Application of Composite Material in Digital Machining Center Construction

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Abstract.
The conventional five-axis CNC machine tool bed is fabricated using gray cast iron. However, it lacks overall rigidity and no longer satisfies processing demands. To improve the overall rigidity of the machine tool and address accuracy errors caused by dynamic and static factors, a new mineral composite bed material is proposed in this study.Gravels of Jinan green granite were used as aggregates with high-strength epoxy resin as the adhesive. Carbon fibers were the filler to reinforce the overall material strength. After casting, the test piece would be tested. The results showed that the maximum compressive stress of the test piece could reach 125.8Mpa, and the density was only 1/3 of that of cast iron. Lastly, the composite material was applied to the numerical control machine tool, which would be tested by modal analysis and instruments using Ansys software. The results showed that the maximum stress was reduced by 68.93% and the maximum strain was reduced by 72.6%, compared with gray cast iron. The first 6-order natural frequencies were significantly increased by 20% to 30%, providing it with better resistance to vibration than that of gray cast iron. The material has improved the stability and machining accuracy of the machine tool.
Keyword: modal analysis, Machine tool bed,composite,Granite,composite material

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I. Introduction

With the continuous development of modern manufacturing industry toward the goal of high efficiency and high precision, Kim, D. I. (2006) [1] proposed that ultra-precision machining tools should meet the requirements of precision and processing stability, and the construction materials should have sufficient rigidity, high vibration resistance, small thermal deformation, and other material characteristics. Bustillo A. (2015) [2] suggested a list of higher requirements for the dynamic and static mechanical properties of the machine tool, especially in higher demand of product's surface finish.The dynamic and static performance of traditional machine tools can no longer satisfy these processing requirements. Kim, H. S. [3] believed that the rigidity of the basic parts of these traditional machine tools was inadequate, which would lead to greater accuracy error.

The five-axis vertical machining center (VMC) is composed of a base, a worktable, a bed, the main axis, an automatic tool changer (ATC), etc., which is suitable for the processing of large and complex parts. Among the structural components, the performance of the support has a great impact on the overall performance of the machine tool. The support of the machine tool mainly refers to the base and columns, which must have high structural stiffness and good damping performance, so only in this way can the parts with higher geometric precision be produced.

Therefore, the performance of the support, whether be superior or not, will directly affect the machining accuracy of the tool [4-6]. Currently, there are two methods to improve the machine tool, by either optimizing its structure or applying new materials to manufacture machine tool [7-8].There are literatures mentioning such as Guo Lina [9], who optimized the reinforcement layout of the moving beam of gantry machining center, and Prabhu Raja Venugopal in 2019 [10] adopted granite as material with reinforcement of various types of steel bar to improve the tool's static and dynamic properties. N. Kepczak and colleagues, in 2015 [11], used cast iron combined with mineral material to make a machine bed and the result showed a significant increase in the dynamic and static strength of the tool. Jung Do Suh et al. [12], due to the relatively poor damping characteristics of metal machine tools to result in stronger vibration to affect the machining accuracy, installed some auxiliary dampers such as Lanchester power absorber and power dampers to increase its shock absorption capacity; however, a careful study found that the effect of such use was only effective to a specific range of frequencies that restricted its use. It was also found that these methods above did not fundamentally improve the performance of the machine tool, and their potential was still limiteThe Studer Company has adopted the latter choice and used synthetic granite to make its Granitan S103 machine tool. Md Mazedur Rahman [13] instead used a carbon fiber reinforced composite material in construction of the bed and the base. Yu Yinghwa [14] and Xu Ping [15] used foamed aluminum and steel fiber in mix and casted with resin concrete. It was evident the use of concrete with larger aggregates by the two researchers above in the manufacturing process would yield mold with large voids. Thus, they required to use more epoxy resin in the process, resulting in relatively higher cost. Rami H Haddsad [16] using the combination of cement concrete and granite in the structure of the lathes, showed that it could significantly improve its anti-vibration capacity and the machining accuracy of CNC machine tools. However, the study found that cement concrete could easily form voids, holes, or even surface cracks, as well as other shortcomings, since rarely a vacuum pump would be used in the mixing process, where air bubbles could be trapped in the concrete, affecting the density of the material and producing holes within. As observed in many literatures, manufacturers around the world are paying more attention to the accuracy problem of five-axis vertical machining center, which has already affected the machining performance and precision, including some issues of dynamic and static properties of machine tools. At present, there are many methods to improve the accuracy of machine tools, including the application of new materials and modeling for simulation analysis or structural optimization.In this study, according to the excellent natural physical properties of Jinan black granite and the mixing of high strength epoxy resin and fillers, and by means of refined manufacturing technology, the cast mineral composite materials were used in the structural parts of the five-axis vertical machining center (VMC). Through dynamic and static mechanical analysis, and compared with gray cast iron machine tools, the results showed the product with lower density, higher damping ratio, higher compressive and flexural strength when compared with traditional cement concrete [17-18]. And, by practical verification, the 1st to the 6th-order natural frequency of the machine tool of mineral composite has increased by 20% to 30%; thus, providing better damping ratio and anti-vibration effect, which further improved the stability and processing accuracy of the machine tool and helped to enhance its overall performance.

