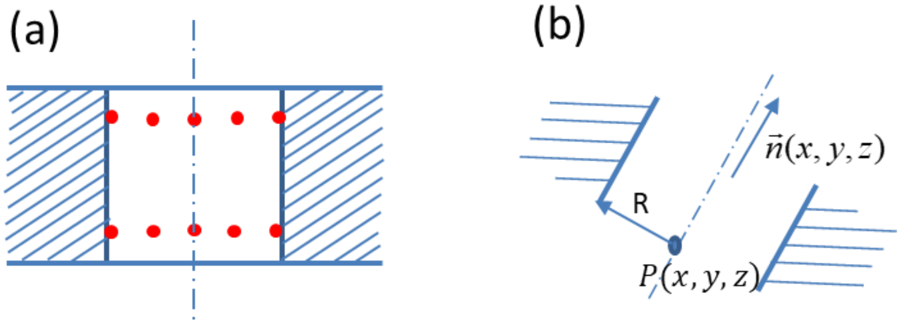


Fig. 1 Hole position detection and position determination (a)Distribution of measuring points (b)Hole position expression

Fig. 1 (a) shows the schematic diagram of the measuring point distribution of the single hole detection by the coordinate measuring machine. During detection, several measuring points are arranged in the hole close to the two ends of the hole, and the measurement coordinates of several points near the two ends of the hole are got by the detection. Fig. 1 (b) shows the expression method of the hole. When determining the radius value R of the hole, the coordinate value of the intersection of hole axis and end face $P(x,y,z)$,and the value of the axis direction vector $\vec{n}(x,y,z)$ are determined, then the position of the hole can be determined. The length of the axis direction vector represents the length of the hole.

According to the measurement point data showed in Fig. 1 (a), two planes can be fitted respectively to determine the plane where the center of the measurement point is located. Suppose the fitted plane equation is:

$$Ax + By + Cz + D = 0 \tag{1}$$

The least square method is used to construct the objective function as the minimum value of the sum of the distances from the measured multiple points to the fitting surface, the minimum value of the formula (2):

$$F(A,B,C,D) = \sum_{i=1}^{N} | Ax_i + By_i + Cz_i + D | \tag{2}$$

Then the values of A, B, C, and D in the fitted plane equation can be obtained, and the plane represented by equation (1) can be determined. Suppose the radius of the circle of the measuring point is R and the value of the circle center of the measuring point is $P(x_0, y_0, z_0)$. Then the center value is on the plane shown in (1), and the fitted space circle can be expressed:

$$\begin{cases} Ax + By + Cz + D = 0 \\ (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = R^2 \\ Ax_0 + By_0 + Cz_0 + D = 0 \end{cases} \quad (3)$$

The coordinates of the center of the circle and the value of the radius R in (3) can be obtained by taking the minimum value of formula (4) by using the least square method:

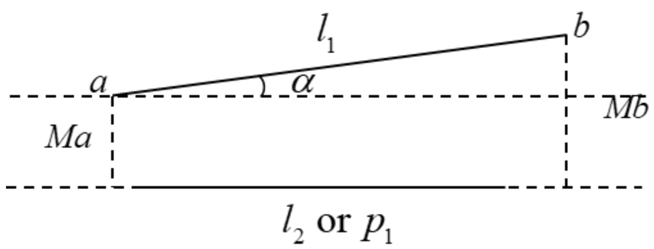
$$F(x_0, y_0, z_0, R) = \sum_{i=1}^{N} (R_i - R)^2 = \sum_{i=1}^{N} (\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} - R)^2 \quad (4)$$

Calculate the coordinates of the centers of the two measuring points circles respectively, and connect the two centers to form the measured vector value of the axis of the hole. The focus of this paper is on the requirements of parallelism and perpendicularity. Therefore, only the characteristics of holes related to the parallelism and perpendicularity of the holes can be considered, the hole is represented by a vector whose mold is equal to the length of the hole and the direction is the same as the axis of the hole.

