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Influence of Vanadium on Microstructure and Properties of Medium-chromium White Cast Iron

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Abstract: White cast iron containing 5wt% chromium and different vanadium contents (up to 10 wt% V) were studied. The microstructures of the samples were analyzed by use of SEM and EDS. The impact energy, Rockwell hardness and wear resistance of the samples were determined. The results indicate that with an increase in vanadium content, the microstructure of medium chromium white cast iron become finer, the impact energy and wear resistance are improved.

Key words: vanadium; medium chromium white cast iron; microstructure; wear resistance

1 Introduction

High chromium cast irons have sufficient wear resistance (in particular, under oxidizing and corrosive conditions), as their microstructures have M_7C_3 carbide in matrix. The discontinuous distribution of rod-like M_7C_3 carbide in matrix makes their toughness higher than that of low alloy white cast irons, which contain continuous brittle cementite. Because of this superior properties high chromium castings have been widely applied to wearing parts of machines in mineral engineering, steelmaking plants, and so forth. However, the demand for higher quality wear resistant materials that can length service life under even more sever conditions becomes greater in many fields. The desire to eliminate frequent shutdown of equipment for replacement of worn or broken castings, plus recognition of the resulting costs in terms of lost productivity, have encouraged engineers to evaluate candidate alloys on a cost/performance basis and, furthermore, to develop and specify new alloys which provide superior abrasive wear resistance along with adequate toughness[1, 2]. It has been reported that the addition of strong carbide-forming elements, such as vanadium, tungsten, niobium and titanium, improves the mechanical properties of high chromium white irons[3]. Vanadium can form vanadium carbide, the Vickers hardness of VC is 2800, which is much harder than that of M_7C_3 (HV 1200~1800) in high chromium cast iron. The round morphology of VC can reduce splitting to matrix, which may be useful to get superior toughness. Alloying high chromium iron with vanadium makes the structure finer. Vanadium is soluble in eutectic M_7C_3 carbides as well as in austenite and influences the transformation of austenite in high chromium iron. Where the vanadium content is higher than 4%, precipitation of dispersive secondary carbides of VC type in austenite are observed, which is favourable for martensitic transformation[4, 5, 6]. In this paper, the influence of vanadium on microstructure and properties of medium-chromium white cast iron is examined.

Table 1 Chemical compositions of the samples (wt%)

Sample No.	C	Cr	V
1	2.25	4.95	2.03
2	2.38	5.11	4.16
3	2.33	5.21	6.10
4	2.24	5.30	8.00
5	2.35	5.06	10.20

2 Experimental procedures

The raw materials for melting vanadium containing medium-chromium white cast irons are pig iron, ferrovanadium and high carbon ferrochrome. The melting of cast irons was carried out in 25kg non-vacuum induction furnace, the melting temperature was about 1500ºC, then cast by sand mould, the size of the mould was 80mm×80mm ×200mm. The final chemical compositions of the samples are shown in Table 1.

The non-notch samples with a size of 10mm×10mm×55mm were made from the cast irons by wire cutting and grinding. The impact energy was measured using a charpy's tester. The samples for hardness measurement were selected from the bars after impact test and measured by a Rockwell tester.
Samples were heat treated in an electric furnace with vacuum atmosphere at 980℃ for 2 hours, followed by oil-quenching to room temperature. The tempering temperature was 250ºC. The technological process of heat treatment is shown as Figure 1.

