Research on the Stength Optimization of Carbon Fiber Reinforced RMC based Micromechanical Modeling

Tao Wang, JianHua Zhang, and Yi Zhang

***Abstract*—Carbon fiber reinforced resin mineral composite (RMC) has ten times the vibration alleviating property than cast iron, which can be used to produce the mechanical basic parts of high precision machine tools. Aggregate, resin matrix and fibers are the key component in RMC to bear loads, different component dosage and aggregate gradation design determine the compression strength of RMC directly. An optimal method to determine the critical dimension of aggregate is proposed based on particle interference theory and fractal aggregate gradation is used to adjust the proportion. The micromechanical model of carbon fiber reinforced RMC is established to certify its work mechanism. Carbon fibers are used after combined surface treatment, typical RMC samples are prepared and the compression strength tests are conducted respectively to get effective variation tendency. The optimal design has better compression strength performance and the fibers play an important role in strength reinforcing.**

***Index Terms*—Compression strength, Carbon fiber, Resin mineral composite, Fractal aggregate gradation**

I. Introduction

WITH the development of high-speed and high-precision machining, products now have been provided better machining quality than ever, as well as more precise equipments for other branches of machinery industry [1, 2]. However, vibration generated in the machining process has much more influence on the precision and surface quality of work piece. As a basic component of precision machine tool, machine tool bed plays an important role in vibration absorption. Development of new machine tool bed materials with excellent vibration alleviating property to replace traditional cast iron and steel is one of the effective ways to improve the overall performance of machine tool and reduce environmental pollution in the future, which would also be beneficial for the development of entire industry [3].

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Using natural granite particles as aggregate and organic resin as binder, resin mineral composite (RMC) is a new material which is prepared at room temperature. Compared to cast iron and steel, RMC has about ten times the vibration alleviating properties that it can better absorbs vibrations generated in the machining process, which is more suitable for high speed and high precision machine tool beds [4–7]. However, the application of RMC is restricted by its limitation in mechanical strength, and much research should be done to improve its mechanical properties.

For their better tensile strength and favorable dispersibility, glass fibers and carbon fibers are usually used in fiber reinforced polymer composite and concrete [8, 9]. Current studies show that carbon fibers have significant effects in strengthening the mechanical properties of polymer composites, but they must be treated systematically because their smooth surface [10–14]. So, the influence of combined surface treatment method to the interfacial bonding strength between fiber and resin matrix is also concerned in this paper.

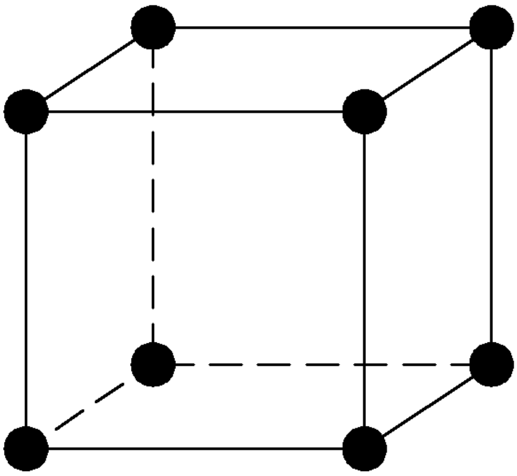
As another one of the key components in RMC to bear loads, the mass fraction of aggregate can be more than 85% of the total weight, its own mineralogy performance and frame strength corresponding to different aggregate gradation influence the mechanical properties of the composite directly. Common gradation design methods include Marshall Design, Superpave Theory, Bailey Method and Fractal Theory, etc, which are mainly applied in cement concrete design and some special uses such as conductive polymers. A good aggregate gradation design should be in principle to wedging theory and be in foundation to filling theory that the best frame strength and porosity performance can be acquired while the coarse aggregate are wedged tightly and the fine aggregate are filled in the interspace [15].

In this article, fractal method and particle interference theory are applied in the aggregate gradation design of RMC. The corresponding simplified assumption is conducted based on the basic principle of Euclidean Geometry. An optimal method to determine critical dimension of aggregate is proposed by considering the dispersion of aggregate in all two-dimension and three-dimension cases. On this basis, the micromechanical model of carbon fiber reinforced RMC is established to certify its work mechanism. In order to validate the aforementioned assumptions, the corresponding samples are designed and compression strength tests are conducted to get effective variation tendency corresponding to different fractal aggregate gradation, resin dosage and combined surface treatment method.

