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Microstructure and abrasive wear properties of high-vanadium-chromium wear resistant alloy

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Abstract

To enhance the wear resistance of high chromium cast iron (HCCI, Cr26), a new wear resistant alloy with high vanadium and chromium contents (HCCI-V, 15Cr5V4MoSiMn) was designed and prepared by sand mold casting. The microstructure and the phase composition were analyzed by SEM, EDS and XRD, and the abrasive wear property was tested compared with HCCI. Results show that the new wear resistant alloy is characterized by multi-scale and multi-type carbides distributed in a metal matrix composed of martensite and retained austenite. The carbides include VC, M7C3, M2C and M23C6 (M stands for (Cr, Fe)), with dimensions ranging from tens of nanometers to tens of micrometers. The hardness and impact toughness of HCCI-V are 65 ± 0.2 HRC and 10 ± 0.12 J cm−2, respectively, far higher than that of HCCI (57 ± 0.2 HRC, 8 ± 0.12 J cm−2). When the abrasive particle size and load are 6.5 μm and 1.41 MPa respectively, the wear weight loss of HCCI and HCCI-V are 5.6 ± 0.1 mg and 0.8 ± 0.1 mg respectively, and the relative wear resistance of HCCI-V is 7. The excellent wear resistance of HCCI-V is attributed to the multi-scale carbides. The micro-scale carbides resist scratch, and the nano-scale carbides strengthens matrix. The multi-scale carbides can work collaboratively to resist abrasive wear efficiently.

1. Introduction

Wear-resistant materials are widely used in the industrial field. High chromium cast iron (HCCI) is one of the most important ones. Due to its unique wear resistance, HCCI is widely used in mining, machinery, metallurgy, electric power, construction and other industrial fields. Its excellent wear resistance directly depends on the matrix structure and the high content of cementing carbide [1–4]. However, HCCI is difficult to resist severe abrasive wear in the process of use, with high failure frequency and unsatisfactory service life [5–7]. Therefore, it is of great significance to further improve the wear resistance of HCCI in the modern industrial field.

Generally speaking, grain refinement and matrix hardening are generally accepted methods to improve the wear resistance of materials [8–10]. In recent years, some studies have shown that carbides play an important role in the wear process, especially the secondary carbides evenly distributed in the matrix can prevent cutting fragments and extended scratches, protect the matrix from wear, and greatly improve the wear resistance of materials [11, 12].

The carbides of HCCI are mainly M7C3 and M23C6, and their excellent wear resistance is mainly related to the higher hardness of M7C3 carbides [13, 14]. M7C3 carbide is in the shape of hexagonal rod or strip with great low fracture toughness (20.76 MN m−3/2), which affects the wear resistance of the material to a certain extent. It is found that vanadium can reduce the size of M7C3 carbide and the austenite dendrite arm spacing, increase the volume fraction of carbide, change the morphology of eutectic group, and thus improve the wear resistance and fracture toughness of high chromium cast iron. According to some studies, the effect is the best when the
vanadium content is 5 wt%, and the size of M7C3 carbide and the austenite dendrite arm spacing were reduced to 44.63% and 52.88%, respectively [15–18]. M. Radulovic et al found that when 1.19 wt% vanadium was added, the wear resistance and fracture toughness of HCCI were improved by 10% and 20%, respectively. The high fracture toughness mainly depends on the strain strengthening caused by very small secondary carbide particles distributed in austenite matrix, which increased the energy required for fracture [19]. VC (HV2600-3000) is the most common strengthening phase of steel matrix, which has high hardness and certain plasticity. When the content of vanadium is 10 wt%, the hardness of VC reinforced phase is 2260 HV, the hardness of matrix is 725–800 HV, and the impact toughness is 8.6 J cm⁻². Compared with high chromium cast iron, the comprehensive mechanical properties are better [20]. As the reinforcing phase, it can improve the wear resistance of wear-resistant materials. According to previous studies, high vanadium high speed steel has been widely used in crusher wear parts. When the vanadium content is 5.5% wt%, the wear weight loss of high vanadium high speed steel is about 16 ± 0.16 mg, and its relative wear resistance is about 3 when compared with the HCCI wear weight loss of 44 ± 0.16 mg [21–24]. Therefore, we consider adding vanadium into HCCI to develop a wear resistant alloy with high vanadium and chromium contents (HCCI-V).

