Materials Research Express

PAPER

Study on microstructure and abrasive wear properties of in-situ TiC reinforced high chromium cast iron matrix composite

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Keywords: high chromium cast iron, TiC, composite material, abrasive wear

Abstract

In this paper, the TiC particle-reinforced high chromium cast iron matrix composite was prepared in situ by the method of injection infiltration, and the effect of adding different volume fractions of moderators on the size of the reinforcing particles, the volume fraction of the reinforcing particles and the abrasive wear of the composite was systematically studied. Performance impact. The research results show that the TiC particles obtained by the in situ method are uniformly distributed in the matrix of high chromium cast iron, and the interface between the particles and the matrix is clean. And as the volume fraction of the moderator increases, the size of the obtained TiC particles becomes smaller and more uniform, and the volume fraction of the reinforcing particles also gradually decreases with the increase of the volume fraction of the moderator. And the introduction of TiC has increased the hardness of the material by up to 69.036%. Abrasive wear experiments show that the introduction of the moderator makes the reinforcing particles smaller, which further improves the wear resistance of the composite material, and the composite material with 20% moderator content has the best wear resistance, compared to The wear resistance of the metal matrix material is increased by 1.8 times.

1. Introduction

Traditional steel wear-resistant materials such as high chromium cast iron, high manganese steel and alloy steel are mainly used in metallurgy, electric power, coal and construction machinery industries. The traditional wear-resistant materials often consume huge amounts and have short service life when dealing with more and more complex working conditions. It is difficult to meet the needs of the industry. The metal matrix composite materials (MMC) have high specific modulus, strength, thermal stability and excellent wear resistance have attracted more and more attention. Therefore, the study of MMC not only has great market demand for the production industry, but also has deep academic value [1–4]. In MMC, the ceramic particle reinforced metal matrix has good mechanical properties and wear resistance and has been widely studied [5]. Among many particle reinforcements, titanium carbide (TiC) was considered to be a good reinforcement due to its high hardness, high melting point, and relatively high thermal and chemical stability [6–11]. There are two methods for preparing the TiC particles reinforced metal matrix by self-propagating high temperature synthesis (SHS) and additive particles.

SHS is a process of synthesizing reinforcement in a metal matrix by chemical reaction between Ti and C in a metal melt [12]. Compared with the traditional external reinforcement particles, the reinforced particles obtained by the in situ reaction generation method have obvious advantages such as clean interface, uniformly distributed particles, and good interface bonding between the reinforcement and the matrix. So the in situ reaction generation method is excellent in selection. The material aspect of wear resistance plays a leading role.
Therefore, researchers have developed considerable interest in these issues. Jipeng Jiang et al. [13] prepared two different TiC particle-reinforced high chromium white cast iron (HCWI) composite materials, namely, direct addition of TiC (TiC/HCWI) and in situ generation of TiCx (TiCx/HCWI). Cast iron (HCWI) composite material. It is found through research that the size of the reinforced particles in the TiC-reinforced MMC synthesized in situ is smaller than that of the TiC-reinforced MMC obtained by the external method, and has more excellent mechanical properties and wear resistance. At present, particle-reinforced MMC is usually prepared by powder metallurgy, self-propagating high temperature synthesis (SHS) and casting infiltration methods [14–16]. These preparation methods affect the wear performance of MMC by controlling the size, distribution and density of TiC particles.

In the past few decades, SHS has attracted much attention as one of the manufacturing technologies of in situ synthetic composite materials. SHS is a method of self-heating and autogenous preparation of materials based on high chemical reactions between reactants. This method has become the main synthesis method of ceramic materials, metals and ceramic matrix composite materials and intermetallic compounds due to its advantages of energy saving, low investment, high productivity, high purity and good activity [17–19].

E Olejnik et al. studied the method of obtaining TiC-FeMn type local composite reinforcement in situ in steel castings. In order to improve the fracture toughness of the composite material, a moderator composed of 70% and 90% by weight of high manganese steel was added to the initial mixture of TiC substrate powder to obtain uniform and dimensionally stable particle-reinforced austenite Matrix composite materials have significantly improved fracture toughness and wear resistance [20].

Most of the above-mentioned research work focuses on the manufacture of composite materials, and then characterizes them from the perspectives of microstructure, mechanical properties and wear resistance. However, the method of gravity casting is used to study the in situ reaction infiltration synthesis of TiC reinforced high chromium cast iron base. The three-body abrasive wear performance of composite materials is rarely mentioned. Based on the above-mentioned articles, this article proposes to introduce a moderator with high chromium cast iron components to prepare in situ TiC-reinforced high chromium cast iron matrix composites. The moderator with high chromium cast iron components and a metal matrix with high chromium cast iron components are selected. It is to avoid the influence of other additives on the interface and composition of the composite zone. After the sample is successfully prepared, the microscopic morphology of the composite zone is observed by scanning electron microscope (SEM) and x-ray diffraction (XRD). Subsequently, the hardness and wear resistance of the material were analyzed through the Vickers hardness test and the three-body abrasive wear test.

