Multi-objective optimization design and performance analysis of machine tool worktable filled with BFPC

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Abstract. In order to explore a new way to improve the static and dynamic performance and lightweight of machine tool, the machine tool worktable filled with basalt fiber polymer concrete (BFPC) is designed, which take a worktable of vertical machining center as the research prototype and meet the stiffness and light weight as the constraint conditions. The static, dynamic performance weight of prototype structural columns are simulated and analyzed by using Workbench software. Taking the width and height of rectangular hole of worktable filled with BFPC as design variable, taking the maximum stress and maximum strain of prototype worktable as constraint conditions, taking maximum of the first three order natural frequency and the lightest mass of worktable filled with BFPC as object function, the sensitivity histogram and response surface of each parameter are acquired by using optimization design. Then the best width and height of rectangular hole of worktable filled with BFPC are finally determined. The static and dynamic performance, quality and the first three order natural frequencies of the optimized filling structure are compared with the prototype structure. Finally we can know that the static, dynamic performance of the machine tool can be improved by using worktable filled with BFPC and ensuring light weight.

1. Introduction

In order to meet the high efficiency, high precision, and high degree of automation of machine manufacturing, machine tools require higher static and dynamic performance and lighter weight. The use of new materials with excellent performance to manufacture machine tool base parts is a more effective way, and it has also become an important topic for scholars at home and abroad[1-6]. BFPC is a concrete composite material formed by incorporating basalt fiber into resin concrete according to a suitable dosage and method. Compared with steel fiber and carbon fiber, BFPC has many advantages, such as a large elastic modulus, high damping, a small linear expansion coefficient, a strong absorption of vibration, high corrosion resistance, low input, high output and sustainable development, it is considered to be a promising new materials for machine base components[4-6]. In the early part of the research group, based on the optimal group allocation ratio of BFPC for the manufacture of machine tool basic parts and the design and performance analysis of integral structural basic parts, the structure of the machine tool table filled with BFPC is designed and optimized. The static and dynamic performance and light weight are analyzed to verify the feasibility and superiority of machine tool table filled with BFPC, so as to further explore the potential of BFPC in the machine tool base parts, and also to provide reference for exploring new ways to improve the static, dynamic characteristics and lightweight of the machine tool.

2. Design of machine tool worktable filled with BFPC

2.1. Selection of prototype worktable

The prototypal designing of BFPC is based on the VX380T vertical machining center worktable. The worktable is a beam structure with a cross section of length L=600mm as shown in Figure 1, and the upper surface T-slot is used to install a jig or directly fix a workpiece to be processed. The following is a double rectangular slot, which is connected with the machine tool rail. The main dimensions of the section are shown in Table 1. Its material is HT300.

2.2. Preliminary design of machine tool worktable filled with BFPC

When we designed worktable filled with BFPC, under the condition that the size of the worktable's external structure and its connection with other components remain the same, the double-rectangular hole of the prototype cross-section is changed to a single-rectangular hole whose width is B and the height is H, and fill BFPC material into it, the main structure size with reference to Figure 2 and Table 1. The values of B and H need to be determined by subsequent equal stiffness theory and light weight constraints. Table 2 shows the material parameters involved in the design of both tables.

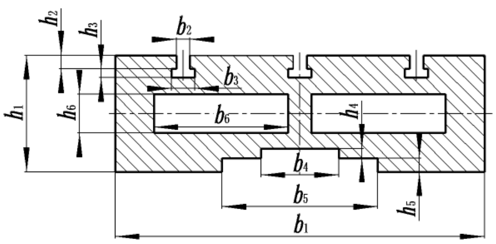

Figure 1. Section diagram of prototype worktable

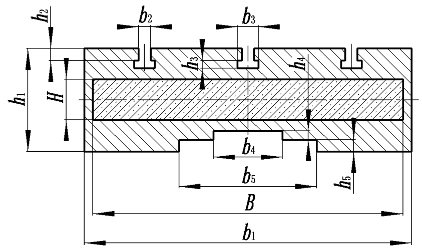

Figure 2. Section diagram of worktable filled with BFPC

Table 1. Main dimension parameters of two tables(mm)

b_1	b_2	b_3	b_4	b_5	b_6	h_1	h_2	h_3	h_4	h_5	h_6
380	14	24	80	160	138	120	14	9	10	14	40