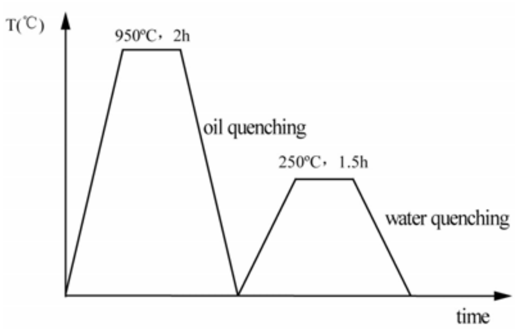


Fig.1 The technological process of heat treatment

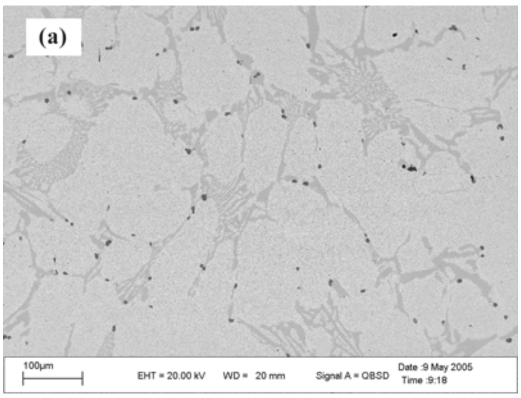
Samples for structural analysis were selected from the bars after impact test. After the samples were roughly and finely ground, polished and etched by use of 4% nital, metallographic observation and analysis were made by a scanning electron microscope, JSM-6301F, using an accelerating voltage of 25 kV.
Abrasion wear experiments were carried out in an ML-10 tester. The cylindrical samples with a diameter of 5mm were made by wire cutting. Silicon carbide waterproof abrasive papers with a mesh of 120 were used in the abrasive wear test. The load was 2 kg. The weight loss was determined by a balance with a sensitivity of 0.1 mg. The relative wear resistance coefficient ε was used to judge wear resistance of the cast iron, the reference specimen was high chromium white cast iron. The following equation was used to calculate the value of ε.

$$\varepsilon = \frac{weight\ loss\ of\ reference\ specimen}{weightloss\ of\ test\ specimen}$$

3 Experimental results and discussion

3.1 Influence of vanadium on microstructure

Figs.2 (a-e) show the back scattering micrographs of the samples with different vanadium contents. The vanadium content is 2.03%, 4.16%, 6.10%, 8.00% and 10.20% respectively. Samples 1-4 are hypoeutectic alloys and sample 5 is a eutectic alloy. It can be seen from Figure 2 that the metallographic microstructure of the samples is composed of white metal matrix, gray eutectic carbides and black granular or rod-like eutectic carbides. Analyzed by EDS and x-ray diffraction patterns, when the vanadium content is lower, the gray eutectic carbides were identified as cementite (M_3C); when the vanadium content is higher, the gray eutectic carbides were identified as $(Cr, Fe, V)_7C_3$ type of chromium carbide (M_7C_3); the black granular or rod-like eutectic carbides were identified as (V, Fe, Cr)C type of vanadium carbides (MC). The EDS results for the three types of carbides are shown in Fig.2 (a-c). For the hypoeutectic alloys, it is found from Fig.2 (a) and (b) that samples 1 and 2 exhibit apparent dendrites morphology, with an increase in vanadium content from 2% to 4%, the microstructure becomes finer, the vanadium carbides distribution is along grain boundary. When the content of vanadium exceeds 6%, it is found from Fig.2 (c) and (d) that the dendrite morphology is not apparent, and a great amount of granular MC type carbides occur, which prevents the formation of the dendrite structure, the vanadium carbides distribution is uniform. For eutectic alloys, the vanadium carbides take on chrysanthemum distribution (in Fig.4 (a)), during solidification, a group of rod-like MC seemed to grow radially from a nucleus and formed a spherical eutectic cell together with austenite as schematically shown in Figure 4 (b)[7, 1]. By increasing the content of vanadium, the amount of MC type carbides increases.