2. Experiment

2.1. The preparation of samples

The metal matrix of this experiment is high-chromium cast iron (HCCI) and the composition was shown in table 1.

| Elements | C | Cr | Mn | Si | Mo | Ni | Cu | Fe |
|----------|---|----|----|----|----|----|----|----|
| Wt%      | 3.0–3.4 | 25–26 | 1 | 0.5 | 0.6 | 0.2–0.4 | 0.4 | Bal. |

| Table 1. Composition of HCCI (Wt%).

The raw materials of titanium powder (purity ≥99.9%, average size about 50 μm) and carbon powder (average size about 50 μm) purchased from Tianjin of China. Ti powder and C powder were mixed with different moderator (0 vol.%, 20 vol.%, 40 vol.%, 60 vol.%, 80 vol.%, table 2) in a DOM-10L planetary ball mill at a rotation speed of 181r/min for 12 h at an atomic ratio of 1:1 to obtain a mixed powder.

| Designation | Ti+C powder [Vol.%] | Moderator [Vol.%] |
|-------------|---------------------|-------------------|
| a           | 0                   | 0                 |
| b           | 100                 | 0                 |
| c           | 80                  | 20                |
| d           | 60                  | 40                |
| e           | 40                  | 60                |
| f           | 20                  | 80                |

| Table 2. Vol.% of Ti+C powders and moderator.

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The moderator chemical composition was shown in table 3.

| Elements | C | Mn | Cr | Mo | Fe |
|----------|---|----|----|----|----|
| wt%      | 3.1| 1.0| 25 | 1.0| 69.9|

The mixed powders were suppressed in a YP-30T tablet press with a pressure of 20 MPa and kept under pressure for 5 min to obtain preforms. The preforms was put into the sand mold and pouring the molten HCCI at 1550 °C (figure 1).

2.2. Detection of microstructure
The composites was detected by VEGA3 TESCAN SEM and EDS. The average particle size and volume fraction was calculated by Image-Pro Plus software. The phases of the composites was analyzed by XRD (D/Max-2500) with the rate of 2° min⁻¹.

2.3. Characterization of hardness and wear properties
The hardness of composite materials and matrix materials were tested by DHV-1000Z type micro vickers, the wear resistance were tested by the MFG-800SQ reciprocating three-body abrasive wear tester. The applied load is 600 N. The sample is taken out every 30 min and cleaned in an ultrasonic cleaning machine before being weighed and recorded. Loss of mass per mill course. And convert it into volume loss. Figure 2 shows a schematic diagram of the three-body abrasive wear experiment. The abrasive uses quartz sand with a particle size of about 0.1 mm. In order to improve the contact between the abrasive and the sample, a 45° angle is provided on the wear surface of the sample according to the wear direction.

3. Results and discussion

3.1. Microstructure
As shown in figure 3, it is the metallographic diagram of the composite material. It can be seen from the figure that during the preparation process of the composite material, a silver-gray particle is generated in the sample. TiC particles, and it can still be observed in the metallographic diagram that the resulting TiC particles are fine, uniform and dispersed in the metal matrix. In order to further verify the composition of the silver-gray particles generated, the composition of the composite material was analyzed by XRD.

Figure 4 shows the XRD analysis results of the composite material. From the analysis results, it can be seen that the structure of all composite regions contains TiC phase. This confirms that TiC particles are generated in situ during the process of infiltration, which verifies the above hypothesis. However, as the content of the
moderator increases, the intensity of the peak representing the crystallographic plane of TiC gradually becomes smaller, which is related to the TiC formation reaction in the initial composition, that is, the decrease in the percentage of the mixed powder of Ti and C. Further analysis showed that, in the d and e samples, the Cr$_7$C$_3$ carbide crystal faces reflected. This carbide is formed by introducing a sufficiently high content of a moderator showing the composition of high chromium cast iron into the initial powder mixture. The presence of α-Fe phases was observed in all recombination zones; and their strength decreased with the increase in the percentage of the introduced moderator.