Table 2. Material parameters

Material parameters	HT300	BFPC
Density (kg·m^{-3})	7800	2530
Poissonby	0.27	0.25
Elastic modulus (Pa)	1.5×10^{11}	4.6×10^{10}

2.2.1. Constraints on B and H required for equal stiffness

Determine the conditions of B and H by using equal stiffness design theory[7]. We should ensure that the static stiffness of the designed worktable filled with BFPC is not lower than that of the prototype worktable, sit:

$$(EI)_1 \le (EI)_2 \tag{2.1}$$

In the formula: $(EI)_1$ is bending stiffness coefficient of prototype worktable section, N·m^2; $(EI)_2$ is bending stiffness coefficient of worktable filled with BFPC section, N·m^2.

A coordinate system is established on the cross section of the prototype structure table. Since the prototype table section is relative to the y_0 axis symmetry, it is set c to the center of the entire table as shown in Figure 3. The coordinates are (0, y_c). Divide section into 6 rectangles such as ABCD, EFHG, IJLK, MNPO, QRTS, UVWX of the prototype worktable, then:

$$y_c = (A_1y_1 - 3A_2y_2 - 3A_3y_3 - A_4y_4 - A_5y_5 - 2A_6y_6)(A_1 - 3A_2 - 3A_3 - A_4 - A_5 - 2A_6)^{-1} \tag{2.2}$$

According to the parallel axis theory, the bending moment of the six rectangles should be:

$$I_{ci} = 12^{-1} b_i h_i^3 + A_i (y_c - y_i)^2 \quad (i=1\sim6) \tag{2.3}$$

The bending moment of the prototype table section should be:

$$I_c = I_{c1} - 3I_{c2} - 3I_{c3} - I_{c4} - I_{c5} - 2I_{c6} \tag{2.4}$$

In the formula: yi is the distance from each rectangular cross-sectional center axis $x_1 \sim x_6$ to the coordinate axis x_0, mm; For each section of the area, mm^2.

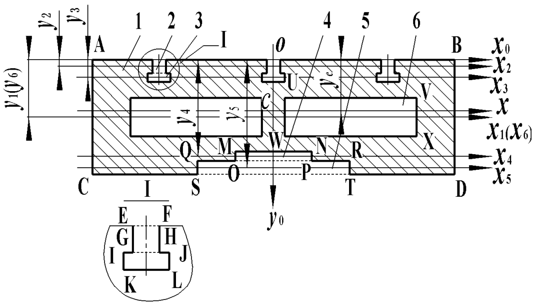

Figure 3. Section division of prototype structure worktable

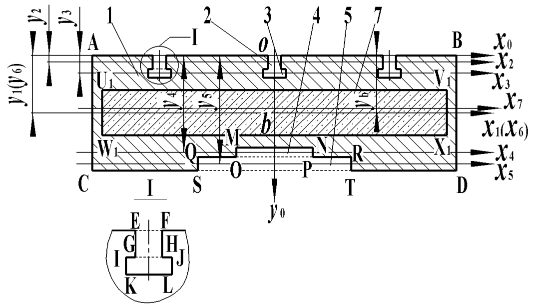

Figure 4. Section division of worktable filled with BFPC

Similarly, as shown in Figure 4, a coordinate system is established for worktable filled with BFPC. *b* is set to be the center of the entire worktable with coordinates, and the worktable sections are (0, y_b), divided into ABCD, EFHG, IJLK, MNPO, QRTS, $U_1V_1W_1X_1$ and other 6 rectangles:

$$y_b = (A_1 y_1 - 3A_2 y_2 - 3A_3 y_3 - A_4 y_4 - A_5 y_5)(A_1 - 3A_2 - 3A_3 - A_4 - A_5)^{-1} \tag{2.5}$$