3.2 Analysis of hole’s position error

To ensure the completeness of this article, this section gives the calculation methods of parallelism and perpendicularity involved in the article. The specific methods are:

（a）



(b)

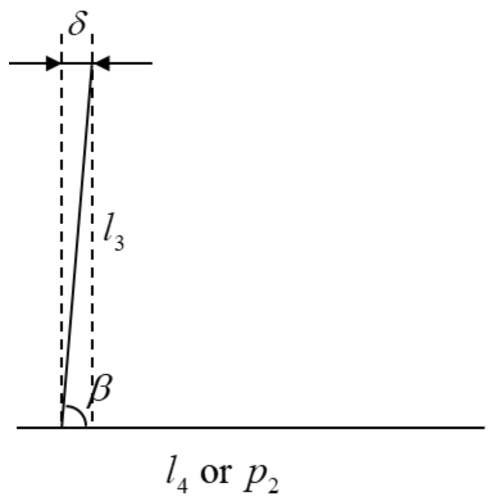


Fig. 2 Holes position error calculation:(a) Parallelism error (b) Verticality error

Fig. 2 (a) showed the calculation of the parallelism error of the hole relative to the hole or plane. l_1 and l_2 respectively represent the axis vector of the hole. p_1 represents a plane. a, b are the end points of the two ends of the axis of the hole. Ma and Mb respectively represent the distance from a, b to the axis l_2 or plane p_1. Then the parallelism error f of hole l_1 relative to hole l_2 or plane p_1 can be expressed as:

$$f = |Ma - Mb| = |l_1| \sin\alpha \tag{5}$$

Fig. 2 (b) shows the calculation of the perpendicularity error of the hole relative to the hole or plane. l_3 and l_4 respectively represent the axis vector of the hole. p_2 represents a plane. δ is the perpendicularity error of hole l_3 relative to hole l_4 or surface p_2, and formula (6) can calculate this value:

$$\delta = |l_3| \cos\beta \tag{6}$$

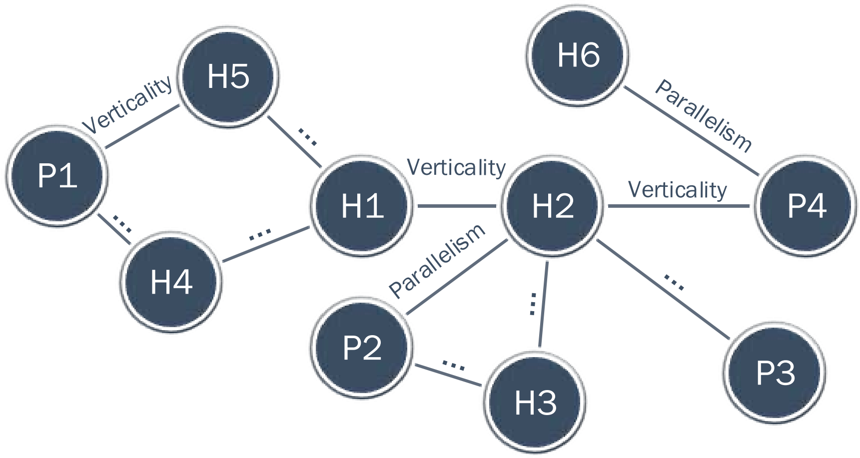


Fig. 3 Position accuracy relationship of multi-hole part

Fig. 3 shows a schematic diagram of the position accuracy relationship of multi-hole part. The circles in the figure represent the holes (Such as H1, H2.) and faces (Such as P1, P2.) in the multi-hole part that have requirements for positional accuracy. The straight line segment shows that there are parallelism and perpendicularity position tolerance requirements between the two connected shape features. It can be easily obtained from this figure: a) For the same shape feature, there may be a position tolerance requirement between multiple other shape features, as shown in the figure, there is a position tolerance requirement between hole 1 and hole 2, hole 4, and hole 5 at the same time; b) For multiple shape features, there will be situations where position tolerance requirements are related, such as the relationship between hole 2, surface 2, and hole 3. Therefore, when the axis direction of the hole is corrected, the accuracy of all positions related to the hole will change, which also means the complexity of the correction. If the position accuracy requirements of multi-hole parts can be met by one correction, the position accuracy requirements of holes and other holes and surfaces on the parts must be considered at the same time. Therefore, this paper establishes a target optimization model.

