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Self-lubricating and Antifriction Characteristics of Three-dimensional Co-continuous Network Graphite / Cast Steel Composites

ZHAN Chunyi[1,2], FENG Shengshan[1,2,a*], WU Weifeng[1,2], BIAN Qingqing[1,2], CHEN Jianli[1,2], HUANG Dong[1,2], WEI Zebin[1], LI Dabao[1], CHEN Zehui[1], ZENG Jincheng[1], TAN Shuixin[1], LI Guancheng[1]

[1]College of Mechanical and automobile Engineering, Guangdong Polytechnic of Science and Technology, Zhuhai 519090, China
[2]Zhuhai Key Laboratory of Advanced Equipment Manufacturing and Material Processing Technology, Zhuhai 519090, China

[a]fss8172@126.com

Abstract. The infiltration casting method is used for the preparation of three-dimensional co-continuous network graphite / cast steel composite material in atmospheric pressure. The friction and abrasion behavior of composite specimen in condition of dry sliding friction are investigated by peg-tray friction abrasion tester. The anti-wear mechanism of composite material is discussed. The results show that the relative wear resistance of the composite material is 6.5～7.1 times of graphitic cast iron, and average friction coefficient is 60.5～73.3% of graphitic cast iron. The composite material provides with good self-lubricating and anti-friction property in condition of dry sliding friction.

1. Introduction

In the field of mechanical equipment, now graphitic cast iron is commonly used as the material for manufacturing important parts such as all kinds of fuselage and guide rail. In the friction and wear processes of graphitic cast iron, a lot of microscopic "pockets" are formed where graphite is worn away, and lubricants can be stored to ensure the continuity of the oil film. Moreover, graphite itself can also be used as a lubricant, so graphitic cast iron has a good wear resistance. Graphitic cast iron also has good castability, damping property and low notch sensitivity, and has good machinability, simple melting ingredients, and low cost. However, with the rapid development of machining technique, all kinds of machine tools are developing towards high precision, high speed and heavy large size. The dynamic load of various important and heavy large mechanical equipment are getting larger and more complex, and related parts produce more and more serious vibration, fatigue and wear, ordinary graphitic cast iron can no longer meet the requirements of modern machine tools. In order to reduce the harm, materials with high strength, damping and wear resistance should be used【1-2】.

Graphitic steel is an ultrahigh-carbon hypereutectoid steel and one part of carbon is precipitated in the form of graphite by proper heat treatment. Graphitic steel has the properties of both steel and cast iron. Its strength is higher than that of graphitic cast iron, but its antifriction, antiwear and damping property are lower than cast iron. Its antifriction property is owed to the supporting framework of the carbides, and antifriction property benefits from the self-lubricating property of the graphite phase【3】.

If the graphite is added, its antifriction and wear resistance will be improved. However, there will be too much carbide, and the graphite in the molten steel will be unevenly distributed due to floating during the melting and casting process, which will significantly reduce its toughness and strength. Therefore, the graphite content in spheroidal graphite cast steel generally cannot exceed 2.0%, and its performance improvement space is limited.

The three-dimensional continuous network structure metal matrix composite material is a research field of new composite material that has been paid more and more attention by material researchers at home and abroad over the past decade. The composite has a completely different spatial topology from the traditional composite material, that is, the metal matrix phase and the composite phase (or modified phase) are continuous (connected) in the three-dimensional space, and exhibit an interleaving network structure. The structure makes this material have very unique mechanical properties, physical properties and chemical properties, and has isotropic properties, , and has the potential to be used as antifriction / antiwear materials, high vibration damping / sound insulation material [4-10]. We took the lead in studying the three-dimensional network structure silicon carbide / graphitic cast iron atmospheric pressure casting composite at home and abroad, hoping that it has excellent wear resistance and good damping property, which can be used to replace gray iron to make important castings such as fuselage and guide rails. The relative wear resistance of the three-dimensional network structure silicon carbide / grey iron composite we prepared is as high as 4.7 times to 7.9 times of the graphitic cast iron, its average friction coefficient is 46% to 89% of graphitic cast iron, its amplitude attenuation is faster than that of graphitic cast iron, and its damping effect is obvious [11-12]. However, the strength is not as good as graphitic cast iron, and it is difficult to meet the performance requirements of more and more developed and heavy mechanical equipments.