According to the parallel axis theory, the bending moment of rectangles 1 to 5 should be:

$$I_{bi} = 12^{-1} b_i h_i^3 + A_i (y_b - y_i)^2 \quad (i=1\sim5) \tag{2.6}$$

The bending moment of table filled with BFPC section should be:

$$I_{BFPC} = 12^{-1} BH^3 + BH(y_b - y_1) \tag{2.7}$$

The bending moment of the HT300 section should be:

$$I_b = I_{b1} - 3I_{b2} - 3I_{b3} - I_{b4} - I_{b5} - I_{BFPC} \tag{2.8}$$

Substituting the known data in Table 1 and Table 2 into form(2.1) ~(2.8), the constraints of equal stiffness theory on B and H are finally obtained:

$$BH^3 + 70.25BH \le 4.18 \times 10^8 \tag{2.9}$$

2.2.2. Lightweight requirements for B and H constraints

In order to meet the lightweight requirements, worktable filled with BFPC M_2 is less than or equal to the prototype worktable M_1:

$$\rho_1 L(b_1h_1 - 3b_2h_2 - 3b_3h_3 - b_4h_4 - b_5h_5 - BH) + \rho_2 LBH \le \rho_1 L(b_1h_1 - 3b_2h_2 - 3b_3h_3 - b_4h_4 - b_5h_5 - 2b_6h_6) \tag{2.10}$$

Finally, the constraints on *B* and *H* of the light weight requirements are obtained:

$$BH \ge 16720.8 \tag{2.11}$$

The isostiffness and lightweight constraint inequalities (2.9) and (2.11) obtained by the above analysis are curvilinear fitted through MATLAB software as shown in Figure 5. Finally, the values of *B* and *H* are derived as green areas in Figure 5. Those are 320 ~ 370mm and 42 ~ 55mm, these dates are input parameters for the subsequent target optimization design.

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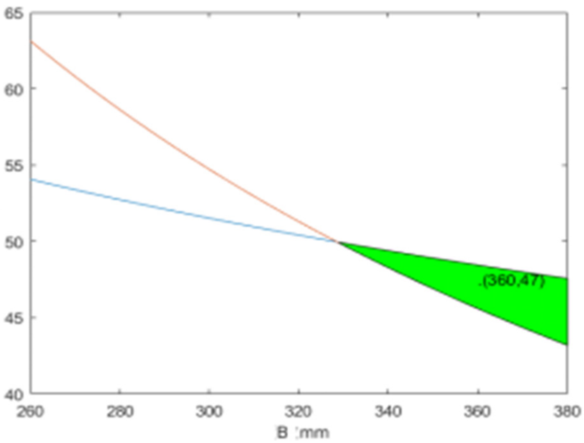


Figure 5. Equal stiffness and equal mass curve

3. Analysis of static and dynamic characteristics of prototype structure worktable

3.1. Analysis of static characteristics

3.1.1. Analytical steps

The 3D physical model of the prototype structure worktable is established, and the grid is divided in ANSYS Workbench software. Set the material parameters according to table 2. A fixed displacement constraint is applied to both sides of the worktable.

Calculating the load of the worktable which is based on drilling condition of the VX380T vertical processing center in order to analyze the static characteristics of the worktable. Taking the 10mm hole of steel workpiece 45# drilled with cemented carbide, the axial force of the worktable and its torque load around the cemented drill axis are:

$$F_f = C_{Ff} d^{z_{Ff}} f^{y_{Ff}} K_{Ff} \tag{3.1}$$

$$M_c = C_{Mc} d^{z_{Mc}} f^{y_{Mc}} K_{Mc} \tag{3.2}$$

In the formula: C_{Ff} is the effect coefficient of the processing material and cutting conditions on Ff, 600; *d* is Drill diameter, 10mm; *f* is the feed, 0.8mm/r; z_{Ff}, y_{Ff}, the effect index of diameter and feed on Ff, 1.0, 0.7; K_{Ff} is the correction coefficient, 1.0; C_{Mc} is the effect factor of the material and cutting conditions on Mc, 0.305; z_{Mc}, y_{Mc}, respectively the impact index of diameter and feed on Mc, 2.0, 0.8; K_{Mc} is the correction coefficient, 1.0.

