

Effect of annealing temperature and time on microstructure and mechanical properties of high Cr ferritic casting steel

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Abstract. A new-type of high Cr ferrite cast steel was designed and investigated. Effects of annealing temperature and time on the microstructure and mechanical properties of the high Cr ferrite cast steel were studied. The results show that the microstructures of the as-cast and annealing steels are composed of ferrite and $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbide. The morphology of carbides is from long rod and the continuous network to crystal precipitation for the steels with increasing of annealing temperature and time. The impact toughness is slightly increased from 6 J/cm² to 8 J/cm² when the annealing temperature increases from 1180 °C to 1200 °C. But the hardness is about HB 200 and no obvious differences between the as-cast and annealing steels. The most suitable annealing temperature and time are 1200 °C and 5 h, respectively. The wear resistance of the high Cr ferrite cast steel is increased and improved with annealing temperature and holding time at 260 °C. The wear mechanism is changed from abrasion wear to abrasive and adhesive wear. The good wear-resistant of the high Cr ferrite cast steel is mainly attributed to the fine uniformly dispersed carbides.

1. Introduction

High chromium cast steel with high strength, good high temperature oxidation resistance, wear resistance and corrosion resistance, is widely used in the heat-resistant parts, such as steam turbine, gas turbine rotor blade, boiler superheater, incinerator grate, etc. [1-3]. Its main failure forms are high temperature oxidation, sulfidation corrosion, thermal plastic deformation, fragmentation, serious wear, and so on. Incineration furnace grate which is prompted waste pushing, rolling and mixing is one of the most important components. Working temperature range is of about 650~950 °C, and continuous working time is more than 10000 hours [4-7]. It is required to have high heat resistance and high wear resistance. Because the working conditions of high temperature and component is extremely bad, the service life is very short, and needs to be replaced frequently. So the actual production cost is high. Heat treatment process is one of the key factors influencing high Cr ferritic casting steel performance and service life, which is associated well with the secondary carbides such as size and distribution, resulting in the final hardness, impact toughness, wear resistance and other performance of the steel[8,9]. But at present, no reliable quantitative relationship between life and heat treatment is



established. It is believed that heat treatment can reduce the use of cost and will bring very considerable economic benefits.

The size and distribution of the carbide precipitates can be altered by heat treatment [10,11]. The aim is to investigate some basic ideas of improving microstructures and mechanical properties in the view of heat treatment and develop this steel in this paper. The microstructure precipitates and mechanical properties of the steel are investigated during annealing process.

2. Experimental

2.1. Materials preparation

The Cr25 cast steel (C content wt.% <0.25, other alloy elements: Mn+Si+Ni+Al<3 wt.%) was melted using 250Kg mid-frequency induction furnace, and then made by casting to shape. The casting ingots were annealed at 1080-1200 °C for 5-10 h, respectively, and followed by cooling in the furnace. And the chemical composition of the high Cr cast steel was given in Table 1.

Table 1. Chemical composition of Cr25 cast steel (mass percent, %)

Element	C	Cr	Si+Mn+Ni+Al	S	P
Cr25 cast steel	0.2457	24.72	<3	0.0092	0.0125

2.2. Methods

The chemical composition of high Cr cast steel alloy was analyzed by high frequency infrared carbon sulfur analyzer, sodium persulfate titration test. The microstructures of as-cast and annealing were observed by PTI optical microscope (OM). The phases of the steels were checked by the type D8 X ray diffraction (XRD), and the wear morphologies of the samples were observed by scanning electron microscope (SEM).

The hardness was tested using an HB-3000 tester with a load of 3000 N and a loading time of 15 s. Impact test was carried out in the type JB-300B semi-automatic impact test machine, and the non-notch impact sample size was 10 mm×10 mm×55 mm. The friction and wear test was carried out by the type MMX-3 pin-on-disc friction and wear testing machine. The pin material was as-cast and annealing high Cr cast steels. The disc material was GCr15 steel with a hardness of HRC 62-64 at room temperature after quenching and annealing at lower temperature. The pin specimens were in the form of cylinder of 4 mm and 15 mm height. The disc specimens were in the form of cylinder with an inner diameter of 40 mm, an outer diameter of 56 mm and a thickness of 10 mm. The test was performed at 260 °C in ambient air, contacted pressure of 42 N, and rotated speed of pin of 200 r/min. The sliding time was 100 h. During the tests, the friction moments were recorded. The mass losses of pins were measured with an analytical balance with a sensitivity of 0.0001 g.