4. Target optimization model construction

$P = \{1, 2, \cdots, N\}$ represents the number of holes, and there are N holes in total. $\vec{n}_i^0 = \{t_i^1, t_i^2, t_i^3\}$, $\vec{n}_i^1 = \{b_i^1, b_i^2, b_i^3\}$ and $\vec{n}_i^2 = \{r_i^1, r_i^2, r_i^3\}$ respectively represent the theoretical value, detection value, and correction value of the axis vector of the i-th hole. The theoretical value, detection value, and correction value correspond to the axis vector of the designed hole, the actual axis vector of the hole fitted by the measured value of the coordinate measuring machine, and the axis vector of the hole after finishing correction. The length of the vector represents the length of the hole.

Set 0-1 variables x_i as follows:

$$x_i = \begin{cases} 1 & \text{If the axis needs to be adjusted} \\ 0 & \text{If the axis does not need to be adjusted} \end{cases} \tag{7}$$

Equation (7) shows whether the i-th hole needs to be corrected. If it needs to be corrected, it is recorded as 1, and if it does not need to be corrected, it is recorded as 0. The value obtained by accumulating x_i is the number of holes that need to be corrected for the entire part. The minimum number of holes to be corrected is used as the optimization target, then the optimization target AimN can be expressed as:

$$AimN = \min \sum_{i \in P} x_i \tag{8}$$

Equation (9) establishes the relationship between whether the axis needs to be corrected and the change of the axis before and after correction.

$$\sum_{k=1}^{3} | r_i^k - b_i^k | \leq Mx_i \tag{9}$$

The left side of the formula (9) represents the difference between the axis vectors before and after correction, and M is a large value. This formula ensures that when the vector difference is 0, when the axis does not need to be corrected, the value of x_i can be 0.

In optimizing the axis vector of the hole, the modulus of the axis vector of the hole represents the length of the hole. Therefore, the length of the hole after correction and before correction should be slightly different. the modulus difference of the axis vector is small, and this needs to be restricted. Then there are:

$$\sum_{k=1}^{3} (r_i^k)^2 - \sum_{k=1}^{3} (b_{\mathrm{j}}^k)^2 < \varepsilon \tag{10}$$

In formula (10), ε is a small value, which limits the change of the length of the shaft hole before and after correction.

The shape and position accuracy requirements of the i-th hole for the j-th hole or the j-th surface are expressed as LB_{ij}, and The mathematical expression of the accuracy requirements of parallelism and perpendicularity shown in equations (11) and (12) can be further obtained from equations (5) and (6) respectively.

$$\sqrt{\sum_{k=1}^{3}(r_i^k)^2}\sin\alpha < LB(i,j) \tag{11}$$

$$\sqrt{\sum_{k=1}^{3}(r_i^k)^2}\,|\cos\beta| < LB(i,j) \tag{12}$$

When formula (11) is the parallelism of hole-to-hole and hole-to-face, the value of $\sin\alpha$ can be obtained by formulas (13) and (14) respectively.

$$\sin\alpha = \sqrt{1-(\vec{n}_i^2 \cdot \vec{n}_j^2 / (|\vec{n}_i^2| * |\vec{n}_j^2|))^2} \tag{13}$$

$$\sin\alpha = \vec{n}_i^2 \cdot \vec{n} / (|\vec{n}_i^2| * |\vec{n}|) \tag{14}$$

When formula (12) is the perpendicularity of hole to hole and hole to face, the value of $\cos\beta$ can be obtained by formula (15) and (16) respectively.

$$\cos\beta = \vec{n}_i^2 \cdot \vec{n}_j^2 / (|\vec{n}_i^2| * |\vec{n}_j^2|) \tag{15}$$

$$\cos\beta = \sqrt{1-(\vec{n}_i^2 \cdot \vec{n} / (|\vec{n}_i^2| * |\vec{n}|))^2} \tag{16}$$

Where $\vec{n}$ represents the normal vector of the plane.

In the process of adaptive processing correction, we hope that the number of correction holes is the smallest and the deviation of the corrected hole relative to the theoretical axis does not exceed the deviation of the hole before the correction to the theoretical axis. Therefore, the following constraints should be added:

$$\sqrt{\sum_{k=1}^{3}(r_i^k - t_i^k)^2} - \sqrt{\sum_{k=1}^{3}(b_i^k - t_i^k)^2} >= 0 \tag{17}$$