For this reason, we first proposed the following conception of research at home and abroad: using cast steel as the metal matrix phase and flake graphite as the composite phase (modified phase), by using the infiltration casting method to prepare the three-dimensional co-continuous network graphite / cast steel composites. The composite has good technical feasibility as a new antiwear / vibration damping composite.

2. Sample preparation

The conventional method for preparing the three-dimensional network structure ceramic / metal composite is pressure casting infiltration method at present. The metal liquid overcomes the permeation resistance under pressure, so that the casting infiltration can be completed. However, the process of the pressure casting infiltration method is complicated, the operation and control are inconvenient, and the production cost is high.

First, we prepare the three-dimensional co-continuous network graphite preform by using foam precursor coating method, drying and curing below 400℃, then coat the surface of foam precursor skeleton with metal, and prepare the three-dimensional co-continuous network graphite / cast steel composite by using the infiltration casting method. That is, the molten metal penetrates into the porous preform at normal pressure after all the external loads are removed. The method for preparing composite material by penetrating metal melt into the porous preform without exterior load under normal pressure can simplify the preparation technology, reduce the production cost, and easy to realize industrialization production.

Coating the surface of foam precursor with metal, that is, coating one or more layers metallized film that has good compatibility with graphite and molten metal on the surface of the ceramic skeleton. There are two purposes: one is to further improve infiltration conditions of the graphite / steel interface and enhance the wetting and infiltration casting capacity of the steel to the graphite, thereby improving the mechanical properties of the composite; the second is to further improve the high temperature strength of foam graphite preform after the medium temperature heating in order to avoid losing strength prematurely and destroy the network structure when subsequent molten steel is poured.

Before metal-modification, the surface of the graphite preform needs to be pretreated as follows: remove oil stain and oxide layer and other adhered or adsorbed matter, clean the surface of the graphite skeleton, so that the living tissue is exposed, to ensure that the coating layer has good adhesion.

The pretreatment process of this experiment is: use ethanol to clean the ceramic parts, and then put them into a constant temperature and humidity drying oven at 100 ℃ to dry and store for use.

In this study the following two ways are used to metallize the ceramic surface:

(1) Metallization process of Ni-Cr-Fe

The specific process of this Ni-Cr-Fe metallization process is: use the ethanol solution of polyvinyl butyral and phenolic resin to make the alloy powder into slurry with proper viscosity, dip on the surface of the pre-treated graphite preform, and then put them into a constant temperture and humidity oven to dry and store.

According to the solid / liquid phase bonding mechanism, coating slurry containing Ni, Cr, Fe alloy powder on the surface of graphite sintered body can form boundary diffusion or reaction layer.

(2) Metallization process of Cu-Cr-Ti

When copper is bonded to materials with different expansion coefficient at high temperature, it can relieve the stress generated by the bonding interface, and after the copper is melted, it can soak graphite better than steel, or permeate the graphite body, thereby enhancing the bonding force between graphite and cast steel. Some articles introduce [13-14] that adding appropriate content (12-16%) of Ti or Cr to Cu can reduce the wetting angle of Cu and C 140 ° to a wetting angle of below or equal to 23°at 1100°C. Generally, when the wetting angle is below or equal to 70°, a good interfacial bonding can be formed.

Therefore,in this study we also tested the metallization process of Cu-Cr-Ti. The specific process is similar to Ni-Cr-Fe metallization.

In this study, the macro-morphology of the composite material specimen (the pore size of the foam ceramic preform used is 8ppi) prepared by normal pressure casting infiltration method is shown in Figure 1.