2. Experimental methods

2.1. Materials and methods

A kind of high vanadium and high chromium alloy (HCCI-V) with vanadium added to common HCCI was prepared by ordinary sand casting in medium frequency induction furnace. The rated capacity of the melting furnace is 18 kg and the maximum heating temperature is 1750 °C. First the ratio of raw materials pig iron, high carbon ferrochrome, ferromolybdenum, ferromanganese and nitride ferrochrome into the furnace smelting, melting after adding aluminum block deoxidization treatment, and then add vanadium ferroalloy. When the temperature of molten iron is 1500 °C ~ 1550 °C, the samples are tested and the composition is adjusted to meet the requirements. After the molten iron is poured into the ingot mold with rare earth modifier and cooled to form, the high vanadium wear resistant and erosion resistant alloy ingot is obtained. The ingot is approximately 30 mm × 50 mm × 250 square. HCCI is the contrast material. The actual chemical composition of the test material was determined by Spectral analysis (see table 1).

The heat treatment process of this experiment is quenching at 1050 °C and tempering at 250 °C. Heat treatment is carried out in the BSK-83 resistance furnace, for its automatic temperature control and heat preservation function. In the quenching process, it is first heated to 800 °C at the speed of 50 °C h⁻¹ and held for 1 h, then heated to 1050 °C at the speed of 100 °C h⁻¹ and held for 1 h, and finally air cooling. This is because high chromium cast iron tends to crack when heated too fast. In the tempering process, the material was heated to 250 °C at a speed of 100 °C h⁻¹, then held for 2 h, and finally air cooling. As the material contains high carbon and alloy elements, too low quenching temperature will make the carbides unable to dissolve into the austenitic matrix in the austenitizing process, so heating to 1050 °C can significantly improve the wear resistance and impact toughness of the material.

2.2. Mechanical properties test

The macro-hardness of the specimen was tested by Rockwell hardness tester (HR-150A), the load is 150 kg load, and the test surface of the specimen was required to be smooth. During the measurement, the average hardness of five test points with spacing greater than 3 mm was taken as the final hardness value. The micro-hardness of the specimen matrix and carbide was measured with a digital microhardness tester (HVT-1000) under a test load of 50 g. Take the average of ten points as the final hardness value. The JB-300B (pendulum type) impact tester was used to determine the impact toughness of specimens. The measured span is 70 mm. The specimen is a defect-free standard sample with a size of 20 mm × 20 mm × 110 mm.

2.3. Abrasive wear performances test

The abrasive wear test was carried out on a pin-on-disk (type ML-100) abrasion tester (as shown in figure 1). During the test, the sample moves in a straight line back and forth with the fixture, and circulates in a circular motion to the grinding material, advancing in a spiral line. The maximum radius is 120 mm. The total distance of the sample wear was determined according to the calculation formula of the spiral line [24]:

\[
\text{Total distance} = 2\pi \times \text{Radius} \times \text{Number of revolutions}
\]
The total wear revolution \( N \) of HCCI-V is 30, the maximum wear radius \( r_1 \) is 120 mm, and the minimum wear radius \( r_2 \) is 30 mm. Therefore, the total wear distance \( S \) is 14.13 m.

