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Analysis of Basalt Fiber Reinforced Polymer Concrete Cast Bed for Horizontal Machining Center

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ABSTRACT

This study takes the bed of a vertical machining center as the research object, conducting static, dynamic, and comparative analyses between basalt fiber reinforced polymer concrete (BFPC) beds and cast-iron beds. Using SolidWorks software, 3D models were created according to the material characteristics of BFPC castings and cast iron. ANSYS software was then employed to perform static and dynamic analyses on both types of beds. Results demonstrate that under identical working conditions, the BFRPC bed exhibits lower deformation than the cast iron bed, effectively increases the natural frequency of the bed structure, and significantly reduces dynamic response when subjected to external excitation.

KEYWORDS

BFPC; Bed; Static Analysis; Dynamic Analysis.

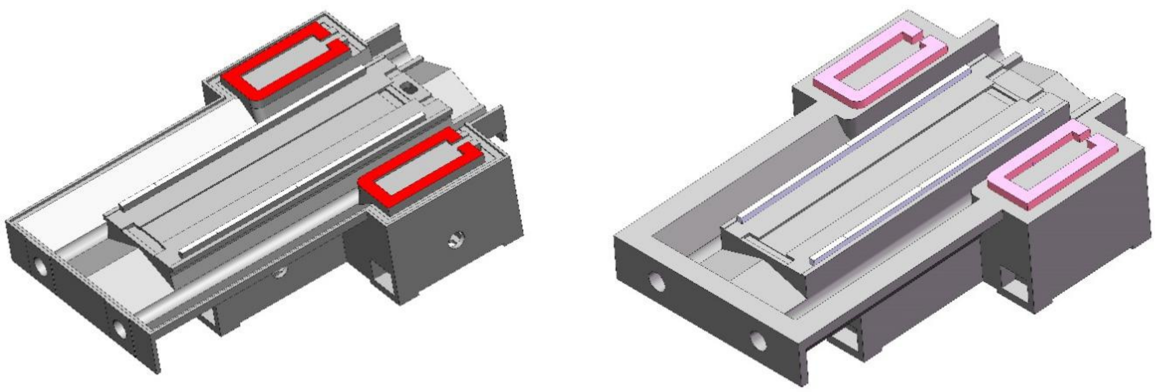
1. INTRODUCTION

Machine tools, also known as mother machines or tooling equipment, are machines that manufacture other machines. The machine tool industry serves as the cornerstone for achieving advanced manufacturing technology and industrial modernization, providing strategic support for national defense and high-tech industries. Today, the performance, quality, and ownership of CNC machine tools have become key indicators measuring a nation's industrialization level and comprehensive power[1-2]. As the core load-bearing component of machine tools, the bed's mechanical properties and lightweight design directly impact machining accuracy and equipment reliability [3] . During operation, it must simultaneously withstand structural loads, gantry weight, spindle system mass, and dynamic cutting forces. Consequently, optimizing static stiffness, dynamic response characteristics, and mass reduction are critical for enhancing machine performance [4-7]. In recent years, novel composite materials have emerged as a significant research direction for improving fundamental component performance. Compared to traditional gray cast iron, Basalt Fiber Polymer Concrete (BFPC) exhibits superior stiffness, strength, and low thermal conductivity, along with higher compressive strength, flexural strength, and impact toughness than conventional concrete[8-10]. Consequently, BFPC is recognized as a promising advanced material. Yinghua Yu et al.[11] manufactured a machine bed using BFPC and conducted analyses demonstrating that BFPC beds enhance static/dynamic characteristics while reducing mass. Xianyu Meng et al. [12] compared cement-resin composites, polypropylene fiber-reinforced polymer concrete, and conventional cast iron lathe beds. Results indicate BFPC beds achieve comparable static accuracy and stress amplitude to cast iron beds, though further modification is required to match cast iron's full performance envelope.

2. PRE-TREATMENT AND ANALYSIS OF STRUCTURAL AND MATERIAL PARAMETERS FOR MACHINE BEDS

2.1. Pre-treatment

To fulfill the requirements for finite element analysis (FEA) mesh generation and first six-order modal calculations of the machine bed, geometric processing of the original 3D model is necessary. During the pre-processing stage, non-critical features with minimal impact on mechanical performance are removed, including threaded holes, backlash grooves, fillets, chamfers, and auxiliary structures. Guided by key dimensions of the cast iron bed, the mineral composite bed was redesigned. Structural simplifications of both gray cast iron and mineral composite beds are illustrated in Figure 1. Material properties of cast iron and BFPC (Basalt Fiber Polymer Concrete) are listed in **Table 1**. The grey cast iron bed body is hollow inside, embedded with cross ribs. When replacing cast iron materials with basalt fibre reinforced resin concrete, maintain the structural dimensions of the important areas on the upper part of the bed body, increase the structural thickness of the edge parts, and change the lower part of the bed body to a solid structure. The guide rail installation surface and the portal frame installation surface are treated with embedded steel components.