2. Materials and method

2.1. Properties of materials

2.1.1. Jinan black granite

The mineral composite material in this study was mainly composed of Jinan black granite, adhesive and fillers, all structured as shown in Figure 1. in which, 01 is the fillers, 02 is the Jinan black granite and 03 is the adhesive.The characteristics of the black granite in Jinan (see Table 1); the materials were from Huashan Town, Licheng District, Jinan City, Shandong Province, China. Jinan black is the trade name of commercial granite. It is generally in block form, which must be first crushed and screened accordingly by particle size, typically as 0.2-0.4 mm (Z); 0.4-0.6 mm (Y); and 0.7-3.5 mm (X). By plotting through a ternary scatter diagram, the best mix ratio of the three particle sizes was 36% (Z): 24% (X): 40% (Y), as shown in Figure 2. (Y = medium granularity; X = coarse granularity; Z = fine granularity)

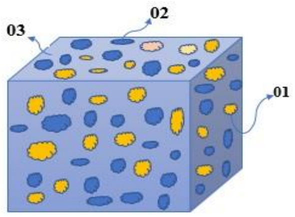

Figure 1. The Structure mineral composite material.

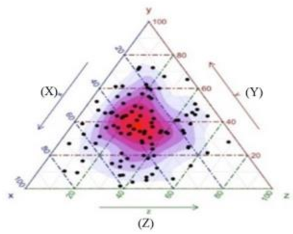

Figure 2. The scatter plot of granite.

2.1.2. The adhesive

In addition to Bisphenol epoxy resin, the adhesive would also contain curing agent, toughening agent and diluting agent, in which the brand of Bisphenol epoxy resin was HEXION, model: EPON58005, with heat resistance and shock resistance, providing a viscosity of 2500P at 25 °C. The curing agent mainly regulated and promoted the curing reaction of epoxy resin; a necessary component to produce curing bonding. Some elements that require accelerated chemical reaction to cure, such as resin, will not harden into a solid state without a curing agent. In this study, Triethylenetetramine was used as the curing agent; it is a moderately viscous yellow liquid with strong alkalinity with a density of 0.98 g/mL, boiling point at 266 °C and freezing point of 12 °C at 25 °C. Supplier of the agent was Guangdong Mingtu Chemical Co., Ltd. The diluting agent helped to reduce the viscosity of epoxy resin and increase its fluidity, allowing epoxy resin to penetrate layers of granite and fillers more easily, which further prolonged the curing time to achieve a better binding effect [19]. The main function of the toughening agent was to improve the ductility of epoxy resin and prevent its fracture under impact due to its inherent properties of brittleness [20-21]. In this study, Benzyl butyl phthalate was used as the toughening agent to increase the ductility and impact resistance of the mineral composite. Supplier of the agent was Nan Ya Plastics Co., Ltd.