The specimens were pins, and the specimen size is \( 6 \, \text{mm} \times 20 \, \text{mm} \). The silica sandpaper used for the test is waterproof sandpaper with particle diameter of 6.5 \( \mu \text{m} \), 13 \( \mu \text{m} \), 32 \( \mu \text{m} \), 68 \( \mu \text{m} \), respectively. The specimen moved from the center of the disk to the edge at a speed of 6 mm s\(^{-1}\) under the loading of 0.35 MPa, 1.41 MPa, 2.48 MPa and 3.54 MPa respectively. Before testing, each specimen was grinded for 3 min to make the surface of the specimen as smooth as possible. Each specimen is reciprocated 15 times and then the wear weight loss of which was measured. In order to reduce the test error, three parallel tests were conducted for each group of tests, and the average value of the three tests was taken as the final weight loss. Relative wear resistance is specified by the process parameter \( \varepsilon = W_0/W \), \( W_0 \) represents the wear weight loss of HCCI; \( W \) represents the wear weight loss of HCCI-V [18]). The weight loss of the specimen was measured by TG328B analytical balance with a range of 0 \( \sim \) 200 g and a relative accuracy of 0.1 mg.

### 2.4. Microstructural analysis and worn surface observation

The microstructure was observed by scanning electron microscope (VEGA3-TESCAN-SBH) and the phase composition was determined by XRD (D8 Advance Bruker, Germany) and transmission electron microscope (Hitachi H-800). At the same time, EDS was used to analyze the distribution and content of carbide and matrix elements in the material. The main parameters of scanning electron microscope are voltage (10 kV), electron beam intensity (8–15), working distance (10 mm–16 mm) and count rate (1500–6000). The main parameters of XRD test are 2 Theta scan range (20°–100°), scan step size 0.02° and scan speed 6° min\(^{-1}\). The surface of SEM test sample should be ground, polished and corroded. XRD test samples require the upper and lower surfaces to be parallel and the test surfaces to be ground and polished. The corrosion reagent used for the corrosion sample is Vilella’s reagent, and the corrosion time is generally 1.5 min. The corrosion time of the sample is generally 1.5 min. TEM test specimens are first ground to less than 50 microns and then the ions are reduced to a point where a distinct hole appears in the middle of the specimen. The wear morphology of the specimen was observed and analyzed by SEM.

### 3. Results

#### 3.1. Microstructure of materials

Figure 2 shows the XRD diffraction pattern of the sample after heat treatment, and its microstructure is shown in figures 3 and 4. In the material of HCCI-V, chromium mainly forms eutectic carbide \( \text{M}_7\text{C}_3 \) (PDF 36-1482) and secondary carbide \( \text{M}_2\text{C}_3 \) (PDF 35-0783) with carbon, while vanadium and molybdenum mainly form VC (PDF 74-1220) and \( \text{M}_2\text{C} \) (PDF 15-0457) with carbon. The matrix is mainly martensite (PDF 06-0696) and retained austenite (PDF 52-0513). The matrix structure was refined to a certain extent, and the morphology and distribution of carbides are improved to a certain extent. The morphology of carbides changed to granular or

\[
S = \frac{\pi N (r_1^2 - r_2^2)}{n_1 - n_2}
\]

Figure 1. The diagram of testing machine.
blocky, and secondary carbides precipitated. This is due to the addition of vanadium will reduce the distance between austenite dendrite walls, refine carbides, and increase the volume fraction of carbide. At the same time, vanadium will form material points with other elements, which will make secondary carbides grow around it, increase the number of secondary carbides and improve the hardness and toughness of the material. Figure 3(c) is the SEM diagram of HCCI. Combined with XRD, it can be seen that the microstructure of HCCI is mainly

**Figure 2.** XRD analysis of samples.

**Figure 3.** Scanning electron microscopy (SEM) diagram (a), and (b) are HCCI-V, (c) is HCCI.
Figure 4. Surface scanning electron microscopy (SEM) of HCCI-V.

Figure 5. TEM analysis of M₇C₃ carbide in HCCI-V (a) selected area diffraction pattern (SADP) analysis under the belt axis [3–15]; (b) and (c) HRTEM images and One-dimensional inverse Fourier transform (IFT) lattice images under the belt axis [100].
martensite, austenite and carbide (M7C3). It can be seen from the figure that the matrix structure of HCCI is fine equiaxed crystal, and the carbides are chrysanthemum-shaped, fine and evenly distributed.

