Effect of different preform structures on interfacial microstructure and wear properties of WC/Fe composites material

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Abstract
The WC preform was prepared by vacuum sintering, and a WC/Fe composite was obtained by an infiltration casting process with different preform structures. The microstructure of the composite was characterized by scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and x-ray diffraction (XRD), and the wear properties of the three-body abrasives were further studied. The temperature field and solid- liquid variable field of the WC/Fe composite were simulated using finite element software. The results show that the microstructure of the WC/Fe composite contains WC, Ni3Fe, Ni17W3Fe3W3C, and M7C3 carbides. With an increase in the preform column spacing from 10 mm to 20 mm, the width of the transition layer of the WC/Fe composite increased, and the hardness increased from 749 HV to 853 HV. The mass loss of the WC/Fe composite decreased initially and then increased with an increase in the preform column spacing. The microstructure and wear resistance of materials are related to the W content in the transition layer, and the diffusion behavior of W is affected by the diffusion distance and time.

1. Introduction
Recent technological developments in the wear-resistant materials industry, equipment replacement, and process upgrades have been gradually applied to metallurgy, mining, machinery, building, and other industries [1–4]. As the requirements of modern industry become more demanding, the service conditions of wear-resistant materials are becoming increasingly complex. Compared with single-metal wear-resistant materials, ceramic particle-reinforced metal matrix composites prepared by the casting infiltration method have attracted increasing attention owing to their stable structure and excellent wear resistance [5]. In these composites, ceramic particles are added to a metal matrix, and the composite materials have high plastic toughness and hardness. This method provides a good research direction for optimizing the design of traditional steel wear-resistant materials. The most common composite ceramics include WC, Al2O3, ZrO2, TiC, and SiC [6–9]. Zheng et al. [10, 11] studied the wear behavior of CPRCs with different ZTA volume fractions. The results showed that under a lower stress load, the wear resistance was significantly improved. However, under higher stress loads, insufficient interface bonding strength causes the ZTA ceramic particles to peel off, and the wear resistance decreases. This is because of the poor wettability between the ZTA ceramic particles and the matrix. In contrast, the wetting angle between WC ceramic particles and steel is almost zero [12], which allows the formation of a good interface structure and greatly enhances the interfacial bonding strength. Compared with high-chromium cast iron, Li et al. [13] produced WC/high chromium white cast iron (WC/Fe), where the wear resistance of the composite was significantly improved.

However, most of the area of the composites with the WC/Fe matrix comprised a uniform lamellar design. Although this design plays a role in protecting the matrix and improving the wear resistance of materials [14], with increasingly harsh service conditions, it is increasingly difficult for layered composites to meet the...
requirements of use. The main problems are as follows [15]: first, the preform of the layered composite material has low strength, and the bottom is thin, with infiltrated molten metal. Second, the poor impregnation effect leads to the formation of shrinkage cavities, cold barriers, and other casting defects during cooling and solidification of the molten metal, which greatly reduces the performance of the material. Therefore, an increasing number of scholars have begun to explore non-uniform complex configurations of materials and found that a non-homogeneous composite configuration is more conducive for promoting synergy between different components of the composite [16, 17]. Lu Dehong et al [18] used 3D printing technology to prepare a framework with a three-dimensional configuration, filled ceramic particles into the pores of the framework, and sintered the filled framework to form a ceramic particle preform skeleton. A ZTA/40Cr three-dimensional interpenetrating network composite was prepared using the squeeze casting molding technology. The impact abrasive wear performance of the material was better than that of conventional composite materials, and the wear rate was 31.24% lower than that of conventional composite materials. Wong et al [19] prepared a ring-shaped Mg-Mg/Al$_2$O$_3$ composite material. The strength of this configuration is slightly lower than that of the layered Mg-Al$_2$O$_3$ composite material of the same composition, but the plasticity if the former is significantly higher. However, there are few studies on the effect of element diffusion on the properties of composites with variation of different structural parameters.