Table 1. Physical properties of granite of jinan

Physics Propertie	Compressive Strength(MPa)	Flexural Strength(MPa)	Water Absorption(%)	Density (kg/m³)
Value	257.1	36.1	12	3.07

2.1.3. Fillers

In the granite composite material, adding proper filler can reduce the amount of resin, reduce the cost, improve the dimensional stability and increase the mechanical strength by eliminating the curing stress [22] in the process of molding and mixing, preventing cracks and voids, and increasing the service life. In this study, A1203 and calcium carbonate were used as the fillers, and they showed the characteristics of slow heat transfer at room temperature but a high heat transfer coefficient at high temperature, which should improve the thermal conductivity of granite composite [23-24].

2.1.4. Reinforcement materials

Both carbon fiber and glass fiber can enhance the strength and toughness of the mineral composite, even though carbon fiber shows better result.

The damping ratio of mineral composite will increase with the increase of fibrous component, because these fibers will increase the internal voids of the mineral material, leading to higher damping ratio. This study would use 1.7% carbon fiber as fillers [25-26].

2.2. Laboratory equipment

The experimental equipment used in this study. Including the followings: a. pressure test machine, model YAW-3000-D, with hydraulic drive, and the manufacturer was Shandong Jinan Fangyuan Test instrument Co., Ltd.; b. planetary concrete mixer, model JJ-5 and the manufacturer was Jufeng Test Machine; c. standard cement maintenance box for constant temperature and humidity, model BG/T 1761-40A and the manufacturer was Beijing Jiwei Test Instrument Co., Ltd.; d. electric blowing dryer box, and model DHG-9030 and the manufacturer was Shanghai Bluepard Instrument Co., Ltd.

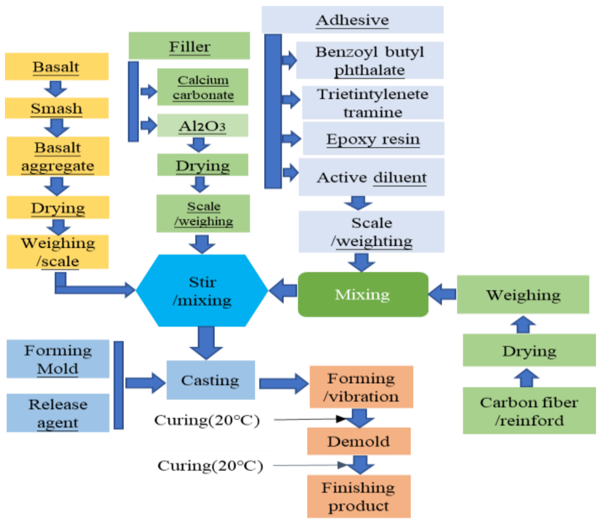

Figure 3. Manufacturing process of granite mineral composite. material

2.3. Production technology and manufacturing process

First, the Jinan black granite was crushed and screened of particle size before they were washed and dried. Epoxy resin, diluting agent, and curing agent were mixed in the ratio of 15, 7, 4 and [27] for 3 minutes, and the toughening agent was added appropriately to produce the final adhesive. Then, after weighing the aggregates, the adhesive, the fillers, along with the reinforcement of carbon fiber in proportion, all ingredients were mixed evenly, before they were coated into a steel mold layer by layer with parting agent, tamping with a guide bar after each loading. The top was scraped to flat smooth surface to reach the top of the mold. The temperature of the standard cement maintenance box was controlled at 22 ±3℃ and the relative humidity was 50 ±5%. The mold would only be released after 36 hours of curing, where a 100mmx100mmx100mm test piece was extracted to further incubation in the box before tested for its performance after 28 days. The manufacturing process is shown in Figure 3.