Figure 5 shows TEM and HRTEM images and analysis results of M7C3 carbide. As can be seen from figure 5(a), M7C3 carbide has a large size, with orthogonal atomic arrangement (PDF 36-1482) and crystal axis [3–15]. There is a twin point in the middle and the twin plane is (130). Figure 5(b) is the HRTEM image of M7C3 carbide under the crystal axis [100], and figure 5(c) is the inverse Fourier Transform (IFT) image of region B in figure 5(b). It can be seen from figure 5(c) that the crystal plane spacing of (011) crystal plane is about 0.44 nm, and there are many dislocations and a small number of layered defects.

Figure 6 shows the TEM image and SADP analysis of the junction between the secondary carbide M23C6 and the matrix. Some second phases are hexagonal or quadrilateral, with a size of about 300 nm. The atomic arrangement of the secondary carbide M23C6 is a face-centered cubic structure (PDF 35-0783), and its crystal axis is [1–1–2]. The matrix includes martensite and austenite, the crystal axes are [0–11] and [−110], respectively, and the included angle of crystal planes is 14°. It can be seen from the figure that the (111) plane and (0–22) plane of austenite are consistent with the (011) plane and (200) plane of martensite. At the same time, At
the same time, the secondary carbides M23C6 in (1–11) and (220) crystal planes were combed. Therefore, there is a certain coherent relationship between secondary carbide M23C6 and martensite and austenite in the matrix. TEM analysis of VC carbides is shown in figure 7, which is eutectic carbides with axes [0–11], and the atoms are arranged in a face-centered cubic structure (PDF 74-1220).

3.2. Mechanical properties

Table 2 shows the hardness and impact toughness of the test materials after heat treatment. The hardness and impact toughness of HCCI-V are 65 ± 0.2 HRC and 10 ± 0.12 J cm⁻² respectively. The hardness and impact toughness of the HCCI are 57 ± 0.2 HRC and 8 ± 0.12 J cm⁻² respectively. The hardness and impact toughness of HCCI-V are higher than those of HCCI, so the mechanical properties are better. According to the impact toughness fracture diagram of the test material in figure 8, it can be seen that both materials belong to brittle fracture. It can be seen from the figure that there are some dimples on the impact fracture diagram of HCCI-V, which have light tearing degrees and relatively good toughness.

3.3. Abrasive wear performances

Figures 9 and 10 show the relationship between wear weight loss and abrasive particle size and load, respectively. Under different load conditions, the relationship between the weight loss of the material and the abrasive particle size is shown in figure 9. Under the same loading condition, the weight loss of the material also increases with the increase of abrasive particle size. However, the relative wear resistance of HCCI-V decreases with the increase of abrasive particle size. As the load and abrasive particle size are 1.41 MPa and 6.5 μm respectively, the relative wear resistance of HCCI-V reaches the maximum value of 7. Under the same abrasive particle size condition, the weight loss of the material doubles with the increase of the load, while the relative wear resistance of HCCI-V first increases and then decreases with the increase of the load (figure 10). It can be seen that the wear rate of materials increases with the increase of abrasive particle size and load.

The scatter plot of relative wear resistance of HCCI-V is shown in figure 11. The scatter distribution, as shown in the shadow of the figure, shows a downward trend. It shows that with the increase of abrasive particle size, the relative wear resistance of the material decreases gradually, and the wear resistance weakens. The relative wear resistance of HCCI-V decreases with the increase of abrasive particle size, between 2.3 and 5.6, and is suitable for high load and fine abrasive wear conditions.

Abrasive wear of a material is caused by scratches in the abrasive material and belongs to micro-cutting. The material surface will form furrow to some extent, which is related to the material, abrasive particle size and load.

![Figure 8. SEM of impact toughness section of materials (a) HCCI-V, (b) HCCI.](image)

![Table 2. Mechanical properties of materials after heat treatment.](table)
Figure 9. The relationship between wear weight loss and abrasive particle size under different load condition (a) 0.35 MPa, (b) 1.41 MPa, (c) 2.48 MPa, (d) 3.54 MPa.