(a)Grey cast iron bed (b)BFPC bed body

Figure 1 Sketch of the structure of the two types of beds

In order to compare the performance of the grey cast iron bed with the BFPC bed, the material properties as shown in **Table 1** were set separately before the analysis. By setting the material properties, the mass of the grey cast iron bed and the BFPC bed was 2043 kg and 2060 kg, respectively. There is not much difference between the two.

Table 1. Material Properties

material	density /($g\cdot cm^{-3}$)	Poisson's ratio	Elastic modulus E/Gpa	Coefficient of thermal expansion /($\times 10^{-5}$°C^{-1})
Grey iron	7.35	0.27	130	1.1
BFPC	2.51	0.25	46	1.4

2.2. Load Calculation

There are two bearing surfaces for the main force of the vertical machining centre bed studied in this paper: one is the guide rail mounting surface beneath the worktable, and the other is the connection surface between the gantry and the bed. When analysing the static and dynamic properties of the bed structure, it is necessary to consider not only the weight of the machine tool itself but also the cutting force load generated by the machine tool when operating.

According to Ref the empirical formula for the circumferential cutting force F_C of a machine tool is：

$$F_c=9.81\times58\times a_e^{0.90} f_z^{0.80} \alpha_p z d^{-0.90} \tag{1}$$

In the formula: a_e is the depth of the milling layer; f_z is the feed per tooth; a_p is the milling width;zis the number of teeth of the milling cutter;dis the diameter of the milling cutter; K_{Fc} is the correction factor. The maximum diameter of commonly used milling cutters d=40mm, the number of milling cutter teeth z=4, the amount of milling layer is a_e=2mm,the feed rate per tooth f_z=0.3mm,and the milling width a_p =30mm.Substitute the above parameters to F_c =1758.12N.From the following equation, the anisotropic cutting force F_x=1582.30N, F_y=1230.68N, F_z=966.97N.The maximum load weight of the worktable is 150kg, and the weight of the gantry and spindle unit is 1650kg.

$$\begin{cases} F_x=(0.6\sim0.9)F_c \\ F_y=(0.45\sim0.7)F_c \\ F_z=(0.5\sim0.55)F_c \end{cases} \tag{2}$$

3. ANALYSIS AND COMPARISON OF STATIC CHARACTERISTICS OF BFPC BED AND CAST IRON BED

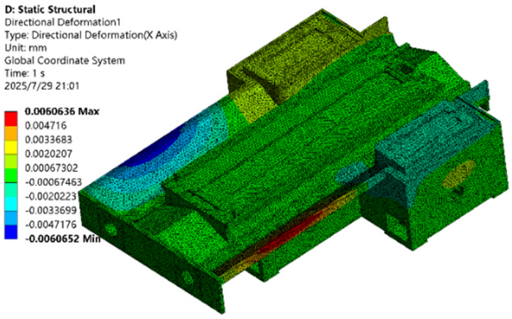
The maximum deformation of the bed of the two materials in each direction is shown in Table 2, with the bottom of the bed as the xOy plane, the guide rail direction in the forward direction of the y-axis, the forward direction of the x-axis in the forward direction of the y-axis, the forward direction of the x-axis in the direction of 90° counterclockwise around the y-axis, and the forward direction of the height of the bed in the forward direction of the z-axis.

Table 2. The maximum deformation of the bed in each direction of the two materials.

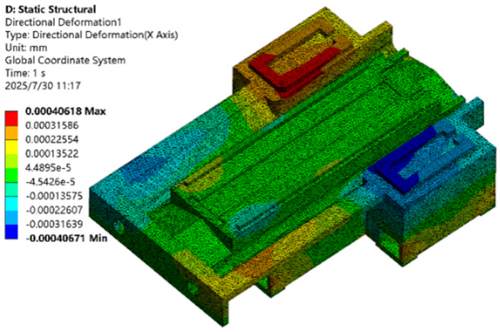
	Grey iron	BFPC
x direction	0.006063	0.000406
y direction	0.001087	0.000984
z direction	0.000039	0.000007
Total deformation	0.01233	0.004616

From the above table, it can be seen that the total deformation of the BFPC bed and the maximum deformation in the x, y and z directions are smaller than those of cast iron beds. The deformation diagram in each direction and the overall deformation diagram of the bed of the two materials are shown in Figure 2.