In summary, the target optimization model can be constructed as shown in equation (18):

$$
\begin{cases}
AimN = \min \sum_{i \in P} x_i \\
s.t. \\
\sum_{k=1}^{3} | r_i^k - b_i^k | \le Mx_i \\
\sum_{k=1}^{3} (r_i^k)^2 - \sum_{k=1}^{3} (b_{\mathrm{j}}^k)^2 < \varepsilon \\
\sqrt{\sum_{k=1}^{3} (r_i^k)^2} \sin \alpha < LB(i, j) \\
\sqrt{\sum_{k=1}^{3} (r_i^k)^2} \, |\cos \beta| < LB(i, j) \\
\sqrt{\sum_{k=1}^{3} (r_i^k \text{-} \mathrm{t}_i^k)^2} - \sqrt{\sum_{k=1}^{3} (b_i^k \text{-} \mathrm{t}_i^k)^2} >= 0
\end{cases}
\tag{18}
$$

5. Experiments:

In this section, several sets of holes data are generated to simulate the method proposed in this paper to verify the effectiveness, and then a set of inspection data after actual box processing is used to verify the feasibility of the method under actual conditions. The tool for solving the model is LINGO11, which is commonly used to solve optimization problems[19, 20].

Exp 1: Parallelism verification

In the experiment, the parameters $M = 100$ and $\varepsilon = 0.05$ of the model represented by equation (18) are set. Set a group of parallel holes, the number of holes is 6, and the theoretical axis vectors of the holes are all (0,100,0). Add 2*(rand-0.5)/40 noise to the three coordinate components x, y, z of the theoretical vector of the axis of the 6 holes, and use the generated new axis vector as the actual processed axis vector. Where rand is a random number in the interval (0,1). Three tests were designed with parallelism requirements of 0.05, 0.03, and 0.01, respectively. The experimental results are shown in Table 1. When the parallelism requirement is 0.05, the parallelism between holes 2 and 5 is out of tolerance. It is only necessary to correct the axis direction of hole 5 to (-0.011, 99.977, -0.008) to meet the 0.05 requirement of holes parallelism. When the parallelism requirement is 0.03, the parallelism between holes 1-2,1-3,1-5,2-4,2-5,2-6,3-5 does not meet the requirements. The experimental results show that only the axis vectors of holes 1, 2, and 3 need to be corrected to (-0.026,99.998,0.007), (0.000,99.996,0.008), (0.002,99.989,0.012) respectively, to make the set of holes meet the parallelism error requirements. When the parallelism requirement is 0.01, the parallelism between holes 1-2,1-3,1-4,1-5,1-6,2-3,2-4,2-5,2-6,3-4,3-5,3-6,4-5,5-6 does not meet the requirements. Only the parallelism between holes 4-6 meets the requirements. After optimization and correction, only the axis directions of holes 1, 2, 3, and 5 need to be corrected to (-0.007,99.989,0.002), (-0.012,99.991,0.004), (-0.010,99.991,0.003), (-0.015 ,99.983,0.004) can make the holes meet the parallelism requirements. The experimental results show that the method can calculate the axis directions of which holes need to be corrected at one time, and the corresponding positions to be corrected. Only the axial direction of some holes needs to be corrected, and the other holes can be processed according to the original processing technology, reducing the correction workload. When the accuracy requirements are high, the number of holes that need to be corrected will increase, but the number of holes that need to be corrected can still be reduced to a certain extent. This phenomenon is of great significance to the actual correction, and an accuracy index higher than the actual machining accuracy requirement can be set during optimization to ensure the effect of the correction.

Table 1 Parallelism verification of holes

Tests number	Holes number	Actual axis vector	Corrected axis vector	Whether to be corrected
1	1	(-0.024,100.004,0.011)	(-0.024,100.004,0.011)	No
	2	(0.022,100.006,0.015)	(0.022,100.006,0.015)	No
	3	(0.006,99.996,0.015)	(0.006,99.996,0.015)	No
	4	(-0.013,99.986,-0.005)	(-0.013,99.986,-0.005)	No
	5	(-0.015,99.976,-0.009)	(-0.011,99.977,-0.008)	Yes