2.4. Performance test

2.4.1. Test of mechanical performance

According to GB/T 5081-2002, the “Standard for Concrete Mechanical Properties Test Method”, a YAW-3000-D universal servo tester was used to test the mechanical properties of the mineral composite material, with the test device shown in Figure 4. The performance parameters after testing are shown in Table 2.

Table 2. Physical properties of granite of workpiece

Physics properties	Bending Strength(MPa)	Compressive Strength(MPa)	Module of Elasticity(MPa)	Density (kg/m³)
Value	125.8	33.4	32	2275

2.5. Structural and performance analysis of a five-axis vertical machining center

2.5.1. Establishing a 3D model of CNC body

Based on the CAD drawing of the existing five-axis vertical machining center, model 850, a 3D model of actual size in SOLIDWORK software was constructed, as seen in Figure 5. Then, it was imported into ANSYS Workbench for finite element analysis. Despite small features such as chamfer, round hole, automatic tool change and relatively less influence on the overall modeling by these small components, due to more resulting irregularities in divided parts during the finite mesh division, which would further reduce the quality and prolong the calculation time, the 3D modeling was appropriately simplified to ignore both small features and small components. The simplified 3D model of the body is shown in Figure 6.

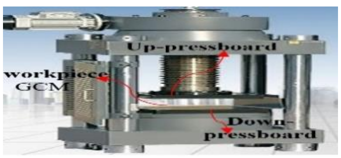

Figure 4. The YAW-3000-D universal servo tester.

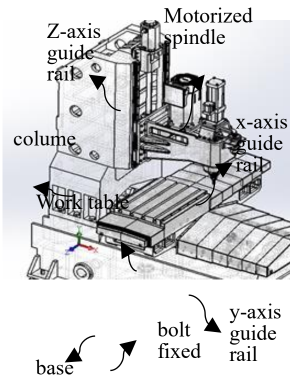

Figure 5. VMC Outline drawing (model 850).

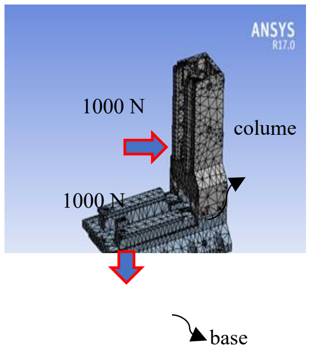

Figure 6. VMC of simplified drawing.

2.5.2. Material properties and boundary conditions

Cast iron (HT300) and the granite mineral composites were set with relevant parameter values and specific material properties based on their inherent characteristics once imported in ANSYS Workbench (see Table 3). By taking into account of forces applied on the body during the machining process, a vertical downward load of 1000 N was applied to the supporting surface of the guide rail above the two types of base, and a load of 1000 N in the horizontal direction was also applied to the column guide rail (as shown in Figure 6). The base was connected with the ground through anchor bolts, and the degree of freedom of the underside of the lathe was set to be fixed according to the actual circumstance of the machine.

Table 3. Granite mineral material and cast iron of Physical properties

Physical properties	Density (kg/m^3)	Poisson's ratio	Elastic Modulus(MPa)
HT300 value	7300	0.25	130
GCM value	2275	0.21	32

2.5.3. Mesh division of the body

According to the actual structure and size of the body, its three-dimensional model was created by SOLIDWORK, saved in STEP format, and imported into Ansys Workbench software. The two types of body were divided into a mesh of 50mm unit, where the cast iron body had 164,508 nodes and 84,752 elements, and the mineral composite body had 64,752 elements and 125,704 nodes. For the actual mesh division of the body, please refer to Figure 6.