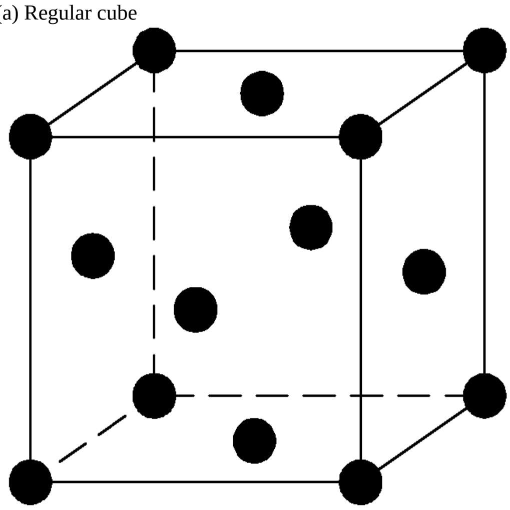
II. MODELING

A. DETERMINATION OF CRITICAL AGGREGATE DIMENSION

How to mix particles of different dimension to reach the most close-grained state is called "Kepler Conjecture" in mathematics. Adopting particle interference and filling theory to determine the critical dimension of aggregate can ensure that particles work together to form a close-grained frame structure. Aggregate system can be classified into coarse aggregate, fine aggregate and mineral powder according to their dimensions. Using mineral powders to fill porosity and avoid segregation phenomenon, which is important to develop uniform RMC.



(a) Regular cube



(b) Face centered cube
Fig.1 Location of aggregates

The aggregate used in RMC are broken and sieved by natural block granite, their shapes and surface characteristics are different from each other, it is difficult to build an accurate filling model. The aggregate shapes are assumed as sphere uniformly. As shown in Fig.1, for aggregates of single dimension R, their location in least close-grained state is regular cube, and the porosity can be calculated as:

$$VV = 1 - \frac{8 \times \frac{4\pi}{3} \times R^3}{(4R)^3} = 1 - \frac{\pi}{6} \approx 48\% \quad (1)$$

Similarly, location of aggregates in most close-grained state is face-centered cube, and the porosity can be calculated as:

$$VV = 1 - \frac{4 \times \frac{4}{3}\pi \times R^3}{(4R)^3} = \frac{\sqrt{2}}{6}\pi \approx 26\% \quad (2)$$

According to the basic content of particle interference theory, porosity can be further reduced by using fine aggregates of proper dimension to fill in the interspaces between coarse aggregates. For example, for aggregates of single dimension R, dimension of subordinate aggregate to fill the interspaces in least and most close-grained state are $(\sqrt{3}-1)R$ and $(\sqrt{2}-1)R$, and the porosity can be reduced to 27.1% and 20.7% respectively.

For the characteristic that lots of schistose aggregate existed, the dispersion of aggregate at two-dimension case is also considered and the subordinate aggregate dimension is acquired as 0.25*R* according to Bailey Model. Percentage of fine aggregate is controlled reasonably in the filling process to avoid suspend-dense structure.

To sum up, the critical dimension between coarse and fine aggregates is determined as $R_{max}/4$, and the critical dimension between fine aggregates and mineral powder is determined as $R_{max}/16$. In order to further reduce segregation phenomenon and control the frame structure, classification is determined in coarse and fine aggregate respectively by using appropriate boundary degree at the range between 0.414*R* and 0.732*R*.

B. EXPERIMENTAL DESIGN BASED ON FRACTAL AGGREGATE GRADATION

The aggregate used in RMC has many irregular characteristics, using fractal theory to discuss the distribution rule of aggregate dimension and to form effective evaluation parameters is necessary for the evaluation and experimental verification. According to fractal theory, for aggregates of dimension *R*, *M(R)* indicates the quality of aggregates that bigger than R, which can be deduced as [16, 17]:

$$M(R) = \frac{R^{3-F} - R_{min}^{3-F}}{R_{max}^{3-F} - R_{min}^{3-F}} \quad (3)$$

Where, *F* is fractal dimension, R_{max} and R_{min} are the maximum and minimum demension of aggregate system. The dimension of mineral powders is far less than the maximum demension of aggregate, the mass distribution function can be simplified as:

$$M'(R) = \left(\frac{R}{R_{max}}\right)^{3-F} \quad (4)$$

Then, more accurate aggregate gradation design can be obtained by adjusting the precision of fractal dimension, as shown in Table I.