In this study, vacuum sintering is used to prepare high-strength preform columns, and WC/Fe composites are prepared using the infiltration casting method. The effect of the preform structure on the interface microstructure and wear resistance of the composite is studied for a given column to column diameter ratio and column distance. The temperature field and solid-liquid phase field of WC-reinforced high-chromium cast iron matrix composites during solidification are numerically simulated using COMSOL Multiphysics. Through the secondary development program, the distribution of W around the preform is numerically simulated to reveal the mechanism by which the column distance influences the W diffusion behavior. The influence of the diffusion behavior of W on the wear properties of WC/Fe composites is studied, providing a theoretical basis for engineering applications.

### 2. Experimental procedures

#### 2.1. Preparation of composite materials

The composite materials were prepared by sintering the preform and infiltration molding of high-chromium cast iron. The WC particles, Ni powder, and Ni60 alloy powders were subjected to vacuum ball-milling at a mass ratio of 5:4:1 at a speed of 250 r min$^{-1}$, and were ball-milled for 4 h. Each ball was made of stainless steel. The chemical compositions of the mixed powders are shown in table 1. The mixed powder was cold pressed for 10 min with a load of 300 kN. The preform in the vacuum sintering furnace was heated as follows: the sample was heated from 20 °C to 500 °C at a heating rate of 5 °C min$^{-1}$, then from 500 °C to 800 °C at a heating rate of 10 °C min$^{-1}$, and from 800 °C to 1000 °C at a heating rate of 3 °C min$^{-1}$, and finally maintained at 1000 °C for 1 h. Table 2 shows the structural parameters of the preform. The sample with 5 mm column diameter and 10 mm column distance, sample with 7.5 mm column diameter and 15 mm column distance, and sample with 10 mm column diameter and 20 mm column distance are called A1, A2, and A3, respectively. Cr22 is termed A0 as a comparison sample, and its chemical composition is shown in table 3. A discontinuous distribution rod-reinforced composite with a certain metallurgical bonding layer was prepared by sand mold casting. Figures 1(a)–(b) show the process for preparing the WC/Fe composite. The casting temperature was set to 1550 °C.

| Table 1. Chemical composition of WC preform (wt.%). |
| --- | --- | --- |
| WC (150–180 μm) | Ni (40–50 μm) | Ni60 (60–90 μm) |
| 50 | 40 | 10 |

| Table 2. Structural characteristics of preform. |
| --- | --- | --- | --- |
| Diameter $D$ (mm) | Distance $L$ (mm) | Amount | Height (mm) |
| A1 | 5 | 10 | 12 | 15 |
| A2 | 7.5 | 15 | 5 | 15 |
| A3 | 10 | 20 | 3 | 15 |
2.2. Examination and analysis of test specimen
A Shimadzu 7000 S XRD instrument was used to characterize the phase composition. An EVO18 scanning electron microscope was used to observe the microstructure and wear morphology, and a GENESIS energy spectrometer was used to analyze the elemental distribution of the composite material interface. The microhardness of the sample was tested using the HX1000 microhardness tester of the Shanghai Optical Instrument Factory.

2.3. Three-body abrasion wear test
The wear resistance of the composites was measured using a reciprocating wear tester at room temperature. The grinding track was hot-rolled AISI1020 steel with a hardness of 150 HV. The abrasive was 40–70 mesh silicon oxide (SiO₂, hardness: 800–900 HV). The three-body abrasive wear specimen was fixed on the abrasive testing machine and a 600 N load was applied. Figure 2(a) shows a schematic diagram of the three-body abrasive wear test. The horizontal speed of the testing machine was 1500 mm min⁻¹. Each wear sample was pre-ground for 60 min. The single wear time was 60 min, and the total wear time was 600 min. The quartz sand abrasive was replaced every 60 min. The worn specimen was soaked in anhydrous ethanol, cleaned by ultrasound treatment for 5 min, dried, weighed using an electronic balance, and the weight loss was recorded. The three-body abrasive wear test for the high-chromium cast iron was carried out under the same test conditions.