2.5.4. Analysis of static characteristics of the body structure

The stress and strain diagrams of two types of the body could be obtained by Ansys' finite element analysis. The maximum stresses of cast iron and mineral composite body were 0.1814974 MPa, as show in Fig 8. and 0.053054 MPa, respectively, As show in Fig 7. The stress of mineral composite body was 71.2% lower than that of cast iron. The maximum strains were 0.05772 μm,as show in 9. and 0.015802 μm,as show in Fig 10. respectively, and the maximum strain of mineral composite body was 72.64% less than that of cast iron. Considering that the density of mineral composite was only 1/3 of the cast iron (see Table 3), the stiffness of machine tool could be further enhanced by increasing the wall thickness of mineral composite bed, as shown in Figure12.

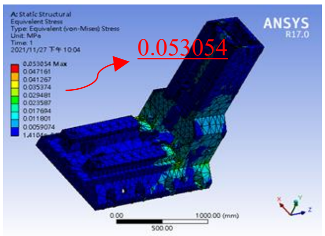

Figure 7. Stress diagram of cast iron material.

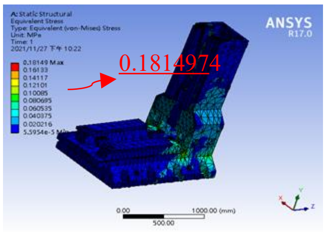

Figure 8. Stress diagram of mineral composite material.

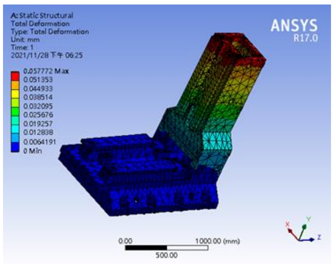

Figure 9. Strain diagram of cast iron material.

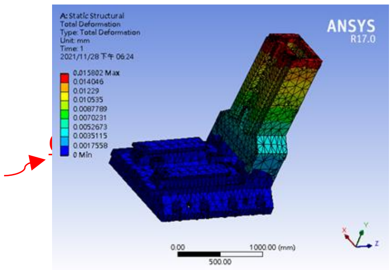

Figure 10. Strain diagram of mineral composite material.

2.6. Analysis of dynamic performance of the body structure

2.6.1. Test principle and device

During the machining process, a five-axis vertical machining center will produce vibration, with its placement resulting in a sinusoidal change over time. The vibration frequency is only related to the inherent characteristics of the bed, such as stiffness, mass, shape, size, where the harder and the smaller the bed is, it will have higher natural frequency and will be more difficult to vibrate in resonance. In order to further study its dynamic characteristics, this study adopted the hammering experiment to conduct the modal analysis of the solid body. The testing system was composed of a vibrator (hammer), a signal acquisition device and a modal analysis module. First, by manually operating the hammer, the researcher would tap the base and column structure of the machine tool to create resonance. The signal of the hammer and the vibration of the bed were captured by the force sensor and the acceleration sensor, respectively, in which the signal information were input into the DHDAS software through the software through the DH5922 dynamic signal testing analyzer for analysis. The dynamic signal testing analyzer is shown in Figure 11.

2.6.2. Vibrator

Vibrations in modal experiment could be categorized into natural and manual control; due to poor controllability and measurability of natural striking of the body, this study would adopt a way of manually controlled strikes, by using a force hammer produced by DongHua Testing Technology Company Limited, model: LC-100,on the main material - steel, with sensitivity of 1 mV/N and an added counterweight to achieve an impact force of 100 kN, which was adequate to produce a vibration frequency of the body. The testing procedure of the detection system in this study is shown in Figure 12.

2.6.3. Signal acquisition device

This experiment used the DH5922 dynamic signal test analyzer produced by East Hwa Company to measure the body's vibration and the responses. The sensor, model YDL-3H, was used to collect signals of forces. The piezoelectric sensor, model DH131E, would help to collect signals of unidirectional acceleration. These sensors were small in size, light in weight and had high sensitivity, which could be mounted on the body at a fixed response test point with the use of magnetic attachment. In order to measure the vibration signals in the X, Y and Z directions, three acceleration sensors were arranged at each measuring point to collect the signals of acceleration in the three respective axes. The force hammer was deployed at each strike point to knock on the body to produce vibration. In order to reduce the error impact caused by the uneven strike position and pulse force, it was tested three times at each measuring point,

before taking the average value of these measurements. The distribution map of measuring points is as seen in Figure 13.