3. Results and discussion

3.1. Microstructure

Figure 1 shows the XRD patterns obtained from as-cast and annealing (temperature 1080-1200 °C, holding time 5-10 h) of Cr25 cast steels, respectively. It can be seen from the Fig. 1 that the crystalline phases of Cr25 cast steel consist mainly of ferrite and $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbide phases. The peaks located at about 45° corresponding to ferrite can be seen. Effect of annealing treatment on the X-ray diffraction patterns of Cr25 cast steels is shown in Figure 1. It can be seen that the peak located at about 45° corresponding to ferrite is almost not changed after the annealing treatment. The phase contents are not changed with increasing of heat treatment temperature and holding time. The key factor influencing the precipitation behavior of Cr25 cast steel is only chemical composition.

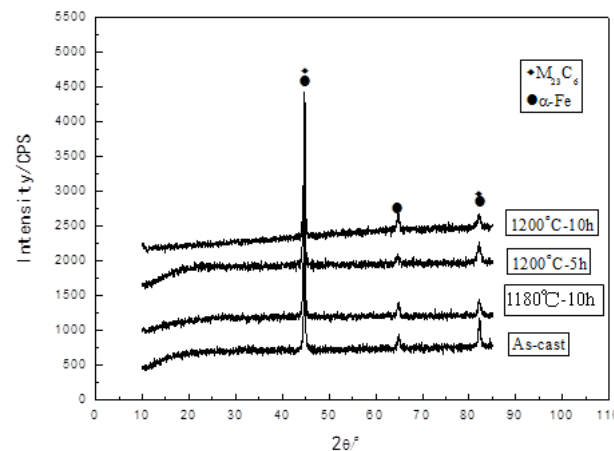


Figure 1. XRD curves of different annealing temperature and holding time of high Cr cast steel.

The microstructures of the Cr25 cast steels which were annealed at different temperatures for 5-10 h are shown in Figure 2. It shows that the microstructures are consisted of ferrite matrix and precipitates. The EDS analysis indicates that the precipitates are consisted mainly of Cr and Fe, as shown Figure 3. The $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ precipitates are identified by XRD in Figure 1 and EDS in Figure 3. The $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ precipitates are distributed in prior ferrite grain boundaries, as shown in Figure 2(a). By comparing with the microstructure of Cr25 cast steels annealing at 1180-1200 °C for 5-10 h, it can be seen that the $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides precipitated from ferrite matrix after annealing treatments. However, when the temperature of annealing treatment is low, i.e., 1180 °C, the precipitated carbides distributed only in the ferrite grain boundaries as seen in Figure 2(b). This may be due to the fact that the motion of Cr and C atoms is slow at low annealing temperature and collection of atoms is difficult. With increasing the annealing temperature to 1200 °C for 5 h, thin rod $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbide uniformly distributed in the ferrite matrix can be observed, as seen in Figure 2(c). Moreover, the $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides were generated in the ferrite matrix. When the annealing time is extremely long, i.e., 1200 °C for 10 h, the dissolution of $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides leads to the size reduction and disappearing of $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides in the ferrite matrix and ferrite grain boundaries, as shown in Figure 2(d). This may be due to the fact that the $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides dissolves in the ferrite matrix at high temperature and long time, as seen in Figure 2(d). The similar phenomenon was also observed by Hou et al[12].

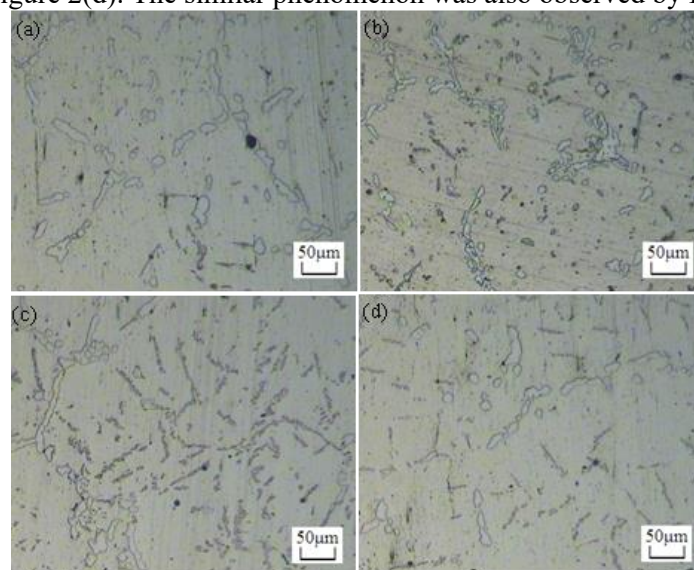


Figure 2. Microstructure of high Cr cast steel under different annealing temperature and holding time. (a) as-cast; (b) 1180 °C for 10 h; (c) 1200 °C for 5 h; (d) 1200 °C for 10 h.

