# On the Preparation and Wear Properties of Ceramic Particle-reinforced High-chromium Cast Iron-based Surface Composite Material

Zhaobin Zheng

Quanzhou Arts and Crafts Vocational College, Dehua, Fujian, 362500, China

**Abstract.** In this study, we successfully developed a composite material that can enhance the local wear resistance of high-chromium cast iron matrix by using 203 and ZTA (ZrO2-toughened Al2O3) ceramic particles and high-chromium cast iron as the basic raw materials, using the preparation methods of melt casting infiltration and porous ceramic preform. The specific operation steps were as follows: firstly, nickel treatment was carried out on the ceramic fragments, and then the treated ceramic fragments were mixed with the preset adhesive and poured into a mold with honeycomb-shaped voids. After pressurization and heating, its texture gradually strengthened, and finally a porous ceramic preform with a honeycomb shape was formed. After that, the preform was stably placed inside the sand mold to prevent the casting from getting worn. After that, it was filled monolithically and penetrated by a high-chromium cast iron metal fluid, thus forming a composite wear-resistant layer composed of ceramics and metals.

**Keywords:** composite material, casting infiltration method, high-chromium cast iron, porous ceramic preform, three-body abrasive wear.

## 1. Introduction

In the process of industrial manufacturing, in numerous industries such as coal-fired power plants, cement, steel, and mining, the equipment operates in harsh environments, posing strict requirements for the comprehensive properties of their operational components, including heat resistance, wear resistance, and impact resistance. Materials with only one property can no longer satisfy the needs of these environments. For this reason, research on various types of ceramic particle-reinforced wear-resistant materials has garnered increasing attention [1-3]. Wang Enze and his team successfully produced a composite material called alumina-reinforced heat-resistant steel by using negative pressure casting infiltration technology. After deep exploration, we found that under the wear condition of 900°C, when the content of Al2O3 reached 39%, the composite material had the best wear resistance, which was 3.27 times that of heat-resistant steel. Dong Xiaorong and her team [3] successfully adopted the method of cast-sintering to produce ZTA ceramic particles, with the purpose of improving the efficiency of high-chromium cast iron-based composite materials. They also discussed ways to improve the overall properties of ZTA ceramics by means of cast-sintering process. Through comparison, we found that after heat treatment, the hardness of ZTA ceramics grew by 2.65 times, and its wear resistance also grew by 1.52 times.

In this study, we employed the approach of alloying ZTA ceramic particles to enhance their adhesion with the metal matrix and strengthen the wear performance of the composite material. Furthermore, the utilization of an open-type negative pressure casting technology ensured consistent temperature distribution of the ceramic prototype during the infusion stage, thereby enhancing the close connection between the ceramic prototype and the metal base. This ultimately resulted in the production of a composite material exhibiting excellent hardness and toughness of chrome cast iron.

## 2. Experimental Materials and Methods for Preparing Ceramic Particle-reinforced High-chromium Cast Iron-based Surface Composite Material

### 2.1 Selection of Experimental Materials

Typically, the particle size of ZTA ceramics was set between -10 and +16 meshes, which not only avoided their fracture when subjected to a strong impact, but also guaranteed the adhesion between the matrix and ceramic particles, and avoided direct falling during wear. Therefore, this method can fully exert the advantages of the mixture of ceramics and metals. See Tab. 1 for details.

Tab. 1 Physical/Mechanical Properties of ZTA Ceramic Particles

| Material: | Density /(g/cm) | Microhardness (HV) | Thermal Expansion Coefficient /10(°C) | Fracture Toughness /(MPa·m2) | Flexural Strength /Mpa |
|---|---|---|---|---|---|
| ZTA: | 4.0~6.0 | 1 800~2 100 | 7.5~9.0 | 6.5~9.0 | 340~550 |

Tab.2 displays the composition of NiCrBSi alloy, a chosen nickel-based material. The essence of this technology lay in coating nickel on the surface of ceramic particles and conducting alloying treatment through vacuum sintering to improve the adhesion between high-chromium cast iron and ceramic particles, making their contact area more wetted.