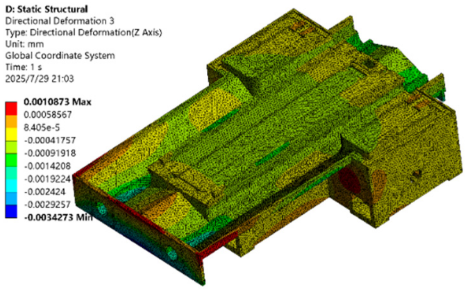
Figure 2 shows that in the x direction, the maximum deformation of the cast iron bed occurs in the weak areas on both sides of the bed, while the maximum deformation of the resin mineral composite bed occurs at the junction of the gantry and the bed. In the y direction, the positions of the maximum deformations for both the cast iron and resin mineral composite beds are roughly the same, concentrated at the front end of the bed and the weak points on both sides.



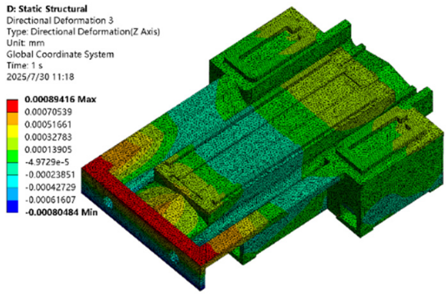
(a) Grey cast iron bed x direction maximum deformation



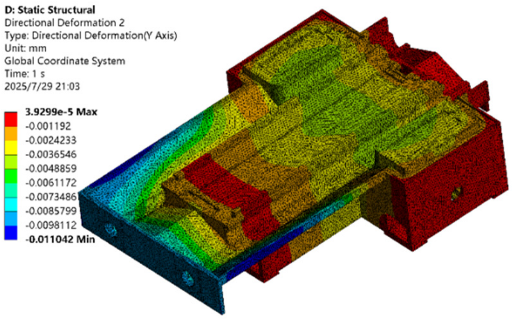
(b)Maximum deformation in the x direction of the BFPC bed



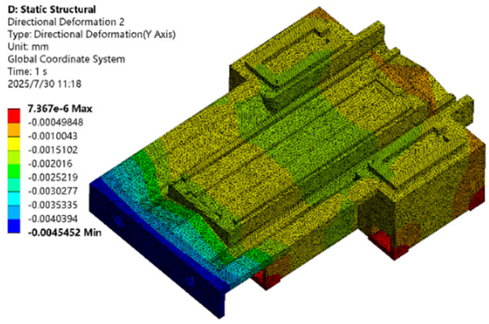
(c) Grey cast iron bed y direction maximum deformation



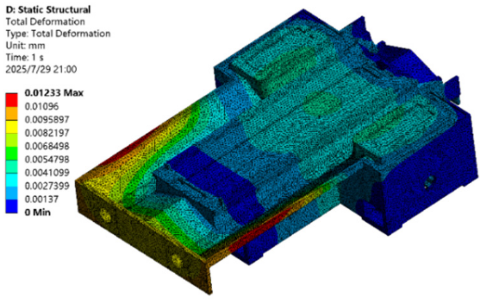
(d)Maximum deformation in the y direction of the BFPC bed



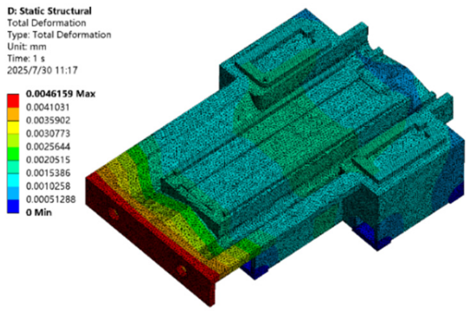
(e) Grey cast iron bed z direction maximum deformation



(f)Maximum deformation in the z direction of the BFPC bed



(g)The grey cast iron bed has the maximum total deformation.



(h)The maximum total deformation of the BFPC bed.

Figure 2. x y z three-way deformation cloud diagram and overall deformation diagram of the bed of the two materials

In the z direction, the maximum deformation of the cast iron bed occurs at the rear end of the bed and the front end of the guide rail, while the maximum deformation of the resin mineral composite bed occurs at the bottom of the bed, specifically at the weak points at the front end.