TABLE I
AGGREGATE GRADATION EXPERIMENTS CORRESPONDING TO DIFFERENT FRACTAL DIMENSIONS

	1.18mm	2.36mm	9.5mm	15mm	F
1	41.1%	11.2%	32.9%	14.8%	2.65
2	36.2%	11.5%	35.6%	16.7%	2.6
3	31.8%	11.7%	37.9%	18.6%	2.55
4	28.0%	11.7%	39.9%	20.4%	2.5
5	24.7%	11.5%	41.6%	22.2%	2.45
6	21.8%	11.2%	43.0%	24.0%	2.4
7	19.2%	10.9%	44.2%	25.7%	2.35

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C. MICROMECHANICAL MODELING

Compared with resin matrix, carbon fiber has higher elasticity modulus, which can better resist deformation under the same external stress conditon [18]. So, assume that carbon fibers are completely wrapped in resin matrix and no pubbles exist on the interfaces, when an external stress applies on carbon fiber reinforced RMC, the stress will firstly work on resin matrix to produce certain deformation. The stress then transfer to carbon fibers through the bonding interfaces. For their different elasticity modulus, there will be different deformation. Resin matrix have the bigger one than carbon fibers. A strong shearing stress is produced in the bonding interface that it can restrain the propagation of crack, which can better manifest the effect of carbon fibers.

Partial debonding and full debonding model between single fiber and resin matrix are as shown in Fig. 2. Assume that the strength of carbon fiber is stronger enough that no fiber breakage phenomenon occurs, the block process of cross-bridged structure can be subdivided into three stages: partial debonding, full debonding and completely pull out.

F_p and F_f are defined as the drawing stress of partial debonding and full debonding process, which can be expressed as follows:

$$F_p = 2\pi r L_d \mu + F_e \tag{5}$$

$$F_f = 2\pi r (L - \delta)\mu \tag{6}$$

Where r is the radius of carbon fiber, L_d is debonding length, F_e is the stresssupplied by bound segment, L is embedment length of fiber and δ is extracted length of fiber, μ is the coefficient of sliding friction.

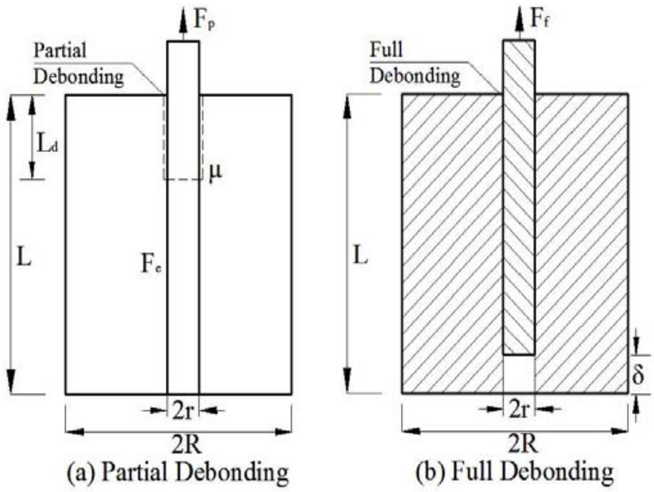

Fig. 2 Interfacial debonding between single fiber and resin matrix

III. EXPERIMENTAL PROCEDURES

A. PREPARATION OF SAMPLES AND COMPRESSION STRENGTH TESTS

The aggregates used in the tests are granite particles produced in Jinan, China. These aggregates aere classified into four groups according to their dimensions in order to maximize compactness and reduce the porosity. The epoxy resin applied is 615A, and stabilizer is ethylenediamine. Acetone is used as diluent to make the liquid composite less mucous. A series of RMC samples are prepared in cube form with 50mm length, 50mm width and 50mm height. The preparation of RMC samples composed of the composite forming process and machining process. Solidification of epoxy resin is exothermic, the moisture among the granite particles may cause air bubbles. As shown in Fig.3, both liquid and solid raw materials are mixed evenly then mixed together to set on the vibration table. Compression strength tests can be conducted after room temperature maintenance for 10 days.

(a) Vibration table

(b) Compression strength test

Fig.3 Preparation of sample and compression strength test

B. COMBINED SURFACE TREATMENT

The surface of carbon fiber is smooth and the surface activity is low that it can not build a strong bonding interface easily between fiber and resin. So, carbon fibers must be treated with combined surface treatment method to improve its surface activity. In this paper, carbon fibers are ultrasonic cleaned in acetone for 30min and dried under 80 centigrade. Then, place fibers in 65% concentrated nitric acid for 1 hour and cleaned too. High temperature oxidation experiment is carried out at 400 centigrade and then placed in KH560 silane coupling agent for 24 hours. Just as shown in the expression below, hydroxyl group on the interface of carbon fibers will

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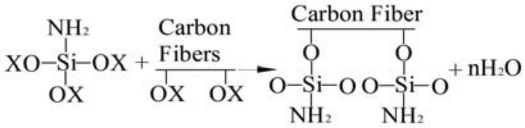
work with silane coupling agent to produce H_2O, which has bigger influence on the strength of RMC. So, the final dying process is necessary and improtant.