Substituting the above data into the formula (3.1) ~ (3.2), the feed force 1197N, the torque 4830N·mm, the drilling force and torque applied at the center point of the worktable surface are shown in Figure 6.

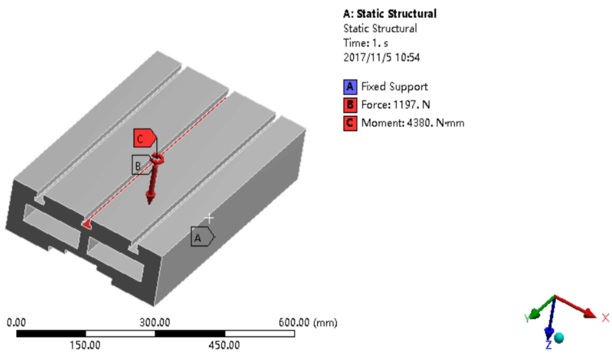


Figure 6. Worktable load and boundary condition constraints

3.1.2. Results and analysis

The equivalent stress and equivalent strain diagram of the prototype structure table are obtained based on the above process analysis as shown in Figures 7 and 8.

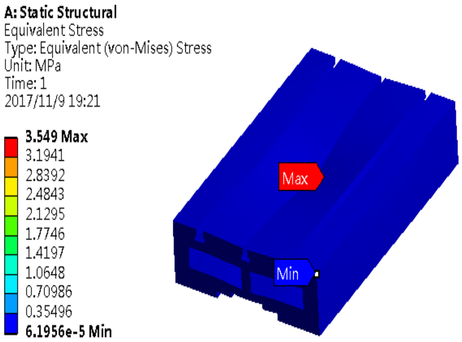


Figure 7. Equivalent stress diagram of prototype worktable

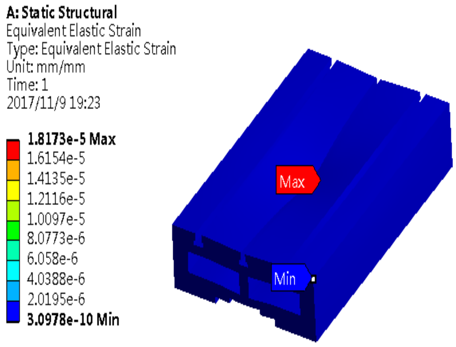
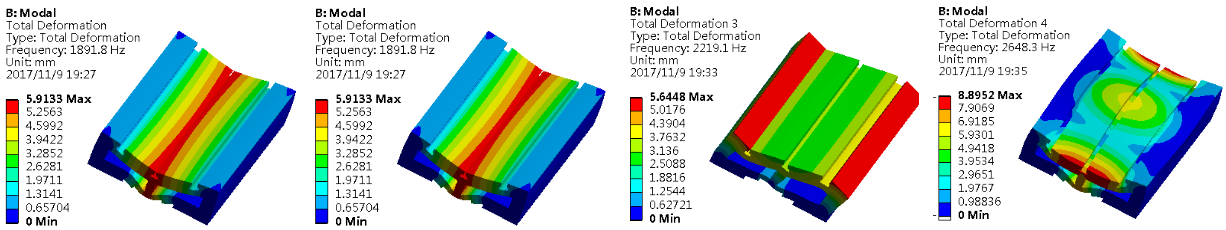


Figure 8. Equivalent elastic strain diagram of prototype worktable

The maximum stress of the prototype worktable is 3.549MPa, and the maximum stress is 1.8173×10^{-5}mm/mm. This static characteristic is used as the constraint condition for the multi-objective optimization of the subsequent worktable filled with BFPC.