Figure 10. The relationship between wear weight loss and load under different abrasive particle size condition (a) 6.5 μm, (b) 13 μm, (c) 28 μm, (d) 68 μm.
When the load is 2.48 MPa, the worn morphologies of the materials under different abrasive particle sizes are shown in figure 12. With the increase of abrasive particle size, the furrows formed on the surface of the material will gradually increase, and gradually deepen and widen, indicating that the degree of wear of the material will gradually increase. Compared with HCCI-V, the number of furrows on the surface of HCCI is increased, and the furrows are wider and deeper. HCCI-V has stronger abrasive micro-cutting resistance and better wear resistance. Figure 13 shows the worn morphologies of the materials under different loading conditions when the abrasive particle size is $28 \mu m$. The degree of material surface increases with the increase of load. Compared with HCCI, HCCI-V has a relatively smooth surface and better wear resistance.

Figure 14 shows the contour diagram of the interaction between abrasive particle size and load. As can be seen from the figure, with the increase of abrasive particle size and load, the wear loss weight of the material increases gradually, but the proportion of abrasive particle size is relatively high. Compared with HCCI, HCCI-V has a wider blue area and a smaller red area, indicating that HCCI-V has lower relative wear loss weight and better wear resistance (figure 14(a)).

It can be seen from figure 15 that the furrows formed on the surface of the HCCI were deeper after the abrasive wear experiment, and the carbides under the worn surface produced microcracks and fractures. In contrast, HCCI-V has a relatively flat surface with shallow grooves and no carbide fragmentation and microcrack formation. Therefore, the wear resistance of HCCI-V is much better than that of HCCI.

It can be seen from figures 15(a) and (b) when the abrasive particle size is small, the worn surface of HCCI-V is very smooth with almost no cutting groove, while some shallow cutting grooves are formed on the worn surface of HCCI, and a small amount of micro-cracks are also generated on the subsurface carbide. With the increase of abrasive particle size, the number and depth of cutting grooves formed on the material surface increase. The number of cutting grooves formed by HCCI-V was significantly less than that of HCCI, and the carbide broken slits were also very small and there were no microcracks (figure 15(c)). When the abrasive particle size is larger, the wear degree of the material is more serious, the bulk shedding of carbide in the subsurface layer increases significantly, and the microcracks are almost absent (figures 15(e) and (f)).

4. Discussion

4.1. Effect of carbide on abrasive wear properties

It can be seen from the above research results that the wear performance of HCCI-V is better than that of HCCI under any abrasive particle size and load conditions, which is mainly related to carbide. Adding V element into HCCI alloy not only forms the hard phase VC with high hardness and good morphology, which can effectively resist the micro-cutting of abrasive, but also changes the morphology of the primary carbide, refines the grain and improves the strength and toughness of the material. At the same time, the addition of V also promoted the precipitation of secondary strengthened carbide $M_{23}C_6$ in the matrix. The uniform distribution of secondary
Figure 12. Worn morphologies of materials under different abrasive particle sizes (a) 6.5 μm, HCCI-V; (b) 6.5 μm, HCCI; (c) 13 μm, HCCI-V; (d) 13 μm, HCCI; (e) 28 μm, HCCI-V; (f) 28 μm, HCCI; (g) 68 μm, HCCI-V; (h) 68 μm, HCCI.
Figure 13. Worn morphologies of materials under different loads (a) 0.35 MPa, HCCI-V; (b) 0.35 MPa, HCCI; (c) 1.41 MPa, HCCI-V; (d) 1.41 MPa, HCCI; (e) 2.48 MPa, HCCI-V; (f) 2.48 MPa, HCCI; (g) 3.54 MPa, HCCI-V; (h) 3.54 MPa, HCCI.
carbides in the matrix can prevent cutting fragments and extension scratches, protect the matrix from wear, and greatly improve the wear resistance of the material. Fishbone and layered M$_2$C carbide is also an important part of improving the wear resistance of materials. It can combine more substrates, protect the substrates more effectively, and improve the wear resistance.

To sum up, adding V element to HCCI can improve the type, shape, quantity and grain size of carbides in the material, make the material more effectively resist abrasive cutting and scratch expansion, and greatly improve the wear resistance.