Tab.2 The Chemical Composition of the NiCrBSi Alloy w(%)

| Element | B | Cr | Co | Ni | Si | W | Fe |
|---|---|---|---|---|---|---|---|
| Content | 4.5~6.5 | 45~7.0 | 0.5~1.5 | 6.0~9.0 | 3.0~5.0 | 0.8~1.8 | Fe |

### 2.2 Manufacturing Process of the Composite Material

Below is the manufacturing process of ZTA/high-chromium cast iron composite materials by using powder metallurgy technology:

(1) Metal alloy: Coat the surface of -10~+16 mesh ZTA ceramic particles using a nickel-based alloy, followed by baking and vacuum sintering to obtain ZTA ceramic particles with metal alloy properties.

(2) Mix materials: Mix the alloyed ZTA ceramic powder with a self-prepared binder according to a specified ratio to form a balanced mixture.

(3) Production process: Put the above mixture into a self-made honeycomb-shaped mold for shaping and drying, to obtain a honeycomb-shaped ceramic prototype.

(4) Production process: To begin with, sinter the dried ceramic material at 1250-1350°C for 90-150 min, and then fix the ceramic particles with a self-prepared binder to form honeycomb-shaped ceramic raw material.

(5) Casting infiltration: Install the prefabricated part on the exterior of the casting mold, infuse by using water pipes and negative pressure input, at the temperature of 1400-1500°C, to generate ZTA ceramic particles and enhance the wear resistance of high-chromium cast iron composites. Select Cr20 high-chromium cast iron as the base material, for it has high wear resistance, toughness and safety, and is capable of controlling interfacial stress and avoiding cracks. Tab. 3 displays its chemical composition. The heat treatment steps of the composite material were: to heat to 980-1050°C, cool for 6 hours, then return to 250-280°C.

Tab.3 The Chemical Composition of Cr20 Alloy w(%)

| Element | c | si | Mn | P | s | Cr | Mo | ni | Re |
|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Content | 2.3-3.0 | ≤1.0 | 0.6-1.0 | ≤0.05 | ≤0.05 | 18~23 | 1.0-1.5 | 0.8-1.0 | 0.3 |

### 2.3 Block-on-ring Three-body Wear Test

We carried out friction and wear tests using a MMH-5 block-on-ring wear test device, with the test sample being 24 mm wide. The principle of the wear test was: The bottom sample (quenched 45 steel rail) was covered with 70-mesh quartz sand, while the top sample (composite material/high-chromium cast iron) rotated stably within it in a circular manner.

The steps of the abrasive wear test were: The pressure of a single bearing was set to 3 kg, and the rotation speed of the spindle was adjusted to 30 rad/min. After 5 min of pre-treatment, a 1 mg BSA224S electronic balance was used to test the mass, 30 min each time, for 150 min in total. Finally, an S-3400N scanning electron microscope was adopted to carry out microstructure analysis and explore the wear surface of the composite material/high-chromium cast iron.

## 3. Experimental Results and Discussion

### 3.1 Study on the Morphology of the Composite Material

The ground ZTA ceramic particles may influence the overall appearance of the reinforced composite material. The ZTA particles were evenly distributed inside the preform, and after casting and infiltration treatment, the voids among the ZTA ceramic preform particles were completely filled by high-chromium cast iron material, thus forming a close connection between the particles and the material, without any void. High-chromium cast iron provided a strong support for the ceramic particles, allowing them to act as a cushion against impact and preventing brittle fracture.

Liquid metal exhibited good permeability and can penetrate the wall of honeycomb-shaped units, overcoming the issue of insufficient permeability of liquid metal in certain directions, thereby enhancing the adhesion between ZTA ceramic particles and high-chromium cast iron base material. Using a fully enclosed pouring path for negative pressure casting can ensure a more even temperature distribution of honeycomb-shaped ceramic preform, avoiding vulnerability issues due to local overheating, and better maintaining their original honeycomb shape.