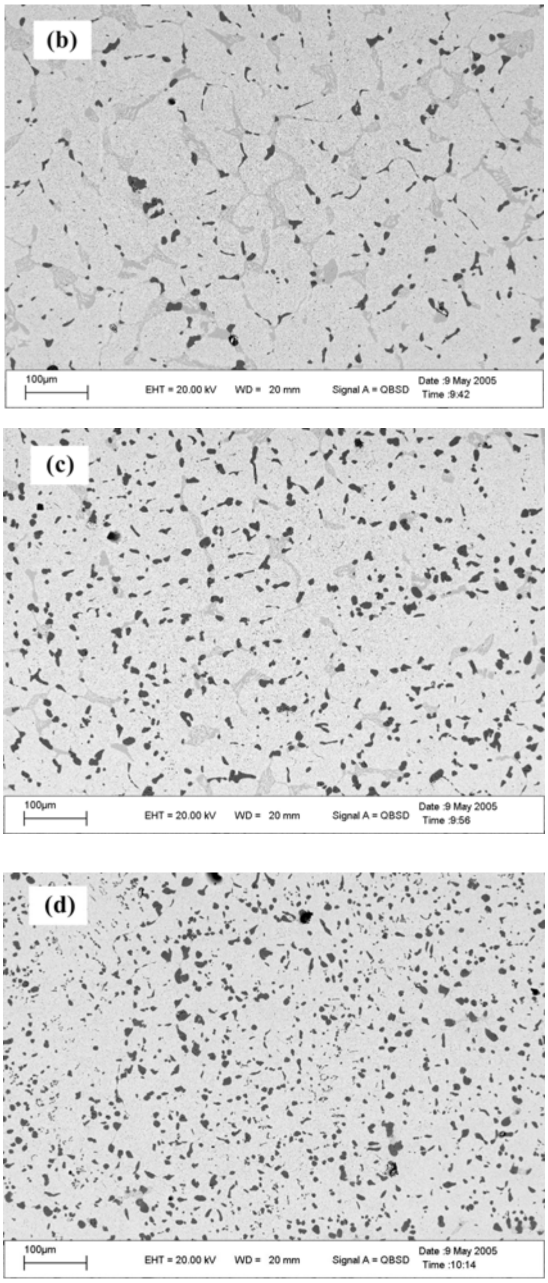


Fig.2 Back scattering micrographs of the samples with different V contents: 2.03%(a), 4.16%(b), 6.10%(c), 8.00%(d) and 10.20%(e) in mass fraction

Fig.3 EDS of three type carbides: M_3C (a), M_7C_3 (b) and MC (c)

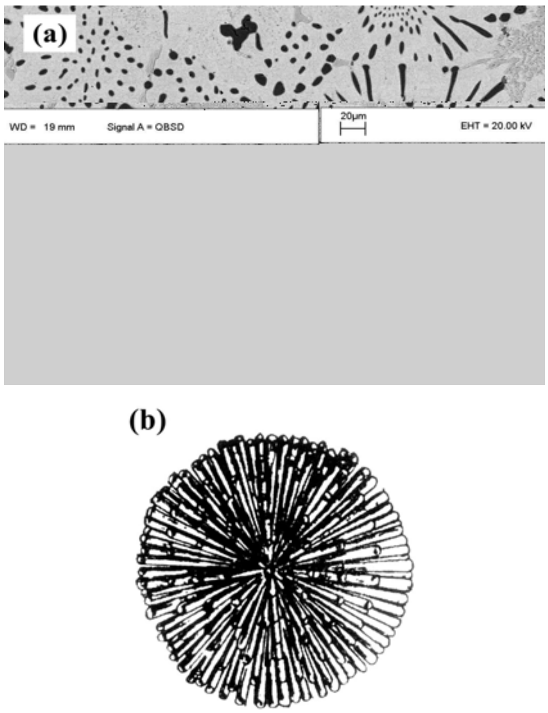


Fig.4 Back scattering micrograph of sample 5 and schematic illustration of eutectic MC

3.2 Influence of vanadium on impact toughness and hardness

Table 2 shows the experimental results of impact test, hardness test and abrasion wear test. The effects of vanadium on the impact toughness and hardness are shown in Figure 5. With an increase in vanadium content, the impact toughness increases, while hardness decreases. Vanadium changed the microstructure parameters of phases existing in microstructure of the alloys examined, including the size of primary austenite dendrites, the morphology and distribution of vanadium carbides and the degree of martensitic transformation, therefore vanadium affected the properties of the alloys examined. Finer primary austenite dendrites and round morphology of MC type carbides, which can reduce the splitting to matrix, result in the increase of the impact toughness. While more alloy content causes the stabilization of austenite, which leads to more retained austenite in the matrix after heat treatment, therefore resulting in the decrease in the hardness.

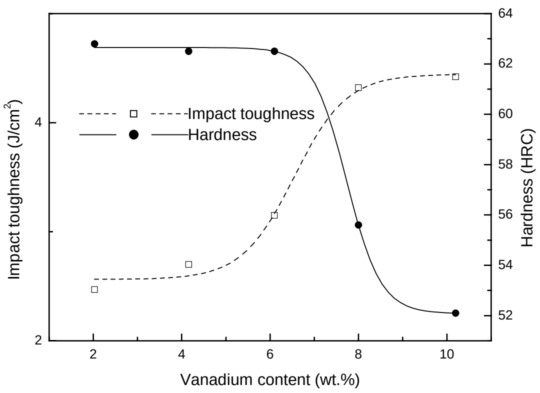


Fig.5 Impact toughness and hardness as a function of vanadium in the alloy

3.3 Influence of vanadium on wear

The influence of vanadium on abrasion resistance is presented in Fig.6. Relative wear resistance improved as the content of vanadium increased.