2.4. Geometric model and mesh of the model
In this study, COMSOL Multiphysics 5.5 finite element software was used to simulate the equivalent temperature field and the solid-liquid phase field during solidification of the composite material melt. In the process of building the model, some conditions that are not important to the results are ignored, and the actual conditions are simplified, such as the specific shape of the runner and riser sand mold and the actual environmental temperature. The finite element models of the sand mold, casting, and preform were meshed.
using software, as shown in figures 3(a)–(b). The mesh of the model uses a physically controlled mesh. After many calculations, it was found that the grid size can meet the calculation requirements, and the calculation results can be obtained quickly. The color of the grid shown in figure 3(b) is essentially the same, indicating that the quality of the grid is good [20]. MATLAB R2015b was used to numerically simulate the distribution curve of W in the melt around the preform through a secondary development program.

3. Results and Discussion

3.1. Interfacial microstructure of the WC/Fe composite

Figures 4(a)–(c) show that structurally, the composite material is composed of three regions: regions 1, 2, and 3 are the preform, transition layer, and high chromium cast iron matrix, respectively. The surrounding high-temperature melt in the preform causes WC to decompose at high temperatures, and W diffuses to form a transition layer. It can be clearly seen that the transition layer of the A1 specimen is significantly narrower than that of the A2 and A3 specimens, and the carbide diffusion in the transition layer is not uniform. The width of the transition layer in the A1 sample is approximately 400 μm. When the column spacing was increased to 20 mm, the width of the transition layer increased to approximately 900 μm. Owing to the different column distances, the larger the column distance, the greater the melt content around the prefabricated parts, and the more efficient the diffusion.

Figure 5 shows the XRD patterns of the A1, A2, and A3 samples. The diffraction peaks of α-Fe, WC, Ni₃Fe, Ni₁₇W₃, Fe₁₇W₂C, and M₇C₃-type carbides (M = Cr, Fe, etc.) were detected in the XRD patterns of the A1, A2,
and A3 samples. The phase diagram for the W–C system shows that WC decomposes to form W$_2$C and C, and C diffuses into the melt to increase (Fe, Cr)$_7$C$_3$. According to the Fe–W–C phase diagram, the melt and W$_2$C undergo a paratactic reaction to form Fe$_3$W$_3$C$_2$. WC and Ni$_{60}$ decompose to increase the content of W and Ni, and form nickel-tungsten compounds Ni$_{17}$W$_3$ and Ni$_3$Fe, respectively.

3.2. Three-body abrasive wear behavior of WC/Fe composites

Figure 6 shows the microhardness of different areas of the different samples. The hardness of the three preform regions and the matrix region are roughly the same, while the microhardness of the transition layer region of the A2 sample was significantly higher than that of the other samples. Figures 7(a)–(d) shows the statistical results of the mass loss under a 600 N load. The results indicate that the mass loss ($y$) increased linearly with time ($x$), and for the A1, A2, and A3 samples, the mass loss gradually decreased and tended to become stable with the increase in the wear time; the A2 sample had the smallest mass loss. For the reference sample A0, the mass loss was more severe during wear. The results indicate that the wear resistance of the WC/Fe composites was significantly
improved by the addition of the WC preform. The wear resistance of a material is directly related to the hardness of the composite material [22].

According to Richardson’s theory, when the ratio of the material hardness to abrasive hardness \( \frac{H_m}{H_a} < 0.8 \), the wear rate of the material increases sharply, which means that the wear resistance of the material is reduced [23]. At the beginning stage of the three-body abrasive wear, owing to the high hardness of the preform and transition layer areas, the resistance to abrasive wear is strong, while the hardness of the matrix material is low, and the ability to resist abrasive wear is weak. Therefore, the matrix area wears severely, resulting in a large amount of mass wear in the composite materials. With the development of wear, the matrix adopts a concave shape because it is first removed by the abrasive, while in relation, the preform protrudes above the matrix, which plays a protective role in the subsequent wear process. In the later stage of wear, when the height difference between the preform and the matrix exceeds the diameter of the abrasive particles, the matrix almost no longer bears the effect of abrasive wear, but the preform begins to bear the main effect of abrasive wear. At this time, the mass wear of the composite decreases to a minimum and tends to become stable [24–26].