	6	(-0.010,99.986,-0.004)	(-0.010,99.986,-0.004)	No
2	1	(-0.024,100.004,0.011)	(-0.026,99.998,0.007)	Yes
	2	(0.022,100.006,0.015)	(0.000,99.996,0.008)	Yes
	3	(0.006,99.996,0.015)	(0.002,99.989,0.012)	Yes
	4	(-0.013,99.986,-0.005)	(-0.013,99.986,-0.005)	No
	5	(-0.015,99.976,-0.009)	(-0.015,99.976,-0.009)	No
	6	(-0.010,99.986,-0.004)	(-0.010,99.986,-0.004)	No
3	1	(-0.024,100.004,0.011)	(-0.007,99.989,0.002)	Yes
	2	(0.022,100.006,0.015)	(-0.012,99.991,0.004)	Yes
	3	(0.006,99.996,0.015)	(-0.010,99.991,0.003)	Yes
	4	(-0.013,99.986,-0.005)	(-0.013,99.986,-0.005)	No
	5	(-0.015,99.976,-0.009)	(-0.015,99.983,0.004)	Yes
	6	(-0.010,99.986,-0.004)	(-0.010,99.986,-0.004)	No

Exp 2: Verticality verification

In the experiment, the parameters $M = 100$ and $\varepsilon = 0.05$ of the model represented by equation (18) are set. Set up a group of holes with verticality requirements, the number of holes is 6, and the theoretical vectors of the axes of holes numbered 1-6 are (100,0,0), (0,100,0), (0,0,100), (100,0,0), (0,100,0), (0,0,100). Add 2*(rand-0.5)/20 noise to the three coordinate components x, y, z of the theoretical vector of the axis of the 6 holes, and use the generated new axis vector as the actual processed axis vector. Where rand is a random number in the interval (0,1). Three tests were designed with verticality requirements of 0.03, 0.02, and 0.01, respectively. The experimental results are shown in Table 2. The number of holes that need to be corrected in the three tests is 2, 3, and 4, respectively. The experimental results show that, similar to the parallelism experiment, this method is also adaptable to the verticality error of the holes.

Table 2 Verticality verification of holes

Tests number	Holes number	Actual axis vector	Corrected axis vector	Whether to be

				corrected
1	1	(99.948,-0.002,-0.031)	(99.963,-0.020,-0.027)	Yes
	2	(0.050,99.985,-0.009)	(0.050,99.985,-0.009)	No
	3	(0.047,-0.002,99.965)	(0.047,-0.002,99.965)	No
	4	(99.992,-0.022,-0.040)	(99.992,-0.022,-0.040)	No
	5	(0.010,100.049,-0.046)	(0.020,100.049,-0.028)	Yes
	6	(0.027,0.021,100.034)	(0.027,0.021,100.034)	No
2	1	(99.948,-0.002,-0.031)	(99.948,-0.002,-0.031)	No
	2	(0.050,99.985,-0.009)	(-0.018,99.985,-0.018)	Yes
	3	(0.047,-0.002,99.965)	(0.047,-0.002,99.965)	No
	4	(99.992,-0.022,-0.040)	(99.992,0.017,-0.034)	Yes
	5	(0.010,100.049,-0.046)	(-0.017,100.049,-0.001)	Yes
	6	(0.027,0.021,100.034)	(0.027,0.021,100.034)	No
3	1	(99.948,-0.002,-0.031)	(99.948,-0.002,-0.031)	No
	2	(0.050,99.985,-0.009)	(0.012,99.985,-0.010)	Yes
	3	(0.047,-0.002,99.965)	(0.034,0.008,99.965)	Yes
	4	(99.992,-0.022,-0.040)	(99.992,-0.022,-0.040)	No
	5	(0.010,100.049,-0.046)	(0.012,100.049,-0.010)	Yes
	6	(0.027,0.021,100.034)	(0.034,0.000,100.034)	Yes

Exp 3: Comprehensive test of actual processing multi-hole part

The actual processing of multi-hole part is taken as an example to verify the effectiveness of the method in the actual holes processing and correction. As shown in Figure 4, the part is a certain type of gearbox part of the actual production process. The left picture is the surface where the key holes are distributed, and the right picture is the other side of the multi-hole part. The most important processing of this part is the processing of holes, and the cooperation of multiple axes of the machine tool is required to realize the processing of holes on multiple sides during the processing. During the machining process, because of the existence of errors, there will be a certain deflection between the actual machined holes and the theoretical position.

When this deflection reaches a certain level, the shape and position accuracy of some holes does not meet the accuracy requirements. In the figure, the holes and faces that have positional accuracy correlation are numbered for the convenience of further analysis.