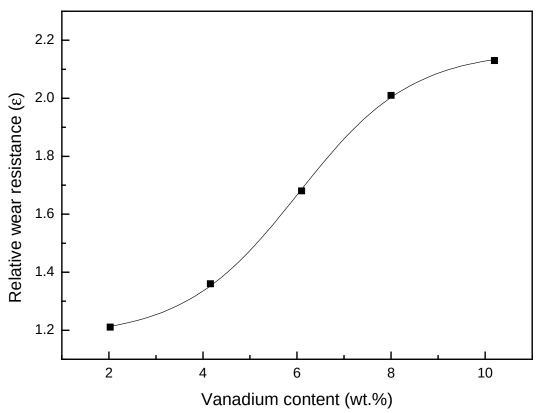


Fig.6 Relative wear resistance as a function of vanadium content in the alloy

The wear mechanism of the matrix changes depending on the magnitude of the impact energy. Under a small impact energy the wear is mainly cutting[8]. In abrasion wear test there were no impact, the matrix was preferentially worn by a cutting action. Some investigations show that when the wear is mainly cutting, if the ratio of the hardness of the material worn to the hardness of the abrasive material is more than 0.8, the abrasion loss will decrease greatly[9]. Table 3 shows the ratios of the microhardness of the phases in cast irons examined and the microhardness of the abrasive material SiC. Since the hardness of the MC type carbides (HV2800) is greater than the hardness of the abrasive material SiC (HV2600), the MC type carbides can obstruct the cutting action of abrasive particles and protect the matrix from direct attack of abrasive particles. Therefore, with an increase of vanadium content, the amount of MC type carbides increases (Fig2), then the abrasion resistance improved.

Table 2 Experimental results of impact test, hardness test and abrasion wear test

Sample No.	Vanadium content (wt.%)	Impact toughness (J/cm^2)	Hardness (HRC)	Relative wear resistance (ε)
1	2.03	2.47	62.8	1.21
2	4.16	2.7	62.5	1.36
3	6.10	3.15	62.5	1.68
4	8.00	4.32	55.6	2.01
5	10.20	4.42	52.1	2.13

Table 3 Ratios of the microhardness of the phases in the cast irons examined and microhardness of SiC

Phases	MC (HV2800)	M_7C_3 (HV1200-1800)	M_3C (HV840-1100)	Martensite (HV500-1000)	Austenite (HV300-600)
SiC (HV2600)	1.08	0.46-0.69	0.32-0.42	0.19-0.38	0.12-0.24

In addition to the volume fraction of MC type of carbides, the size of phases present in the structure is another microstructure variable which affects the abrasion resistance of the alloys examined. The smaller size of primary austenite dendrites and the mean free path, i.e. the average distance between carbides particles caused by increasing the content of vanadium in the alloy, better protect the matrix from direct attack by abrasive particles.

It is important to note that wear resistance under low-stress abrasion conditions also depend on the matrix microstructure. In addition to the fact that the matrix help control the penetration depth of abrasive particles, it also plays an important role in preventing bodily removal of smaller carbides and cracking of massive ones. Martensitic matrix more adequately reinforces MC carbides than austenitic matrix. With an increase in vanadium content, there is more retained austenite in the matrix, the hardness of the alloys examined decreases, while the abrasion resistance increases, it seems contradictory. The reason is that the contribution to improvement of the abrasion resistance is mainly due to the amount increase of MC type carbides. This also suggests that hardness was not a sufficient indicator of a material's wear resistance.

4 Conclusions

(1)Vanadium influenced the microstructure characteristics of medium chromium white cast iron. By increasing the vanadium content, the structure became finer and the amount of MC type carbides increased.

(2) With an increase in vanadium content, the impact toughness and wear resistance were improved. Compared with high chromium white cast iron, the vanadium containing medium chromium white cast iron investigated has better wear resistance.

Acknowledgements

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