We carried out an in-depth study on the connection between ZTA ceramic particles and high-chromium cast iron using the JSM-6510 SEM and successfully obtained an accurate interpretation of SEM images. Given the fine morphology of the ZTA-reinforced composite material and absence of shrinkage cavity and other defects, their permeability significantly improved during the preparation. At high temperatures, the ZTA ceramic particles didn't react with high-chromium cast iron, but were tightly bonded to the metal matrix by mechanical means. Since the surface of the ZTA ceramic particles was alloyed, they can be firmly fixed on the high-chromium cast iron material, which greatly improved their binding force with the metal matrix, effectively prevented the ceramic particles from dropping during wear, and further improved the wear resistance of the composite material.

### 3.2 Analysis of the Wear Properties of the Composite Material

As for the volume loss of composite material and high-chromium cast iron base material in the block-on-ring three-body abrasive wear test, through an in-depth comparative analysis, we found that during wear, the volume loss of the composite material was significantly less than that of the high-chromium cast iron base material. As manifested by numerical analysis, the three-body wear resistance of the ZTA composite material was 4.85 times better than that of high-chromium cast iron.

The SEM images displayed the morphology of high-chromium cast iron and composite material after wear. Under three-body abrasive wear, high-chromium cast iron mainly experienced wear at the microscopic level. During this process, due to the high hardness of quartz sand, its sharp parts penetrated the base layer, generated many lips and flips and formed deep grooves. There were two main wear modes for the composite material: one was that high-chromium cast iron metal had micro cutting wear and the other was that the ceramic particles experienced brittle fracture or directly fell off under pressure. After wear, there were significantly more ZTA ceramic particles than the composite material and high-chromium cast iron base. In addition, these ceramic particles were tightly bound to the metal matrix without any void. In the process of wear, ceramic particles and metal matrix formed relatively deep cracks, primarily due to the load-bearing characteristic of ceramic particles, which can effectively block the intense cutting of metal matrix, trigger a “shadow effect” and gradually reduce the wear area of the matrix. For this reason, compared with the base material, the wear resistance of the composite material was significantly improved, and the loss of its absolute volume also gradually decreased with the wear. 、

## 4. Actual Applications of Rollers and Liners

In order to test the performance of developed composite material in the practical environment, some companies had applied it to the field of thermal power generation, and successfully produced medium-speed coal mill rollers and liners, which were introduced by a domestic power plant. After one year of use, the wear condition of the ZTA ceramic particle-reinforced metal composite rollers and liners that we made was as follows. The overall thickness of the honeycomb-shaped composite wear resistance of rollers and liners was 70mm (the thickness of the ceramic layer was 35mm), and the wear degree of the ceramic layer thereof was about 6mm and 4mm. Through on-site observation and explication, it was found that with the extension of grinding cycle, the honeycomb-shaped ceramic layer on the surface of the high-chromium cast iron-based material became more prominent. This indicated that the wear resistance of the ceramic material was superior to that of high-chromium cast iron, and mainly played a wear-resistant part, which was highly consistent with our previous simulation in the laboratory. It was expected that the durability of the rollers and liners would be 2-3 times that of the original high-chromium cast iron.

## 5. Analysis of Three-body Abrasive Wear Mechanism

### 5.1 Application of the Three-body Abrasive Wear Mechanism in the Ceramic Particle-reinforced Iron-based Composite Material

In the three-body abrasive wear environment, there were two wear modes for materials: one was the friction between the sharp part of the abrasive material and metal shell, i.e., micro-cuttings, which occurred at the furrow of surface layer. The other was continuous deformation of the object when it was under pressure, leading to fatigue and destruction and resulting in peeling and damage. When the iron-based wear-resistant composite material underwent three-body abrasive wear, ceramic particles can improve their wear resistance. As the most wear-resistant part, ceramic particles bore the majority of the wear, while the base material provided stability and support for these ceramic particles. A physical model described the three-body abrasive wear process of the ceramic particle-reinforced iron-based composite material. Before the wear, the ceramic particles and the matrix were at the same level. At the early stage of wear, as the wear progressed, the high hardness of ceramics effectively prevented damage from the grindstone, while the matrix, with low hardness, was easily impacted and excavated by the hard grindstone. Due to severe groove wear, the loss of matrix material first increased and then gradually decreased. At this stage, the volume loss of the composite material was also relatively large.