Figures 8(a), (c), and (e) show the wear morphology of the WC/Fe composite transition layer region and the matrix region, with different preform distances. The matrix region has long and parallel furrows, which are the result of abrasive micro-cutting. Figures 8(b), (d), and (f) show the wear morphology of the WC/Fe composite preform area, with different preform distances. The transition layer and preform can effectively hinder the cutting action of the abrasive, and there is almost no plastic deformation during the abrasive wear. Therefore, the preform and transition layer areas are mainly affected by fatigue wear [13]. However, some short furrows are still
observed in the wear morphology of the preform because a small part of the soft phase in the composition of the preform is microcut by the abrasive, which has little effect on the wear resistance of the WC/Fe composites.

### 3.3. Finite element simulation of solidification of WC/Fe composite

Figure 9 shows that the temperature distribution of the entire casting system is very uneven at the beginning of the solidification process. This is caused by the low temperature of the sand mold and the preform, which is almost negligible compared with the temperature of the molten metal. When WC/Fe was cooled for 5 min, the temperature of the molten metal was still high, and the composite did not completely solidify. After cooling for 30 min, the temperature of the preform and the metal were basically the same, and the temperature of the sand mold increased. After cooling for 60 min, the temperature distribution of the pouring system was similar to that at 30 min, and the overall temperature followed a downward trend.

The diffusion of W was further explored, and the distribution of W around the preform was numerically simulated. The W diffusion zone is regarded as a semi-infinite object driven by the movement of the solid-liquid interface, and the diffusion time is approximately the solidification time of the melt in the preform hole [27, 28]. Figure 11 shows the liquid-solid phase transition during solidification of the molten metal.

To observe the internal solidification, for the images in figure 10, we set a filter $z < 10$ cm. For the scale bar on the right side of the figure, the liquid phase and 0 represents the solid phase. The presence of the preform is equivalent to that of cold iron [20], and the time required for the molten metal around the preform to become a solid phase is very short.

Equation (1) [28] is the expression of the boundary conditions of the W diffusion zone, and equation (2) [28] is the expression of the unsteady analytical solution of the W diffusion equation:

$$
C(x, t) = \begin{cases} 
C_{SL}, & x = x(t) \\
C_{LS}, & x < x(t)
\end{cases}
$$

In the formula, $C_{SL}$ and $C_{LS}$ are the W content on the solid and liquid sides of the solid-liquid interface, respectively, $x$ is the diffusion distance, and $t$ is time. According to the Gauss error function, the W distribution is represented as:
In formula (2), \( x \) is the W diffusion distance, \( t \) is the W diffusion time, \( T \) is the W diffusion temperature, \( D \) is the W diffusion coefficient, \( k \) is a constant, \( E_A \) is the activation energy for W diffusion, and \( R \) is the gas constant. Equation (3) \[^{[29]}\] represents the total time for W diffusion:

\[
t_{\text{max}} = \frac{R^2}{64k^2D}
\]  

In addition, with an increase in the preform distance, the melt high-temperature zone around the preform increases, which increases the average temperature. The W diffusion coefficient is affected by the W diffusion temperature; the higher the diffusion temperature, the greater the diffusion coefficient. Figure 11 shows the distribution curve for W around the WC/Fe composite preform with different preform column distances. It was found that the W content around the preform is a monotonically decreasing function of the W diffusion distance. Because the ratio of the diameter to column distance of the preform is the same, and the W diffusion zone is a semi-infinite body driven by the movement of the solid-liquid interface, it is assumed that the initial W