3.2. Dynamic characteristics analysis

Modal analysis are mainly used to determine the natural frequency and vibration type of the structure in the design. The weight factor of each modal decreases with the increase of the modal frequency, which means that the low order modal characteristics basically determine the dynamic performance of the machine tool product[8] and only the first four modes of the worktable are studied here in the dynamic analysis of the structure. The results of the analysis are shown in Figure 9 and Table 3.



(a) (b) (c) (d)

Figure 9. The first four modes of prototype structure worktable

Table 3. Modal natural frequency (Hz)

Worktable	First order	Second order	Third order	Fourth order
prototype	1891.8	2018.2	2219.1	2648.3

It can be seen that the first three order natural frequencies of the prototype structure worktable are 1891.8Hz, 2018.2Hz, and 2219.1Hz respectively. Taking the weighted average of the natural frequency of the first three order modes as one of the objective functions of the subsequent worktable filled with BFPC target optimization.

4. Multi-objective optimization design of worktable filled with BFPC

4.1. Design variables and objective function settings

Using Workbench's DM module to draw three dimensional model of worktable filled with BFPC, and to define the design variables according to the previous preliminary design, set the width P8 and height P9 of the rectangular hole, and taking 360mm and 47mmthe as initial values. Set the material parameters as shown in table 2. The loading and constraint conditions of worktable filled with BFPC are the same as those of the prototype structure. The mass P4, the first three-order weighted natural frequency P10, the maximum equivalent stress P3, and the maximum equivalent strain P14 are the output variables. The sensitivity of each design variable to the objective function and the response surface are analyzed through the Resone Surface module. Optimization module optimization is used to obtain the optimal structure[9,10].

The multi-objective optimization design is to find the optimal width B and height H of the rectangular fill hole. Siting the quality of the worktable is minimized and the weighted natural frequency of the first three orders is maximized, under the condition that the maximum equivalent static stress and maximum equivalent static strain are not greater than the relative performance of the prototype worktable. The first three weighted natural frequencies $f_{10}(P)$ are:

$$f_{10}(P) = 0.5 \times f_1(P) + 0.3 \times f_2(P) + 0.2 \times f_3(P) \tag{4.1}$$

In the formula: $f_1(P)$, $f_2(P)$, and $f_3(P)$ are the natural frequencies of the first three modes; 0.5, 0.3, and 0.2 are the weight factors corresponding to the natural frequency of the first three modes.

The width and height of rectangular filled holes are used as the design variables, the weighted natural frequency maximum are multi-objective functions with the first three steps and mass minimum of the worktable, and constraint conditions are the corresponding results of the static maximum equivalent stress and strain not greater than the prototype worktable. Considering the size of the worktable and the minimum casting wall thickness required for the worktable casting, the range of design variables is as follows: $320 \le B \le 370, 42 \le H \le 55$. Finally, establish optimized mathematical model[11] is:

$$min\, F(P) = [f_4(P), -f_{10}(P)]^{\mathrm{T}}$$
$$s.t. \begin{cases} g_3(P) < 2.7587; g_{14}(P) < 1.8173 \times 10^{-5} \\ P = [P_8, P_9]^{\mathrm{T}} \\ 320 \le P_8 \le 370; 42 \le P_9 \le 55 \end{cases} \tag{4.2}$$

4.2. Sensitivity and response surface analysis

In order to avoid its blindness, effective control strategies must be adopted in the process of structural optimization. At present, the sensitivity analysis of design parameters is widely used. The basic principle is: the sensitivity of the objective function and the main performance parameters with the structural design variables is calculated through a certain mathematical method and means, and design parameters are corrected according to the size of the sensitivity value and the positive and negative values. It is more convenient, quick and accurate to determine the structural design parameters through the sensitivity analysis of the structure, and then use the method of modifying the structural reanalysis, find the optimized structural design scheme in finally[12].