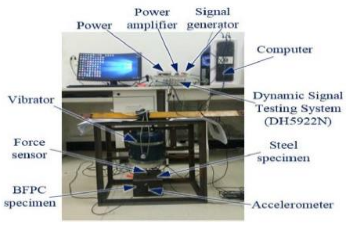

Figure 11. Dynamic signal acquisition and analysis system.

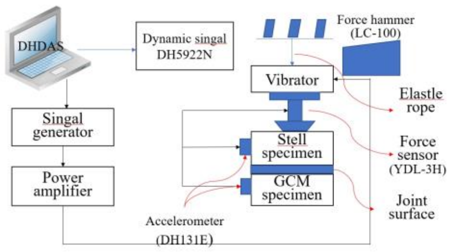

Figure 12. Dynamic process detection system.

2.6.4. Modal analysis system

The DHDAS modal analysis software was used to pick up the vibration and response signals of the force hammer on the body structure, and the collected data were imported to identify and calculate the peak values using the peak search method. The resulting first six-order natural frequencies of the body structure are listed in Table 4. It was learned that the vibration frequencies of order 1 to 6 of mineral composite material were much higher than those of cast iron, with an average increase of about 25% to 40%. Generally, the higher the natural frequency, the better it could improve the static and dynamic performance of the machine tool to significantly reduce vibrations in the machining process, as well as avoiding resonance, to improve the overall processing accuracy of workpiece.

Table 4. Result of modal analysis

Modal number	Natural frequency(Hz) Cast-iron	GCM	Amplification	Damping ratio
Step1	95.964	138.6	30.76%	0.6924
Step2	73.550	166.77	42.45%	0.5589
Step3	203.58	258.55	21.26%	0.7874
Step4	243.32	330.35	26.34%	0.7365
Step5	260.77	357.25	27.03%	0.73
Step6	258.32	389.35	33.65%	0.6632

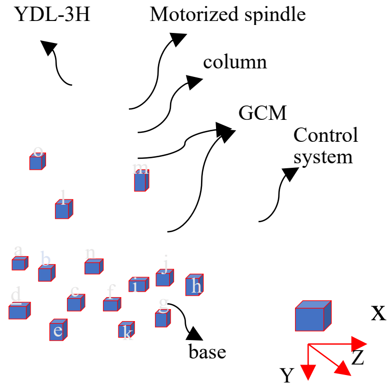

Figure13. Vibration testing point on VMC body

3. Results and analysis

(1) Jinan black granite with excellent natural physical properties was selected as the main aggregate.

From analyzing the ternary scatter plot, it was found that the best mixing ratio was 36% (medium size particle): 28% (small size particle): 40% (coarse particle). Then, adhesive and fillers were added, along with 1.7% carbon fiber in the mixing process. The compressive strength of the material could reach 125.8 MPa, and the flexural strength could reach 33.4 Mpa, comparable to the high compressive strength grade C120 of concrete [28]

(2) The static analysis of bodies of cast iron and granite mineral composite was carried out using ANSYS Workbench simulation software. The maximum stresses obtained were 0.1814974 MPa and 0.0563054MPa, respectively, indicating that the stress of mineral composite body was reduced by 71.2%, compared with that of cast iron. The maximum strains were 0.05777 μm and 0.015802 μm, respectively, indicating that the maximum strain of mineral composite body was reduced by 72.64%, compared with the cast iron. In terms of static performance, the stiffness and strength of granite mineral composites have been greatly improved.

(3) For deformation of materials, there was only slight difference between mineral composite and cast iron, but the density of mineral composite was only 1/3 of that of cast iron. The stiffness of machine body and the stability of machine tool could be further improved by increasing the wall thickness of granite mineral composite.