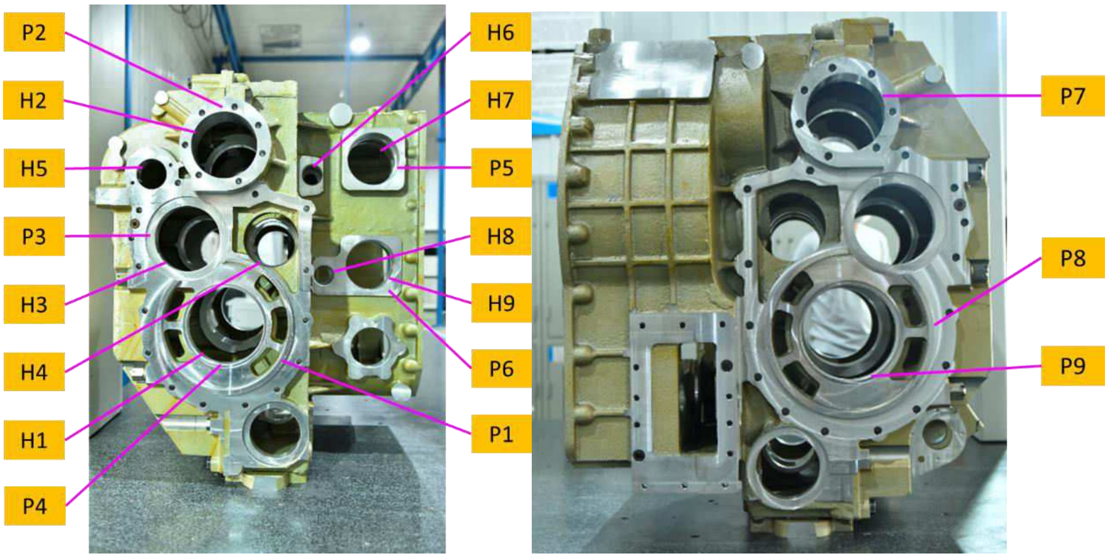


Fig. 4 Multi-hole part in the actual production process

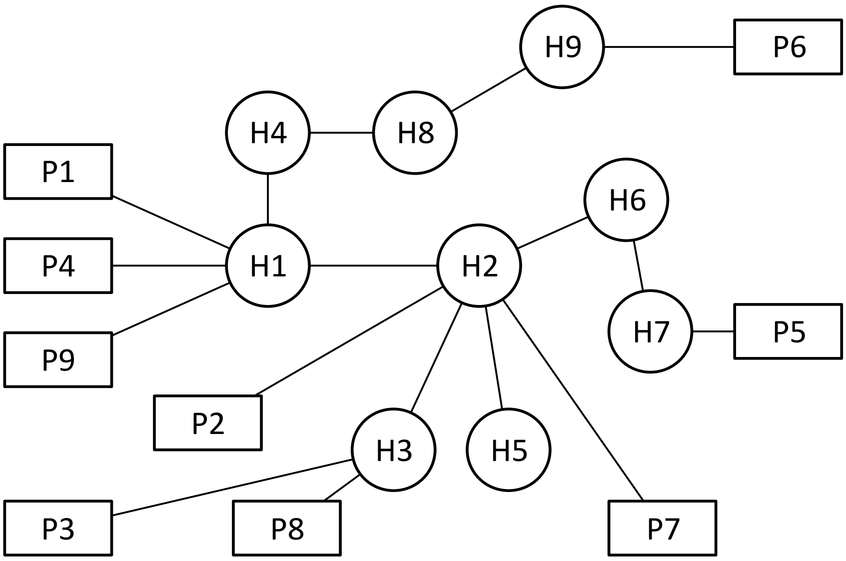


Fig. 5 Gearbox part position accuracy requirements

The position accuracy requirements of the gearbox parts in Fig. 4 are shown in Fig. 5. In Fig. 5, the circles represent holes with different numbers, and the rectangles represent planes with different numbers. The connection between them shows that there is a position accuracy requirement between the connected holes or surfaces. There is a parallelism requirement of 0.06 between the hole and the hole in the figure, and a perpendicularity requirement of 0.06 between the hole and the surface. It can be seen that the complexity of this part is mainly manifested in: (1) The complexity of the accuracy index: there are requirements for both parallelism and perpendicularity. As shown in the figure, there is a perpendicularity requirement between the hole and the surface, and there is a parallelism requirement between the hole and the hole. (2) The complexity of the relationship: one hole may have requirements for shape and position accuracy between multiple holes and surfaces. As shown in the figure, there is a parallelism requirement between hole 1 and hole 2 and hole 4, and there is a perpendicularity requirement between face 1, face 4, and face 9 at the same time.