The design variables B and H affect the sensitivity of the worktable quality, the weighted natural frequency of the first three orders, the maximum equivalent static stress and the maximum equivalent static strain as shown in Figure 10, and the corresponding response surfaces as shown in Figure 11.

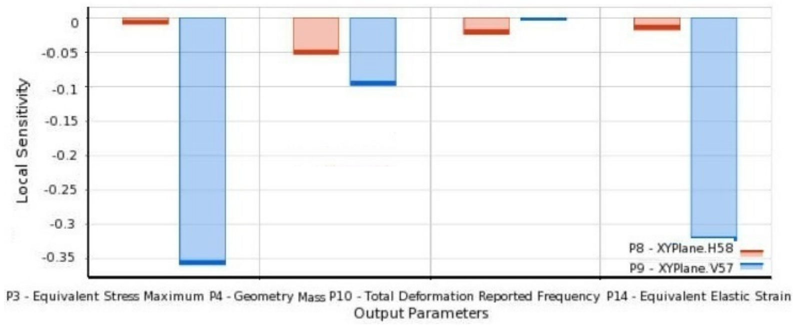


Figure 10. Sensitivity diagram

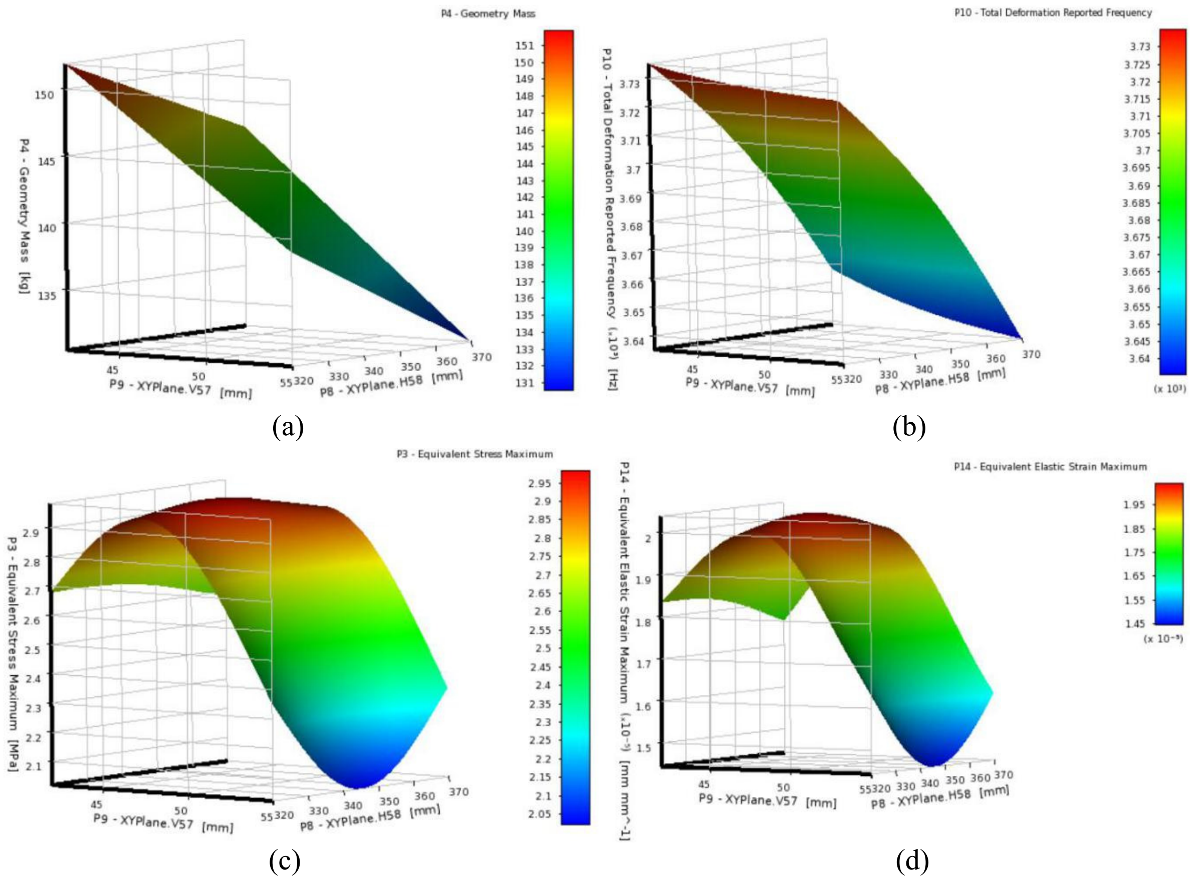


Figure 11. Response surface diagram

It is show that as the two design variables increase, the value of the objective function decreases accordingly in Figure 10. The height *H* of rectangular hole in the section of worktable filled with BFPC has the greatest influence on the worktable quality, maximum equivalent stress and maximum equivalent strain. The width *B* has the greatest effect on the weighted natural frequency of the first third order. It can be seen that the quality of the BFPC filled structure worktable and the weighted natural frequency of the first third order are constantly decreasing with the increase of the width and height of the rectangular hole combined with Figure 11. The maximum equivalent stress and strain of the worktable first increases with the width and height of the rectangular hole. When the width and height increase to a certain value, the equivalent stress and strain decrease with the width and height of the rectangular hole.

4.3. Outcomes and discussions

Two best candidate design points are optimized as shown in Figure 12. The lightweight of worktable is great significance that reduce the power consumption of driving worktable, to improve the low speed motion stability of the table, to improve its rapid starting and stopping, and even to improve the machining accuracy and productivity of the machine tool. Therefore, Candidate Point 2 was selected as the optimal design point. The results are rounded and *B* is taked 335mm and *H* is taked 55mm.

11		Candidate Point 1	Candidate Point 2
12	P8 - XYPlane.H58 (mm)	327.5	335.5
13	P9 - XYPlane.V57 (mm)	53.505	54.318