Figure 8. Wear morphology of WC/Fe composites with different preform distances. (a) Wear morphology of the matrix area and the transition layer area of the A1 sample, (b) wear morphology of the preform area of the A1 sample, (c) wear morphology of the matrix area and the transition layer area of the A2 sample, (d) wear morphology of the preform area of the A2 sample, (e) wear morphology of the matrix area and the transition layer area of the A3 sample, (f) wear morphology of the preform area of the A3 sample.
content is the same. With an increase in the column distance of the preform, the absolute value of the slope of the W distribution curve (in the original hole) decreases, so the W content around the preform when $L = 10$ mm is lower than that when $L = 15$ mm. However, when $L = 15$ mm, the W diffusion distance is shorter than when $L = 20$ mm, so the W content around the preform is the highest when $L = 15$ mm, followed by $L = 20$ mm, and is lowest when $L = 10$ mm; that is, the numerical simulation is consistent with the experimental results.

When the preform column distance is larger, there is more melt around the preform, and the temperature is higher. On one hand, the diffusion time is longer, which is conducive to W diffusion, but on the other hand, the diffusion distance is longer, which is not conducive to uniform W diffusion and reduces the W content around the preform. In the same way, when the preform column distance is small, the diffusion distance is short, but the diffusion time is short, which also leads to insufficient W diffusion, so that the W content around the preform is low, leading to uneven W diffusion. Therefore, when the preform column distance was moderate, W diffusion was the most uniform because of both the diffusion distance and the diffusion time. In summary, the W diffusion process is affected by both the diffusion distance and diffusion time [29].

4. Conclusion

(1) The dissolution of the WC preform generates the surface layer, and W, Ni, Fe, and Cr diffuse into this layer. A metallurgical bonding transition layer is formed between the preform and the matrix. With an increase in the preform column spacing from 10 mm to 20 mm, the width of the transition layer increases from 400 $\mu$m to 900 $\mu$m.

(2) Compared with high-chromium cast iron, the addition of the WC preform can significantly improve the wear resistance of the material. With an increase in the preform column distance, the hardness of the transition layer first increased and then decreased, and the mass loss of the WC/Fe composite first decreased and then increased.

(3) The transition layer and preform can effectively hinder the cutting action of the abrasive, and there is almost no plastic deformation during abrasive wear of the composite.
The microstructure and hardness of the composite transition layer are affected by the diffusion of W, which is related to the diffusion distance and time. When the distance reaches 15 mm, W diffusion is favorable for forming a good transition layer.