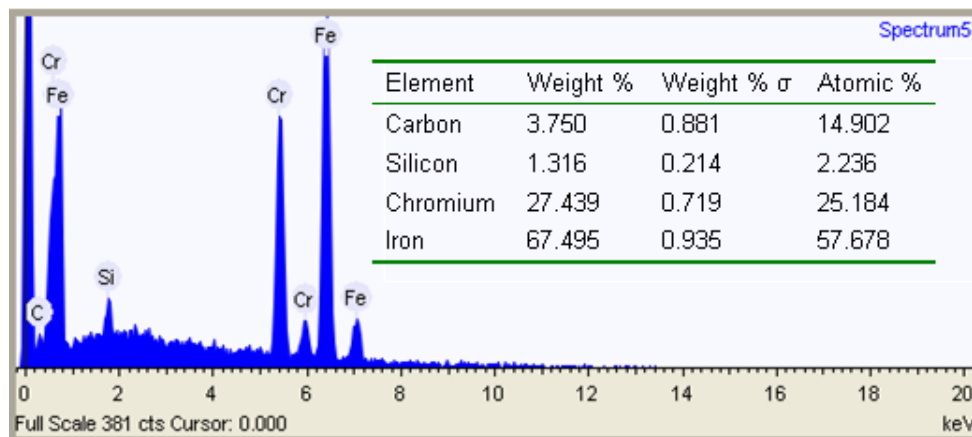


Figure 3. EDS of Cr25 cast steel at 1200 °C for 5 h

3.2. Mechanical properties

Figure 4 shows mechanical properties of the high Cr cast steel on the hardness and the impact toughness with the heat treatment process. It can be seen from the Fig. 4 that the Brinell hardness is always about HB 200 whether as-cast or annealing at 1180-1200 °C for 5-10 h. But the impact toughness is slightly increased from 6 J/cm² to 8 J/cm², when the annealing temperature increases from 1180 °C to 1200 °C. The matrix is ferrite with annealing process and no phase transformation, and (Cr•Fe)₂₃C₆ carbides are distributed uniformly in intragranular precipitation. So the impact toughness is increased slightly. In the process of heat treatment, (Cr•Fe)₂₃C₆ carbides will be certainly affected the wear resistance of the material.

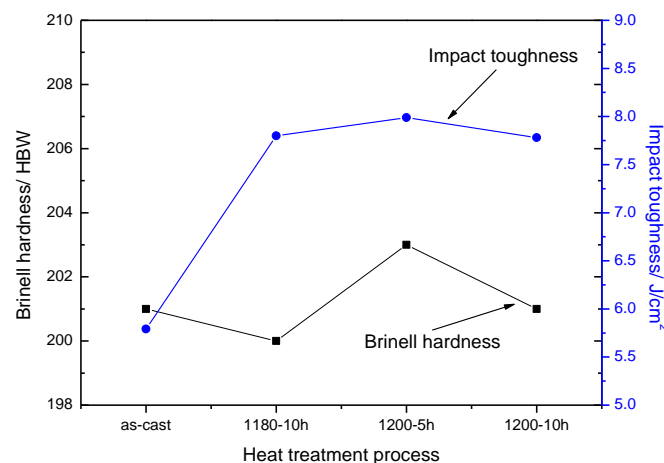


Figure 4. Mechanical properties of the high Cr cast steel on the hardness and the impact toughness with the heat treatment process.

The wear resistance is also contributed by the synergistic effect of microstructure, hardness and toughness [13]. The wear loss of the high Cr cast steels with different heat treatment processes at 260 °C is shown in Figure 5 as a function of wear time. It can be seen in Figure 5 that, at a given 100 h, the wear resistance of the alloys is obviously improved at 260 °C with the increase of annealing temperature and holding time. The wear loss increases first and then decreases with the increase of wear time. After 10 h of wear, the wear curve tends to be gentle. The main reason for the increase of wear resistance is due to the precipitation of (Cr•Fe)₂₃C₆ carbides during the annealing treatment process. It seems to be in agreement with the view in literature that the carbide is a significant contributor to the improved abrasion resistance [14-16]. The better wear resistance with annealing treatment is mainly due to (Cr•Fe)₂₃C₆ carbides, which are precipitated inside grain, hindering the abrasive.