The total deformation cloud diagram of the two beds shows that under the same static load, the deformation of the grey cast iron bed is larger, and it is easy to occur in the edge area of the bed, while the deformation of the resin mineral composite bed is concentrated in the weak part of the front end of the bed.

4. ANALYSIS AND COMPARISON OF DYNAMIC CHARACTERISTICS OF BFPC BED AND CAST IRON BED

In order to clarify the vibration characteristics of the beds of the two materials, modal analysis is required to determine whether they are close to the frequency of external excitation, and then predict whether they resonate. Therefore, the Block-Lanczos method is used to extract the first four natural frequencies and their mode characteristics of the vibration characteristics of the beds of the two materials (Table 3), and the first four modal cloud diagrams are shown in Figure 3.

Table 3. The natural frequencies of the 4th modality in front of the bed of the two materials.

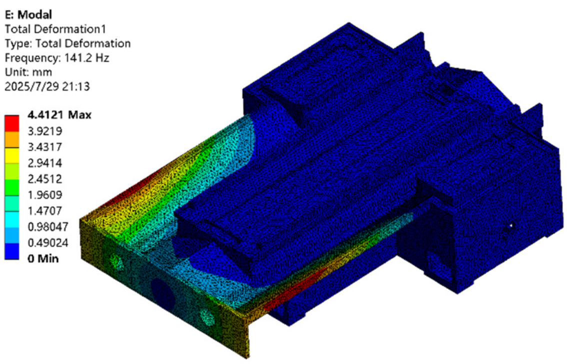
Steps	Grey cast iron bed has natural frequency.	BFPC bed body
1	141.2/Hz	290.22/Hz
2	155.58/Hz	319.24/Hz
3	169.48/Hz	405.19/Hz
4	177.89/Hz	474.06/Hz

From Table 3, it can be seen that the natural frequency of the BFPC bed is higher than that of the cast iron bed, and the first-order natural frequency is 290.22 Hz, which is 105.5% higher than that of the first-order natural frequency of the cast iron bed of 141.2 Hz. Cutting resonance is mainly concentrated in the low-order natural frequency, and increasing the low-order natural frequency can increase the cutting speed range of the machine tool, avoid the occurrence of resonance, and have a significant effect on improving the machining capacity of the machine tool. In addition, the first three maximum deformations of the BFPC bed are less than the first four maximum deformations of the cast iron bed. The analysis believes that the reason is that resin materials have strong vibration absorption, and basalt fibre resin concrete contains a large amount of resin materials. In addition, the solid structure of the BFPC bed is different from that of the cast iron bed, which leads to an increase in natural frequency and a change in mode.

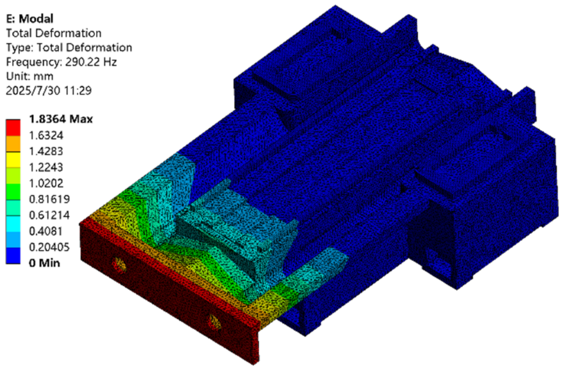
5. CONCLUSION

(1)The static analysis results of basalt fibre resin concrete and cast iron beds show that the static properties of the two materials are similar when the external dimensions and total weight of the bed are similar, but the deformation of basalt fibre resin concrete beds is much smaller than that of grey cast iron beds, which proves the superiority of basalt fibre resin concrete to a certain extent.

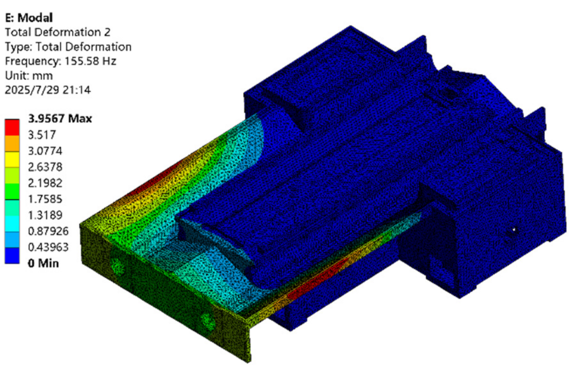
(2)The results of bed modal analysis of the two materials show that the bed of the machining centre made of basalt fibre resin concrete has a higher natural frequency of each order, which is more than twice that of cast iron material, and the area with large bed deformation is significantly reduced.