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References

[1] da Silva A E, de Melo I N R, Pinheiro I P and da Silva L R 2020 Characterisation and machinability of high chromium hardened white cast iron with and without the addition of niobium Wear 460–461 203463
[2] Sarac M F and Dikici B 2019 Effect of heat treatment on wear and corrosion behavior of high chromium white cast iron Mat. Testing 61 61659–66
[3] Yi Y L, Xin J D, Ren X Y, Fu H G, Li Q and Yi D W 2019 Investigation on abrasive wear behavior of Fe–B alloys containing various molybdenum contents Trib. Int. 135 135237–45
[4] Li Y W, Li Y G and Wang X G 2019 Effect of temperature and rolling rate on high chromium cast iron/low carbon steel composite plate prepared by hot rolling Mat. Exp. 9 9235–64
[5] Miracle D H 2005 Metal matrix composites—from science to technological significance Composites Science & Technology 65 2526–40
[6] Kambakas K and Tsakiropoulos P 2019 Solidification of high-Cr white cast iron-WC particle reinforced composites Mat. Sci. Eng. A 413 538–44
[7] Beste U and Jacobson S 2008 A new view of the deterioration and wear of WC/Co cored carbide rock drill buttons Wear 264 1129–41
[8] Liu D, Li L, Li F Q and Chen Y B 2008 WCP/Fe metal matrix composites produced by laser melt injection Surf. Coat. Tech. 202 1771–7
[9] Pagoulias E and Lindroos V K 1998 Processing and properties of particulate reinforced steel matrix composites Mater. Sci. Eng. A 246 221–34
[10] Zheng B C, Li W, Tu X H, Xu F W, Liu K and Song S C 2020 Effect of titanium binder addition on the interface structure and three-body abrasive wear behavior of ZTA ceramic particles–reinforced high chromium Ceram. Int. 46 13798–806
[11] Zheng B C, Li W, Tu X H, Song S C and Huang W J 2019 Effect of ZTA ceramic particles strengthened high chromium white cast iron on three-body abrasion behavior Mater. Res. Express 6 116581
[12] Cai X L, Xu Y H, Zhong L S and Liu M X 2017 Fracture toughness of WC–Fe cermet in W–WC–Fe composite by nanoindentation JALCOM 7 128–788–96
[13] Li Z L, Jiang Y H, Zhou R H, Lu D H and Zhou R F 2007 Dry three-body abrasive wear behavior of WC reinforced iron matrix surface composites produced by V–EPC in-filtration casting Wear 262 649–54
[14] Wang W Q et al 2017 Fabrication, microstructure, and wear performance of WC–Fe composite/metal coating fabricated by resistance seam welding Mater. Charact. 134 182–93
[15] Sima A A, Phuong V, Steve Y and Richard R C 2017 Erosive wear behavior of cold-sprayed Ni-WC composite coating Wear 376–377 566–77
[16] Neville B P and Rabiei A 2008 Composite metal foams processed through powder metallurgy Materials & Design 29 388–96
[17] Moon R J et al 2009 Evaluation of crack–tip stress fields on microstructural-scale fracture in Al–Al2O3 interpenetrating network composites Acta Mater. 57 570–81
[18] Zhao X Y et al 2016 Preparation of spherical structure steel-based MMCs/steel three-dimensional interpenetrating network composite Special Casting & Nonferrous Alloys 36 852–5
[19] Wong J C, Paramsothy M and Gupta M 2009 Using Mg and Mg–nanoAl2O3: Concentric alternating macro–ring material design to enhance the properties of magnesium Composites Science & Technology 69 438–44
[20] Xu R J, Chong Y Y, Zhou Y X, Jiang Y H and Feng J 2019 Temperature and stress field analysis of solidification process in high chromium cast iron matrix composite reinforced by ZTA ceramic particles Mater. Res. Express 10 106551
[21] Zhang Z Z et al 2017 The effect of volume fraction of WC particles on wear behavior of in-situ WC–Fe composites by spark plasma sintering Int. J. Refrac. Met. Hard Mater. 69 196–208
[22] Zhou Z F et al 2019 Effect of nanoscale V2C precipitates on the three-body abrasive wear behavior of high-Mn austenitic steel Wear 436–437 203009
[23] Richardson R C D 1967 The wear of metals by hard abrasives Wear 10 291–4
[24] Chen H H, Xing J D and Li W 2006 Application Manual of Wear Resistant Materials (in Chinese) (Beijing: Machinery Industry Press)
[25] Rabiniwicz E and Motis A 1965 Effect of abrasive particle size on wear Wear 8 381–90
[26] Sin H, Saka N and Suh N P 1979 Abrasive wear mechanisms and the grit size effect Wear 55 163–90
[27] Zhang J X, Pei Y and Mi Y Q 2004 Characteristics of isothermal solidification stage and analytical solutions for the stage in transient liquid phase bonding process Welded Pipe and Tube 27 25–31 (in Chinese)
[28] Liu A N et al 2014 Prediction of temperature holding time and B element diffusion distance of TLP bonding for DD6 superalloy Hot Working Technology 43 190–3 (in Chinese)
[29] Zhang Z X et al 2019 Effect of surface W alloying on microstructure and hardness of high chromium cast iron Materials Reports 33 362–5 (in Chinese)