(4) By using DH5922N dynamic signal test analyzer, the vibration frequency of the solid body of granite mineral composite material was much higher than that of cast iron in the orders of 1 to 6 (see Table 4). The results showed that the overall stiffness of the machine body of granite mineral composite material has improved, which greatly reduced the vibration generated during processing.

4. Conclusion

The application of granite mineral composites in five-axis vertical machining center greatly improved the dynamic and static performance and stability of the machine tool. The improvement of damping ratio significantly improved the shock absorption, which has proven to be an effective way to increase the machining accuracy and speed of machine tool for wider range of application. Granite mineral composites can yield better economic benefits to the machine tool manufacturing industry.

Reference

1. Kim D.I, S C Jung, E Lee.Parametric Study on design of Composite Foam Resin Concrete Sandwish Structure for Precision Machine Tool Structures[J].Composite Structure,2006,75(3):pp.408-414
2. Doi: https://www.koreascience.or.kr/article/JAKO200622219623468.page
3. Bustillo,A.,Oleaga,I., Zulaika,J.J.,and Loix,N.,2015,New Methodology for the Design of Ultra -Light Structural Components for Machine Tool,Int.J.Comput.Integr.Manuf.,**28**(4),pp.339-352
4. DOI 10.1007/s00170-009-2129-1
5. Kim H S,PARK K Y, A "Study on the expoy resin concrete for the Ultra-precision Machine Tool Bed," [J].Mater Process.Technol.,1995,48(1-4),pp.649-655
6. **doi.org/10.1016/0924-0136(94)01705-6**
7. Suh J D, Dai G L, Design and manufacture of hybrid polymerconcrete bed for high-speed CNC milling machine, International Journa of Mechanics & Material in Design, 2008,4(2):pp.113-121. DOI: 10.1007/s10999-007-9033-3
8. Munoa J, Chatter suppression techniques in metal cutting, Cirp Annals-Manufacturing Technology, 2016, 65(2):pp.785-808. Doi.org/10.1016/j.cirp.2016.06.004
9. Qilong Li, XH2130 Gantry machine crossbeam system static and dynamic and thermal properties research, Suzhou:SOOCHOW University,2015. Doi:10.3901/JME.2019.09.127
10. Yang Q J, Kong L L et al., Research on MFBD modeling method for a grantry machining center beam components,Advanced Materials Research, 2011,188: pp. 487-493.
11. DOI：10.4028/www.scientific.net/AMR.188.487
12. Moehrin H C,Brecher C, Abele E et al., Materials in Machine tool structures, CIRP Annals-Manufacturing Technology,2015,64(2):pp.725-748. DOI：10.1007/978-1-349-05172-4_50
13. Linna G, Jiaquan J U, et al., Structural design and optimization in the beam of moving beam iongmen processing center[J].Modern Manufacturing Engineering , 2017(6):pp. 90-93.
14. Prabhu Raja Venugopal, M Kalayarasan, P R Thyla et al., Structural investigation of teel-

reinforced epoxy granite machine tool column by finite element analysis[J]. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials:for Olympic planning ,2019(9): pp. 2267-2279.