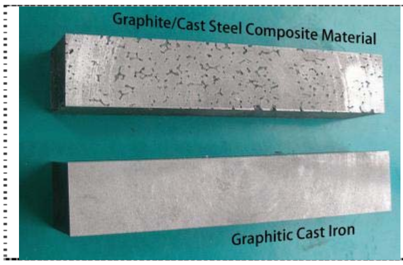

Figure 1. Macro-morphology of co-continuous network graphite / cast steel composites and HT150 graphitic cast iron specimen

3. Test equipment and method

The test performance equipment used in this study is XP-1 friction and wear tester and its data acquisition system, spiral micrometer. We combined the composite whose dimension are 10×10×15mm and the HT150 graphitic cast iron friction and wear specimen for comparison respectively with the sand plate whose dimension are Φ43mm×10mm to form a fiction pair, and conduct dry friction and wear test under pure sliding conditions.

Grind the ground surface of the specimen from coarse to fine with sandpaper and then polish it. The rotational speed of the test machine is 100 r / min, the corresponding linear speed is 0.2 m / s, and the frictional load is 30 N. After five minutes' running-in, measure the initial thickness of the sample with a screw micrometer, and then continuously wear for 30 minutes to determine the final thickness and friction coefficient of the specimen. The friction coefficient is automatically collected by the data acquisition card and stored in the computer, and the result is averaged.

The antifriction and antiwear ability of the specimen is expressed by relative wear resistance, which is the ratio of the thickness decrement of the graphitic cast iron and the composite material samples under the same test condition.

4. Experimental results and analysis

4.1. Friction coefficient

Table 1 lists out the average friction coefficient of the three-dimensional co-continuous network graphite / cast steel composites and the HT150 graphitic cast iron specimen for contrast under the equal load.

Table 1. The average friction coefficient of the composite material specimen and graphitic cast iron for comparison under the equal load.

Sample No.	1#	2#	3#
Material type	Graphitic cast iron	Composites	Composites
Metallization process of graphite preform	—	Ni-Cr-Fe method	Cu-Cr-Ti method
Average friction coefficient	0.476	0.349	0.288

The friction pairs in this study are composites and HT150 graphitic cast iron pins specimen and SiC sand discs, which are all dry friction.

The friction between the graphitic cast iron specimen pin and the SiC sand disc mainly belongs to abrasive wear and adhesive wear. The friction process between the graphite / cast steel composites specimen pin and the SiC sand disc is more complicated. The beginning stage is mainly abrasive wear, as the graphite is cut and spread to lubricating film, it may change to boundary lubrication conditions, that is mainly adhesive wear.

In this experiment, the average friction coefficients of the two composite materials are 0.349 and 0.288, which are significantly lower than that of graphitic cast iron 0.476, among which the average friction coefficient of the composite material specimen which is made from the network graphite preform after Ni-Cr-Fe metallization treatment is 73.3%, and the specimen after Cu-Cr-Ti metallization treatment is only 60.5%. Due to the uniform distribution of graphite network in the composites, as the graphite is cut during friction process, a uniformly distributed graphite film will be formed through diffusion at the interface of the friction pair, and in-situ lubrication is produced. The friction state changes from the initial abrasive wear to self-lubricating, which reduce the friction coefficient of the material and then maintain a certain stability. The network metal phase in the three-dimensional co-continuous network graphite / cast steel composite material forms hard asperity on the worn surface and plays the role of load bearing. At the same time, its unique structure restricts the plastic deformation and high temperature softening of the matrix cast steel, making the graphite film formed on the worn surface not easy to damage and reduces the adhesive wear, so that the average friction coefficient of the composites is lower than graphitic cast iron.

Figure 2 shows the relation of friction coefficient and friction time of the three-dimensional co-continuous network graphite / cast steel composite specimen and the comparative specimen HT150 graphitic cast iron prepared by the graphite foam preform treated by different metallization methods under the same load.