According to the content of Section 2, the hole and the surface are detected, and the corresponding fitting calculation is performed to obtain the value of the axis vector of the hole and the normal vector of the plane. The shape and position accuracy between them is calculated, as shown in Table 3. It can be seen from Table 3 that the shape and position accuracy calculated for the verticality number 1, 2, 3, 4, 5, 7 exceeds the allowable range, so the workpiece needs to be corrected and optimized accordingly.

Table 3 Calculation results of the position accuracy of box parts

Parallelism number	Corresponding profile	Calculation results	Verticality number	Corresponding profile	Calculation results
1	H2- H 3	0.030	1	H 1-P1	0.065
2	H 1- H 2	0.018	2	H 2- P 2	0.093
3	H 1- H 4	0.017	3	H 2- P 7	0.109
4	H 2- H 5	0.001	4	H 3- P 3	0.081
5	H 2- H 6	0.007	5	H 3- P 8	0.013
6	H 6- H 7	0.010	6	H 1- P 4	0.047
7	H 4- H 8	0.010	7	H 1- P 9	0.150
8	H 8- H 9	0.008	8	H 7- P 5	0.003
			9	H 9- P 6	0.002

Because the surface is usually machined first and then the hole is machined in the machining process of multi-hole parts, for convenience, only the axis of the hole is corrected in the correction process, and the plane is usually not corrected. The corrected results are shown in Table 4, where the fitted axis is the axis of the hole fitted from the detection point, and the corrected axis is the axis required for finishing obtained by the method in this paper. It can be seen that the method in this paper also applies to the correction of the holes of the part in actual processing.

Table 4 Holes correction result

Holes number	1	2	3
Fit axis	(0.041,669.606,0.045)	(0.031,745.970,0.060)	(0.056,668.705,0.045)
Corrected axis	(-0.020,669.606,-0.040)	(0.007, 745.969,-0.045)	(0.001, 668.705,-0.018)
Holes number	4	5	6
Fit axis	(-0.054,627.576,0.050)	(-0.002,-24.016,-0.003)	(-0.008,-24.762,-0.003)
Corrected axis	(0.011,627.576,0.015)	(-0.002,-24.016,-0.003)	(-0.008,-24.762,-0.003)
Holes number	7	8	9
Fit axis	(0.002,-26.194,0.000)	(0.002,-17.716,-0.010)	(0.000,-10.661,-0.002)
Corrected axis	(0.002,-26.194,0.000)	(0.002,-17.716,-0.010)	(0.000,-10.661,-0.002)

5.Conclusion:

This paper aims to solve the problem of adaptive machining scheme for multi-hole part with multi-position accuracy requirements, reduce the number of correction holes on the premise of meeting the requirements of position accuracy, and improve the efficiency of compensation processing. This paper first gives the calculation method of the parallelism and perpendicularity error of the multi-hole part and the correlation between the position accuracy requirements and then establishes the target optimization model. Correlative experiments verify the feasibility of using optimization methods to reduce the workload of correction. Experimental results show that the method proposed in this paper can reduce the number of holes that need to be corrected, and give reasonable correction suggestions for holes that need to be corrected, and provide accurate reference suggestions for the final compensation processing. The research results of this paper have certain reference significance for the optimization of other shape and position accuracy, and laid the foundation for the subsequent establishment of more complex shape and position accuracy models.

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Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

Availability of data and material

The original data detected by CMM is uploaded to the submission website together with the manuscript, and the name is "rawdata.txt".

Code availability

The code cannot be shared at this time due company secret.

Authors' contributions

Sun Zhen, Zeng Long and Feng Pingfa designed and implemented the hole position correction model for multi-hole part, and got the solution of the model. Zhang Shaoqiu and Cheng Xi conducted the experiment. Sun Zhen wrote this paper.

Ethics approval

The authors declare that this manuscript was not submitted to more than one journal for simultaneous consideration. Also, the submitted work is original and not have been published elsewhere in any form or language.

Consent to participate

The authors declare that they participated in this paper willingly.

Consent for publication

The authors declare to consent to the publication of this paper.

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