15. DOI：10.1177/146442071984059
16. Kepczak N and Pawlowski W., Cast iron and mineral cast applied for machine tool bed-dynamic behavior analysis. Arch Metall Mater 2015; 60: pp.1023-1029. DOI：10.1515/amm-2015-0254
17. Suh J D, Lee D G, Design and manufacture of hybrid polymer concrete bed for high-speed CNC milling machine [J].springerScience+Business Media B.V,2008(4):pp113-121. DOI: 10.1515/amm-2015-0254
18. Md Mazedur Rahman, Saiaf Bin Rayhan et al.,Impact of Micromechanical and Carbon Fiber Properties on the Elastic Modulus of CFRP Woven Composites[J] International Conference on Mechanical Engineering and Applied Composite.2020(25):pp.295-303.
19. DOI：10.1007/978-3-030-67958-3_32
20. Yu Yinghua, RUAN Deling et al., Optimal design of machine tool filled with foam aluminum, *Journal of Machine Design*,2014(11):pp.52-55. DOI：10.13841/j.cnki.jxsj.2014.11.013
21. Xu Ping,GAI Werwei, YU Yinghua et al.The pertormance of machine tool component of steel fiber concrete filled structure [J]Manufacturing Technology & Machine tool,2011(4),pp. 66-68
22. Doi.org/10.1007/s12404-008-0444-z
23. Haddad H, Kohaisi M A. Influence of moisture content on the thermal and mechanical properties and curing behavior of polymeric matrix and polymer concrete composite. Materials&Design.2013(49):pp.850-856. Doi.org/10.1016/j.matdes.2013.01.075
24. Diaconescu R M, Barbula M, Harja M, Predicion of properties of polymer concrete composite with line rubber using neural networks[J]Materials Science &Engineering B,2013,178(19).pp.1257-1267. Doi.org/10.1016/j.mseb.2013.01.014
25. Xu ping, SHEN Jiaxing, YU Ying,et al.Study on damping properties of basalt fiber reinforced concreted, Nonmetalic Mines,2017,40(1):pp.30-32. DOI：10.2991/emcpe-16.2016.120
26. Mukherjee A, Arwikar S J, Performance of Externally Bonded GFRP Steels on Concrete in Tropical Envinontures,2007,81(1):pp.21-33. Doi:10.1016/j.compstruct.2006.05.013
27. Yao Binghua, Li Dexin Ying Jinch et al., UnStudy of Artificial Granite Composites and its Application Materials For Mechanical Engineering.1993,17(4):pp.37-39.
28. www.soolun.com/periodical/79296556eef21e72ba182f469f040198.html
29. Hannawi K, Bian H, Prince A W et al., Effect of different types of fibers on the micro structure and the mechanical behavior of ultra-high performance fiber-Reinforced concretes, Composites Parts B: Engineering, 2016,86:pp.214-220. Doi.org/10.1016/j.compositesb.2015.09.059
30. Fung K L, Li Robert K Y, Mechanical Properties of Short Class Fiber Reinforced and Functionalized Rubber-Toughened PET Blends, Polymer Testing,2006,25:pp.923-931.
31. DOI: 10.1016/j.polymertesting.2006.05.013

32. Varughese K T, Chaturvedi B.K, Fly Ash as Fine a Aggregate in Polyester Based Polymer Concrete[J].Cement Concrete Composite,1996,18:pp.105-108.
33. Doi.org/10.1016/0958-9465(95)00006-2
34. Černý R, Poděbradská J, Totová M, et al., Hygro-thermal Properties of Glass fiber Reinforced Cements Subjected to Elevalted Temperature, Scientific Report,2004,37(9):pp.596-608.
35. Doi.org/10.1007/BF02483289
36. DAWOOD Eethar Thanon,RAMLI Mahyuddin.Mechanical Properties of High Strength Flowing Concrete with Hybrid Fibers[J].construction and Building Materials,2012,28(1):pp.193-202.
37. DOI: 10.1016/j.conbuildmat.2011.08.057
38. K Murali Mohan Ra, A V Ratna Prasad, K. Mohan Rao et al. Tensile properties of elephant grass fiber reinforced polyester composites, Journal of Materials Science, 2007,42(9):pp.3266-3272.
39. DOI:10.1007/s10853-006-0657-8
40. Xu Huasheng, Experimental research on artificial granite material for the bed of ultra-precision cylindrical grinder, 2017, Zhengzhou Zhongyuan Institute of Technology
41. https://link.springer.com/article/10.1007/s10853-006-0657-8
42. Standard for evaluation of concrete compressive strength (GB/T 50107-2010).