As shown in figure 5, it is a scanning electron microscope image of a composite material. It can be observed more intuitively from the figure that each group of samples contains TiC particles, and with the addition of the moderator, the size of the reinforced particles becomes small. And the more the content of the introduced moderator, the smaller the size of the reinforcing particles. At the same time, the volume fraction of the reinforcing particles is also decreasing. This is because with the increase of the content of the moderator, TiC will generate raw materials. And the content of the mixed powder of Ti powder and C powder is continuously decreasing, so the volume fraction of the generated reinforcing particles is also continuously decreasing. And Cr$_7$C$_3$ carbides can be observed in samples (d) and (e).
Figure 4. XRD pattern of composite material: (b) No moderator, (c) 20% moderator; (d) 40% moderator; (e) 60% moderator; (f) 80% moderator.

Figure 5. Scanning electron microscope image of composite material: (a) Matrix; (b) No moderator; (c) 20% moderator; (d) 40% moderator; (e) 60% moderator; (f) 80% moderator.

Figure 5 shows the spot scanning area map of the composite material. The reinforcement particles of each group of samples are selected for comparison with the metal matrix. The spot scanning results are shown in tables 4 and 5.

As shown in tables 4 and 5, with the increase of the content of the moderator, that is, with the decrease of the content of the mixed powder of Ti and C, the results of the enhanced particle spot scanning show that the Ti content is reduced, and at the same time the metal matrix is spot scanning. The results show that the Ti content is
also reduced, which is consistent with the previous analysis that the volume fraction of reinforcing particles decreases with the increase of the moderator content.

Next, use the Image Pro Plus software to analyze the average particle size of the reinforced particles and the volume fraction of the reinforced particles. As shown in figure 6, the average size of the composite material reinforced particles obtained after the Image Pro Plus software is analyzed and the data is fitted. It can be seen from the figure that the average size of the reinforced particles is 2.1 um without the moderator. With the increase of the moderator content, the size of the reinforced particles gradually decreases, respectively 0.56 um, 0.44 um, 0.38 um and 0.25 um. The addition of the moderator effectively refines the size of the reinforcing particles, so that the reinforcing particles are more dispersed and distributed in the metal matrix. It also can be seen from figure 6 that with the increase of the content of the moderator, the volume fraction of the reinforcing particles continuously decreases. This is because when the content of the moderator increases, the content of the mixed powder of Ti powder and C powder decreases. Therefore, the number of TiC particles generated also decreases, which is manifested as a decrease in the volume fraction of reinforcing particles.

| Spots | Ti    | Fe    | Cr    | Bal. |
|-------|-------|-------|-------|------|
| b1    | 63.8  | 25.3  | 4.8   | 5.9  |
| c1    | 51.4  | 19.3  | 24.4  | 4.9  |
| d1    | 36.0  | 27.8  | 32.4  | 3.8  |
| e1    | 26.0  | 33.2  | 37    | 3.8  |
| f1    | 16.0  | 66.9  | 13.9  | 3.2  |

| Spots | Ti    | Fe    | Cr    | Bal. |
|-------|-------|-------|-------|------|
| b2    | 24.9  | 60.2  | 8.1   | 6.8  |
| c2    | 24.2  | 21.7  | 49.1  | 5    |
| d2    | 16.2  | 22.7  | 55.2  | 5.9  |
| e2    | 10.0  | 65.3  | 20.9  | 3.8  |
| f2    | 5.2   | 69.0  | 22.3  | 3.5  |

Figure 6. Average particle size and volume fraction: (b) No moderator; (c) 20% moderator; (d) 40% moderator; (e) 60% moderator; (f) 80% moderator.
3.2. Hardness

Figure 7 shows the vickers hardness value of the metal matrix used in the experiment and the TiC reinforced high chromium cast iron matrix composite material obtained by infiltration. It can be clearly seen from the figure that the hardness value of the composite material is higher than the hardness value of the metal matrix is high, and in the composite material, as the content of the moderator increases, the hardness value of the composite material shows a downward trend. As the previous analysis belongs to, this is because when the content of the moderator increases, the volume fraction of the reinforcing particles decreases, so the hardness value is reduced. The average Vickers hardness values of the metal matrix and the samples a, b, c, d and e are 545.8 HV, 922.6 HV, 859.1 HV, 785.8 HV, 704.6 and 629.1 HV, respectively. In this experiment, through the introduction of TiC particles, the hardness of the material is increased by 69.036% at the highest. It is proved that the introduction of TiC particles can greatly increase the hardness of the material.