At the middle stage of wear, the ceramic particles experienced significantly higher levels of wear compared to the matrix, leading them to bear the primary wear and creating a “shadow effect” on the matrix. In the main wear area, the metal structure suffered considerable damage, whereas in other regions, the slope of the metal structure was more pronounced. The lower slope resulted in less material consumption, meaning that when the abrasive cut the metal matrix, it was constrained by protruding ceramic particles, thus avoiding excessive loss of the metal matrix around the ceramic particles. Additionally, the matrix material exhibited good elasticity, providing support for the ceramic particles and effectively reducing wear during the mid-stage through synergistic effects.

At the advanced stage of wear, the ceramic particles were widely dispersed due to the excessive loss of matrix material. In an exposed wear environment, ceramic particles might fracture, weakening the matrix's support for them. With diminishing support force, the bonding strength between the ceramic particles and the matrix decreased, causing all ceramic particles to drop off. This stage resulted in significant volume loss of the composite material. Following the damage of the surface of the composite material, new ceramic particles would protrude, restoring the composite material to its initial wear state.

### 5.2 Study on the Wear Resistance of Ceramic Particle-reinforced Iron-based Composite Materials with Different Compositions

The microstructures of No. 203 high-chromium cast iron, ZTA (25.30% ZrO2), ZTA (55.60% ZrO2), and high-chromium cast iron matrix after three-body abrasive wear were studied. By comparing the SEM images, we can clearly see that in the three-body abrasive wear process, the pure base 203, high-chromium cast iron, and two types of high-chromium cast iron composite materials with ZTA (25.30% ZrO2) all contributed to the enhancement of the wear resistance of the composite material, the ceramic particles didn't prominently protrude from the matrix, but were almost worn together with the matrix. By observing the wear curve, we can see that this approach didn't significantly enhance the wear resistance of the composite material. The wear resistance of the high-chromium cast iron composite material with ZTA (55.60% ZrO2) was found to be relatively low because of the presence of ceramic particles that were significantly higher than the matrix in terms of quantity. However, as the high-chromium cast iron matrix experienced severe wear, the surface carbides began to peel off, creating deep cracks in certain areas. Experimental tests demonstrated that increasing the hardness of ceramic particles didn't lead to improved wear resistance. As a matter of fact, the toughness of ceramic particles alone was the key factor affecting the wear resistance of composite material.

## 6. Conclusion

In this study, vacuum sintering was employed to coat nickel alloy on the surface of ceramic particles, followed by processes including mixing, mold compaction, and sintering to produce a honeycomb-shaped preform. Subsequently, negative pressure casting technology was utilized to successfully fabricate ZTA ceramic particle-reinforced high-chromium cast iron-based composite material. Our research demonstrated that in a three-body abrasive wear environment, ZTA ceramic particles enhanced the wear resistance of high-chromium cast iron composite material by 4.85 times. Furthermore, our study revealed several key findings. Firstly, utilizing locally reinforced ceramics to repair the most severely worn parts in wear-resistant components not only improved their wear resistance, but also maintained the overall elasticity of the workpiece. Secondly, mixing the ceramic particles with the self-prepared binder to create a honeycomb-shaped porous ceramic preform can significantly improve the permeability of casting, increased the thickness of the composite layer, and prevented excessive brittleness in the composite layer. Thirdly, we investigated the effect of the hardness, elasticity and size of ceramic particles on the wear resistance of the composite material by constructing complexes using ceramic particles with varying parameters and conducting three-body abrasive wear tests.

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