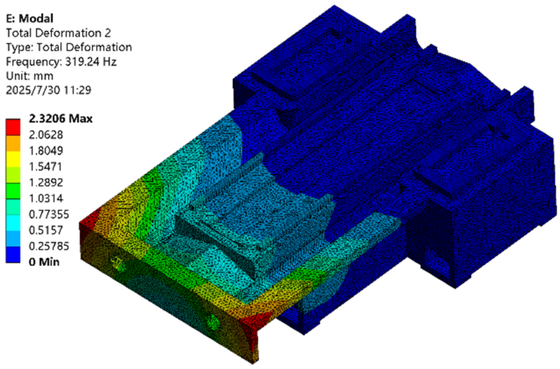
(a)The grey cast iron bed is in a first-order



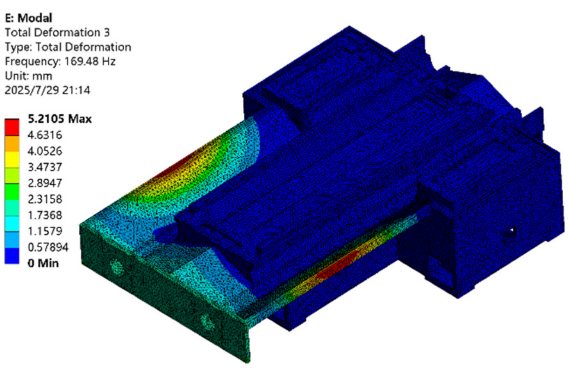
(b)BFPC bed body first-order mode



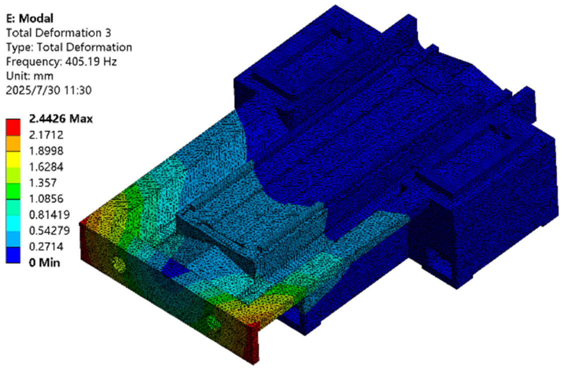
(c)Grey cast iron bed second-order mode



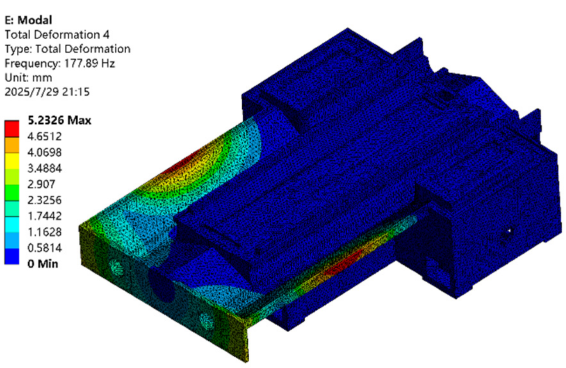
(d)BFPC bed body second-order mode



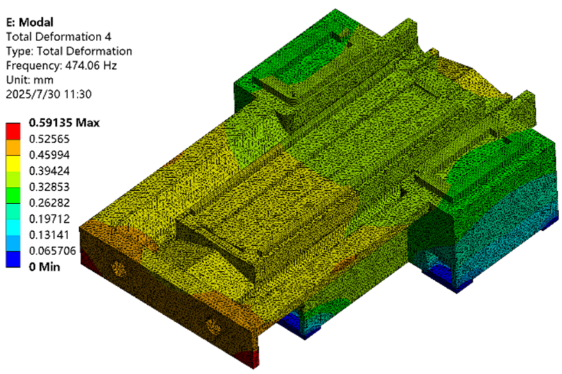
(e)Grey cast iron bed three-order mode



(f)BFPC bed body three-order mode



(g)Gray cast iron bed fourth-order mode



(h)BFPC bed body fourth-order mode

Figure 3. The fourth-order modal cloud diagram in front of the bed of two materials

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