Surface morphology of carbon fiber after combined surface treatment is shown in Fig. 4. Due to the etching process of concentrated nitric acid, lots of micro grooves are randomly distributed on the original smooth surface of carbon fiber, which can provide additional meshing force between fiber and resin matrix and produce a more stronger bonding interface state.

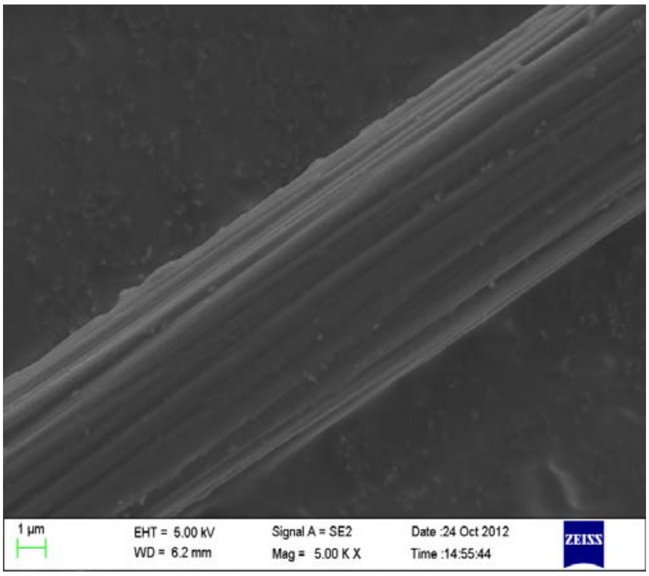


Fig. 4 Surface morphology of carbon fiber with combined treatment×5000

IV. Results and Discussion

A. Variation of Compression Strength

The variation tendency of compression strength is shown in Fig.5. With the reduction of fractal dimensions from 2.65 to 2.35, the compression strength of typical samples increase at first and then decrease. The best and worst strength performance of RMC samples are 130.75MPa and 115.73MPa when the fractal dimensions are 2.45 and 2.65 respectively.

The actual compression strength of aggregate and resin are 170MPa and 85MPa respectively. So that aggregate in RMC is the main part to bear loads with the same bond strength of resin. As shown in Table I, with the constant reduction of fractal dimensions from 2.65 to 2.35, the mass fraction of fine aggregate is reduced and coarse aggregate is increased. The quantity of fine aggregate is far bigger than coarse aggregate during the first stage that coarse aggregates are suspended between fine aggregates, the porosity of fine aggregate plays an important role in the total porosity performance. Following the quantity of fine aggregate reduced till the fractal dimension reach 2.45, coarse aggregate wedged tightly and fine aggregate filled in the interspaces, which means more aggregates used and compression strength achieveed its highest level. Similarly, if fine aggregates were reduced continually, it could not fill in the interspaces of coarse aggregates totally, the compression strength of RMC decreased again.

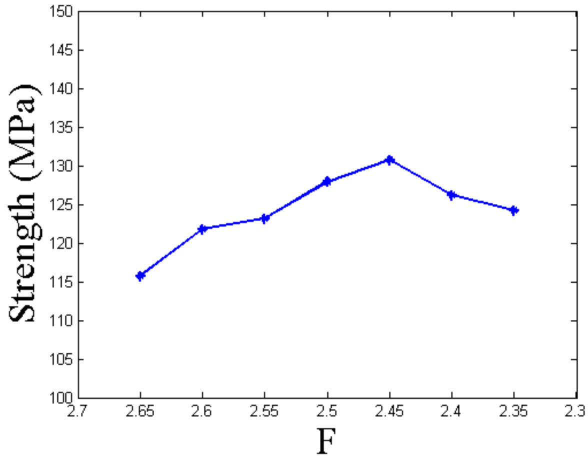


Fig.5 Variation of compression strength

B. Influence of Resin Usage on Compression Strength

The relationship between compression strength of RMC and mass fraction of resin while the fractal dimension is 2.45 is shown in Fig.6. With the mass fraction increasing of resin, compression strength of RMC samples increased at first and then decreased. The best and worst strength performance of RMC samples are 132.19MPa and 109.71MPa when resin dosage are 9% and 7% respectively.