4.2. Effects of abrasive particle size and load on wear properties

Previous research results show that the particle size and load have a significant impact on the wear of materials [25, 26]. With the increase of abrasive particle size, HCCI is more likely to be scratched, as shown in the figure 12. When the abrasive particle size is small, the wear resistance of HCCI-V is the highest, which is 7 times that of HCCI, which indicates that HCCI-V is suitable for micro-cutting environment. With the increase of abrasive particle size, the wear weight loss of the material gradually increases. In severe cases, a large number of carbide fragments will fall off, and the fallen fragments will become wear particles with high hardness, which will further aggravating the weight loss of the material. However, the weight loss of HCCI is much higher than that of HCCI-V. Meanwhile, the wear weight loss of the material increases with the increase of the load, while the relative wear resistance of HCCI-V increases first and then decreases. As shown in figure 14, by comparing the wear distribution of the two materials under the conditions of abrasive particle size and load, it is found that HCCI has a wide dark distribution areas, which indicates that the wear is serious.

Through the above analysis, it can be seen that the wear resistance of the material is mainly related to the type, form and amount of carbide, while the wear of the material is mainly determined by the abrasive particle size and load. Adding V element to HCCI can greatly improve the wear resistance of materials.

5. Conclusions

(1) The microstructure of HCCI-V is mainly martensite, residual austenite and carbides (M$_7$C$_3$, M$_2$3C$_6$, VC and M$_2$C).

(2) The hardness and impact toughness of HCCI-V are 65 ± 0.2 HRC and 10 ± 0.12 J cm$^{-2}$ respectively. Therefore, HCCI-V has better mechanical properties.

(3) The weight loss of abrasive wear depends mainly on abrasive size and load. According to the experimental data analysis of abrasive wear, the abrasion resistance of HCCI-V is about 7 times that of HCCI.

(4) From the wear morphology of the material, it can be seen that, compared with high chromium cast iron, HCCI-V’s wear surface is relatively flat, and the furrows and micro-cutting grooves formed are thin and shallow.

(5) The excellent wear resistance of HCCI-V mainly depends on the type, quantity and form of hard phase carbide.
Figure 15. Abrasive wear cross section of material (a) 13 μm, HCCI-V; (b) 13 μm, HCCI; (c) 28 μm, HCCI-V; (d) 28 μm, HCCI; (e) 68 μm, HCCI-V; (f) 68 μm, HCCI.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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References

[1] Zheng R, Xing J, Liu Y and Li W 2020 Two-body abrasion behaviors characterization of white cast iron with various chromium concentrations Tribol. Trans. 63 519–27

[2] Huang Y X, Li Z, Huang Y Q, Li Y and Xiao P 2019 Microstructure and wear properties of SiC woodceramics reinforced high-chromium cast iron Ceram. Int. 46 2992–601

[3] Lu H, Li T Z, Cui J, Li Q Y and Li D Y 2017 Improvement in erosion-corrosion resistance of high-chromium cast irons by trace boron Wear 376-377 578–86

[4] Liu C, Xu W W, Jiang Y G and Yang T 2020 Mechanistic force modeling in drilling of SiCp/Al matrix composites considering a comprehensive abrasive particle model Int. J. Adv. Manuf. Tech. 109 1–22

[5] Xu L J, Song W L, Ma S Q, Zhou Y C, Pan K M and Wei S Z 2021 Effect of slippage rate on frictional wear behaviors of high-speed steel with dual-scale tungsten carbides (M6C) under high-pressure sliding-rolling condition Tribol. Int. 154 106719

[6] Bedolla-Jacuinde A, Guerra F V, Mejía I, Zuno-Silva J and Rainforth M 2015 Ablative wear of V–Nb–Ti alloyed high-chromium white irons Wear 332–333 1006–11

[7] 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 cast iron Ceram. Int. 46 13798–806

[8] Cortés-Carrillo E, Bedolla-Jacuinde A, Mejía I, Zepeda C M, Zuno-Silva J and Guerra–Lopez F V 2017 Effects of tungsten on the microstructure and on the abrasive wear behavior of a high-chromium white iron Wear 376–377 77–85