3.3. Wear resistance

Figure 8 shows the volume loss of the matrix material and the composite material. It can be seen from the figure that as time goes by, the metal matrix material and the composite material both have different degrees of volume loss. And with the extension of time, the volume loss of the metal matrix material is the largest. In the composite material, the sample a, that is, the sample without the moderator, has the largest volume loss, and the sample b, the sample containing 20% of the moderator. The volume loss is relatively small. The reason for this phenomenon is that the size of reinforcement particles of sample a is relatively large, and the volume fraction of reinforcement particles is too high. In the process of abrasive wear, the larger TiC particles are more likely to be broken and peeled off from the matrix together with a part of the metal matrix. Flaking, and the broken and peeled TiC particles have higher hardness than the metal matrix material, so the broken and peeled TiC particles act as abrasives to further aggravate the wear of the material, so the volume loss of the a sample will be greater. In sample b, while the reinforcing particles have higher hardness and higher volume fraction, due to the introduction of the moderator, the reinforcing particles become dispersed and fine, so the volume loss is also small. It has excellent wear resistance.

Figure 9 shows the wear morphology of the composite material. From the figure, it can be seen that the metal matrix material has a relatively serious plastic deformation and deep furrows after wear. Test a without adding a moderator In this way, due to the large size of the TiC particles formed, when the particles are broken during wear, they will peel off along with a part of the metal matrix material, so there are some pits in the a sample. The rest of the composite materials have different degrees of particle breakage and slight plastic deformation. This is because the broken and fallen TiC particles have higher hardness than the metal matrix material, and continue to act as new abrasives while being broken and fallen off, thereby intensifying the wear of the material. On the whole, sample b, that is, the sample with a moderator content of 20%, has a smaller degree of wear and shows better wear resistance.

In order to more intuitively indicate the wear degree and wear scar depth of the composite material, a 3D color map is used to show the wear morphology of each group of samples, as shown in figure 10. From the color
The degree of wear and the depth of the wear scar of the composite material can be more intuitively represented. It can be seen from the figure that the wear scar depth of the base metal material and the sample without the moderator is deeper, and the wear scar depth of the sample in the other samples is shallower, showing better wear resistance. This result is consistent with the volume loss results of the metal matrix material and composite material described above. Therefore, the abrasion resistance of sample b, that is, the sample with 20% moderator added, is better. Because sample b has a higher volume fraction of reinforcement particles while the reinforcement particles are smaller, it shows better dispersion strengthening and therefore exhibits better wear resistance.

Figure 11 shows a simplified diagram of the wear mechanism of the metal matrix and composite materials. It can be seen from the figure that in the process of abrasive wear of the base metal, since the hardness of the base metal is softer than the abrasive, the abrasive can easily scratch the metal during the abrasion process, so a deeper furrow will be formed on the metal surface. Cause more serious abrasive wear. As shown in figure (a), for TiC-reinforced composite materials, the hardness of the reinforced particles is higher, which can better organize the wear of the abrasive to the metal matrix, showing better wear resistance. However, the size of the reinforced
particles formed without the addition of the moderator is larger, and the finer particles are more likely to peel off from the metal matrix during abrasion, and part of the matrix material will be peeled off together, as shown in figure (b), so it is macroscopically resistant. The abrasion resistance of materials added with moderators is poorer, and the wear morphology is accompanied by deeper pits. For the composite material added with the inducer, the formed reinforcing particles are fine, and the metal matrix has a strong coating effect on the reinforcing particles, so it can better resist the wear of abrasives. See c for details. It shows better wear resistance.

Figure 10. Three-dimensional wear morphology of matrix and composite materials: (a) matrix; (b) no moderator; (c) 20% moderator; (d) 40% moderator; (e) 60% moderator; (f) 80% moderator.

Figure 11. Wear mechanism diagram of matrix and composite materials: (a) Matrix, (b) No moderator, (c) 20% moderator, (d) 20% moderator a half an hour after wear.
The macro morphology is shown as a shallow furrow, but with the extension of the wear time, the reinforcement particles will still break or fall off, see d. At the same time, with the further wear of the matrix material, there will be other reinforcement particles. The metal surface is exposed again to resist the abrasive wear.

4. Conclusion

1. The in situ generation method is adopted, that is, the mixed preform of Ti powder and C powder is introduced into the cavity, and TiC particles can indeed be generated in situ in the case of molten metal infiltration.

2. The introduction of the moderator can indeed reduce the size of the reinforcing particles, so that the reinforcing particles can achieve a fine dispersion effect.

3. The 20% moderator-incorporated composite material enables the reinforcement particles to achieve fine dispersion strengthening while retaining a higher volume fraction of the reinforcement particles, so the volume loss during the wear process is the least, which shows better wear resistance.

Acknowledgments

This work was funded by the Yun Nan Fundamental Research Projects (grant NO. 202101AU070155) and supported by the Talent Training Program of Kunming University of Science and Technology, China (KKSY201901004).

Data availability statement

No new data were created or analysed in this study.

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