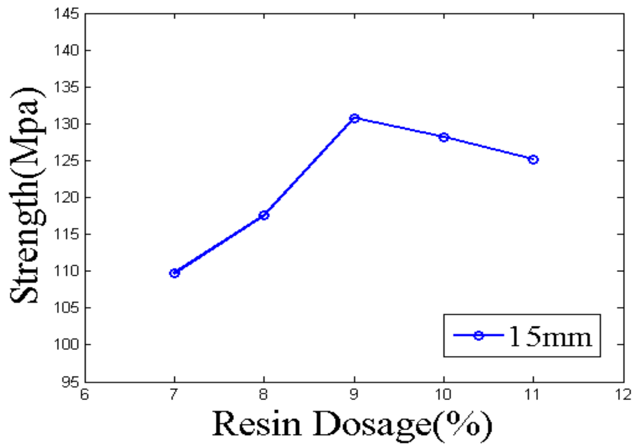


Fig.6 Relationship between strength and resin dosage

Resin dosage at beginning could not fill the interspaces fully and aggregates could not be bounded together completely, which lead to low compression strength. The compression strength of RMC samples increases with mass fraction of resin. Finally, if resin dosage increases continuously, the compression strength decreases for the reason that the mass fraction of aggregate is decreased. The aggregates used for RMC are broken and sieved by natural granite, their shapes and surface characteristics are different. The actual optimum mass fraction of resin might be slightly bigger than 9%.

C. Influence of Combined Surface Treatment Method

Compared with normal RMC samples, by using carbon fibers of combined surface treatment method to reinforce RMC can get a bigger compression strength performance. According to the test of comparative samples, the biggest strength is 143.23MPa, which is increased by nearly 10%.

For the characteristic that carbon fiber reinforced RMC belongs to two phase material, random stess concentration phenomenons are certainty generated in material preparation, resin curing and post processing, which will produce lots of tiny axial cracks and normal cracks randomly distributed on the internal interfaces. Material damage will firstly be produced by the tiny cracks and their extension. Axial crack expansion led to the interface debonding and normal crack expansion led to the cross-bridged structure. Interface debonding phenomenon and cross-bridged structure work together to block the continue expanding of cracks. Its effect depends on the interface bonding strength directly.

According to the expression (5) and (6), a strong interface bonding state is equal to a larger elastic bearing capacity in early debonding stage, which can consume larger external stress in the same debonding length. Similarly, just as shown in Fig. 7, in the later interface debonding stage, more surface attachments are existed on the carbon fibers because of the strong bonding interface between fiber and resin, which is equal to a large coefficient of sliding friction, it can improve the reinforcement effect of fibers effectively. So, strong bonding interface not only can improve the reinforcement effect, but also increases the consumption of internal energy, which will influence the impact toughness indirectly.

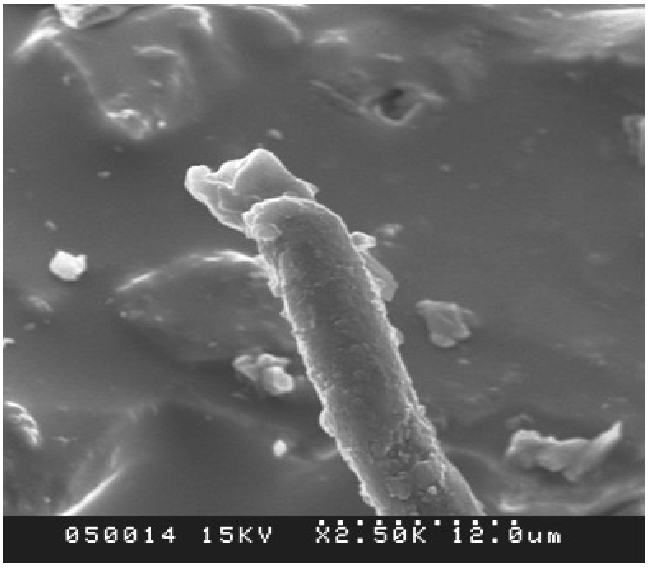


Fig. 7 Surface attachment of carbon fiber

V. Conclusion

(1) Compared with the constant reduction of fractal dimension from 2.65 to 2.35, the compression strength of RMC increase at first and then decrease.

(2) The optimum compression strength of RMC samples is 130.75MPa when the fractal dimension is 2.45, and more accurate aggregate gradation formula can be obtained by adjusting fractal dimension precision.

(3) The best compression strength performance of RMC samples is 132.19MPa when resin dosage is 9%. The aggregates used for RMC are broken and sieved by natural granite, their shapes and surface characteristics are different. The actual optimum mass fraction of resin might be slightly bigger than 9%.

(4) Combined surface treatment of carbon fibers can better improve the bonding strength of interface between fiber and resin, which can better strengthing the compression strength of RMC.

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