14	P3 - Equivalent Stress Maximum (MPa)	2.3707	2.4297
15	P4 - Geometry Mass (kg)	139.25	137.09
16	P10 - Total Deformation Reported Frequency (Hz)	4117.8	4107.8
17	P14 - Equivalent Elastic Strain Maximum (mm mm^-1)	1.6481E-05	1.6646E-05

Figure 12. Optimized candidate design points

Rebuild the model according to the size of the optimal scheme and the simulation analysis is redone. The analysis results are compared with corresponding performance parameters of the prototype worktable as shown in Table 4. It can be seen that compared with the prototype worktable, the optimized worktable filled with BFPC reduced the quality by 3.9 % while the maximum equivalent stress and strain decreased by 31.6 % and 8.4 % respectively, and the weighted natural frequency of the first third order has increased 105.8%. The worktable filled with BFPC can effectively improve the static and dynamic performance of the worktable on the premise of ensuring light weight.

Table 4. Comparison of results before and after optimization

Constraints and objective functions	Prototype worktable	Worktable filled with BFPC	Comparison of results
Maximum equivalent stress(Mpa)	3.549	2.429	-31.6%
Maximum equivalent strain(mm/mm)	1.8173×10^{-5}	1.6646×10^{-5}	-8.4%
Mass(kg)	142.6	137.1	-3.9%
The first three weighted natural frequencies(Hz)	1995.2	4105.8	+105.8%

5. Conclusion

(1) The sensitivity and regularity of main dimension parameters on optimization target are obtained by conducting the multi-objective driving optimization analysis of worktable filled with BFPC. It has a great reference value that guide the determination of the best main structural parameters.

(2) The worktable filled with BFPC designed by multi-objective drive optimization design method can effective improve the static and dynamic performance of the worktable under the premise of lightweight. It is proved that BFPC is effective on improving the comprehensive performance of the foundation and even the whole machine.

Acknowledgments

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