[9] Jian Y X, Xing J D, Huang Z F and Wu T H 2019 Quantitative characterization of the wear interactions between the boride and metallic matrix in Fe-3.0 wt% duplex alloy Wear 436–437 203021

[10] Xu L J, Wei S Z, Han M R and Long R 2014 Effect of carbides on wear characterization of high-alloy steels under high-stress rolling-sliding condition 2014 Tribol. Trans. 57 631–4

[11] Ye F X, Hojamberdiev M, Xu Y H, Zhong L S, Zhao N N, Li Y P and Huang X 2013 Microstructure, microhardness and wear resistance of VCP/Fe surface composites fabricated in situ Applied Surface Engr. 280 297–303

[12] Lu F, Wei S and Xu L 2019 Investigation on erosion-wear behaviors of high-chromium cast iron with high nitrogen content in salt–sand slurry Mater. Res. Express 6 106558

[13] Zhi X H, Xing J D and Fu H G 2008 Effect of titanium on the as-cast microstructure of hypereutectic high chromium cast iron Mater. Charact. 59 1221–6

[14] Zhong L S, Xu Y H, Liu X C, Ye F X, Tian J L and Liu X J 2011 Infiltration casting and in situ fabrication of (Fe, Cr)3C particulates bundle-reinforced iron matrix composites Adv. Mat. Res. Vols 284–286 273–6

[15] Song R K, Ye F, Yang C X and Wu S J 2018 Effect of alloying elements on microstructure, mechanical and damping properties of Cr-Mn–Fe–V–Cu high-entropy alloys J. Mater. Sci. & Tech. 34 48–55

[16] Huang T, Pei Y B, Chen F X and Xiang N 2020 Review on the damage behavior of metal laminated composite Mater. Res. Express 7 112002

[17] Chong X Y, Jiang Y H, Zhou R and Feng J 2014 Electronic structures mechanical and thermal properties of V–C binary compounds RSC Adv. 4 44959–71

[18] Xu L J, Wei S Z, Xiao F N, Zhou H, Zhang G S and Li X W 2017 Effects of carbides on abrasive wear properties and failure behaviours of high speed steels with different alloy element content Wear 376–377 968–74

[19] Radulovic M, Fiset M, Peck K and Tomovic M 1994 The influence of vanadium on fracture toughness and abrasion resistance in high chromium white cast irons J. Mater. Engr. 29 5085–94

[20] Xu L J, Xing J D, Wei S Z, Zhang Y and Long R 2006 Investigation on wear behaviors of high-vanadium high-speed steel compared with high-chromium cast iron under rolling contact condition Mater. Sci. Eng. A 434 63–70

[21] Xu L J, Wei S Z, Xing J D and Long R 2014 Effects of carbon content and sliding ratio on wear behavior of high-vanadium high-speed steel (HVHSS) under high-stress rolling-sliding contact Tribol. Int. 70 34–41

[22] Ning A G, Gao R, Yue S, Guo H J and Li L J 2020 Effects of cooling rate on the mechanical properties and precipitation behavior of carbides in H13 steel during quenching process Mater. Res. Express 7 016503

[23] Wei S Z and Xu L J 2021 Review on research progress of steel and iron wear-resistant materials Acta. Metall. Sin. 56 523–38

[24] Xu L J, Wang F F, Zhou Y C, Wang X D, Chen C and Wei S Z 2021 Fabrication and wear property of in situ micro-nano dual-scale vanadium carbide ceramics strengthened wear-resistant composite layers Ceram. Int. 47 953–64

[25] Xu L J, Xing J D, Wei S Z, Zhang Y Z and Long R 2006 Investigation on wear behaviors of high-vanadium high-speed steel compared with high-chromium cast iron under rolling contact condition Mater. Sci. Eng. A 434 63–70

[26] Baig M, Cook R, Pratten J and Wood R 2020 The effect of shape and size distribution of abrasive particles on the volume loss of enamel using micro-abrasion Wear 448–449 203212