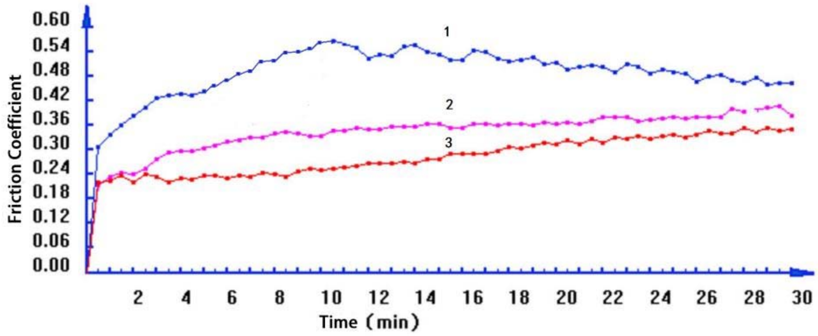

Figure 2. The relation of friction coefficient and friction time of composite material and graphitic cast iron.

1- graphitic cast iron 2- the composite material that graphite foam preform is treated by Ni-Cr-Fe

3- the composite material that graphite foam preform is treated by Cu-Cr-Ti

For graphitic cast iron specimen, under a certain load, as the friction time increases, the material friction coefficient μ will gradually decrease and tend to be stable. This is due to the fact that the temperature of the material surface is low in initial stage of friction, and the mechanical engagement theory caused by the uneven friction surface plays a leading role, so the friction coefficient is large. As the friction time is further increased, the temperature of the friction surface is increased due to the absorption of energy, which leads to decrease in the shear strength of the molecular bond at the bonding point, and the friction coefficient gradually decreases. When oxide forms on the friction surface, the friction coefficient gradually tends to be stable, as shown in line 1 of Figure 2.

The research shows that, for the three-dimensional co-continuous network graphite / cast steel composites, under a certain load, with friction time prolonged (within 30 minutes) , the friction coefficient μ of the material is tending to a steady state, increasing rather than decreasing slowly. It is likely that after the network graphite preform is metalized, the affinity of Cr, Ti and C in the metalized layer is strong, and it reacts with C during high-temperature molten steel pouring to form hard brittle metallic carbide, which makes the shear strength of the graphite film increase, resulting in increased friction resistance. At the same time, the metallic carbide hard spots cut from the friction surface of the composite specimen and the SiC abrasive dust worn away from the SiC sand disc are partly left on the friction interface, which produces abrasive wear to a certain extent and delays the process of reaching steady state.

4.2. Wear resistance

Table 2 shows the contrast result of wear degree between graphitic cast iron and composite material under the same experimental condition.

Table 2. The contrast of wear degree of graphitic cast iron and composite material specimen

under the same loading.

Sample No.	1#	2#	3#
Material type	graphitic cast iron	Composites	Composites
Metallization process of graphite preform	—	Ni-Cr-Fe method	Cu-Cr-Ti method
Thickness decrement（mm）	0.78	0.12	0.11
Relative wear resistance	1	6.5	7.1

It can be seen from the above table that the thickness decrement of the three-dimensional co-continuous network graphite / cast steel composite specimen is much lower than that of graphitic cast iron, and the relative wear resistance of the composite is as high as 6.5 to 7.1 times of graphitic cast iron.

It can be seen by comparing Table 1 and Table 2: Under the same test condition, the smaller the friction coefficient of the composite material, the better the self-lubricating property, the lower the frictional resistance to the grinding body. Therefore, the smaller the wear loss, the higher the wear resistance.

5. Conclusion

(1) In this experiment, the graphite preform after the Ni-Cr-Fe and Cu-Cr-Ti metallization process, the average friction coefficient of the composite material of the graphite preform is reduced to 73.3% and 60.5% of the graphitic cast iron.

(2) Under dry friction and wear conditions, the relative wear resistance of the three-dimensional co-continuous network graphite / cast steel composite material is as high as 6.5 to 7.1 times of graphitic cast iron.

(3) Due to the uniform distribution of the graphite network, the three-dimensional co-continuous network structure graphite / cast steel composites produce in-situ lubrication. The network metal phase forms hard asperity on the worn surface and plays the role of load bearing. At the same time, its unique structure restricts the plastic deformation and high temperature softening of the matrix cast steel, reduces the adhesive wear, and it is beneficial to the retention of the oxide film on the worn surface. Therefore, the composites show a lower friction coefficient and good wear resistance.

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