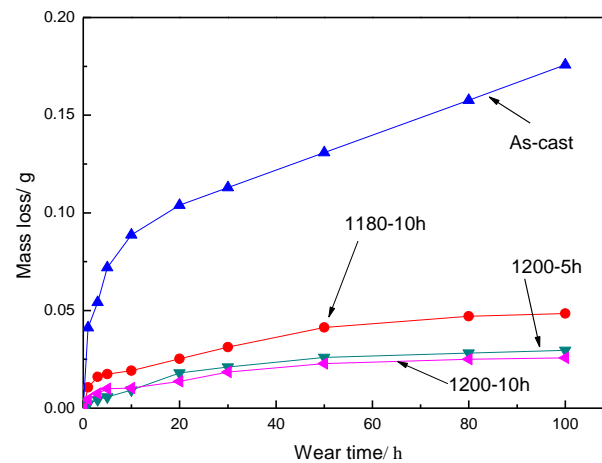


Figure 5. Curves of wear resistance of high Cr cast steels under different heat treatment process.

3.3. Worn surface features

Figure 6 shows the local worn surface morphologies of different the high Cr cast steels with different heat treatment processes at 260 °C after the wear test. It can be seen from the figure that for as-cast Cr25 steel, numerous cracks vertical to the wear direction and some grindings appear at the worn surface, as seen in Figure 6(a). In such a case, the wear loss is relatively high, as seen in Figure 5. It can be attributed to the following two causes. First, casting defect existed in the sample edge. Second, brittle and reticular $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides on grain boundaries happen to crack under certain load. Extensive wide and deep surface furrow and abrasive areas are in evidence of the annealing 1180 °C for 10 h in Figure 6(b). The GCr15 alloy with a hardness of HRC 62-64 penetrates into the reticular $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides of as-cast and annealing 1180 °C for 10 h samples so as to generate serious furrow and scratching action. From the worn surfaces analysis, the dominant 260 °C sliding wear mechanisms of the as-cast and annealing 1180 °C for 10 h samples are considered as abrasive wear.

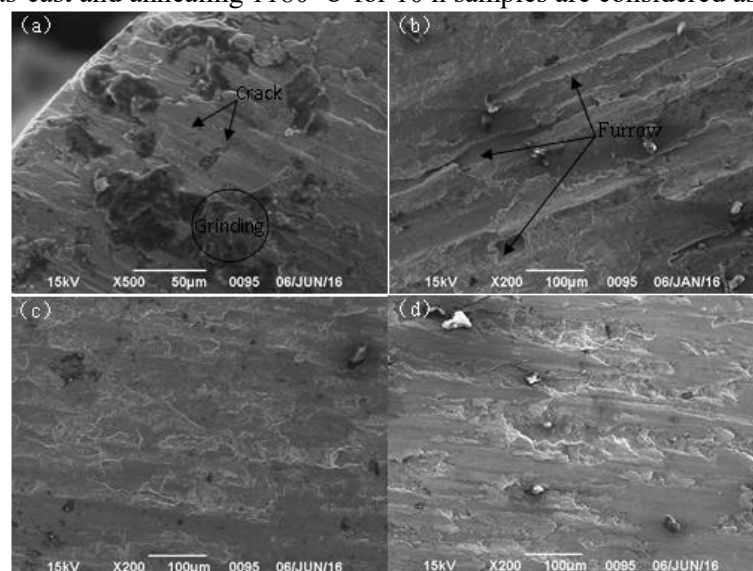


Figure 6. SEM micrographs of the 260 °C worn surfaces for the high Cr cast steels under different heat treatment process. (a) as-cast; (b) 1180 °C for 10 h; (c) 1200 °C for 5 h; (d) 1200 °C for 10 h.

For the steel with the annealing treatment at 1200 °C for 10 h, the worn surface becomes smooth and some micro-cutting can be found, as seen in Figure 6(c). By comparing with as-cast steel, the wear loss is relatively low, as seen in Figure 5. The improvement of the wear resistance of the annealing

steel was due to precipitation of $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides within ferrite matrix, as seen in Figure 2(c). By comparing with the as-cast steel, the annealing treatment steels shows slightly high toughness. Hence, the improvement of the wear resistance of the annealing treatment may be due to the increase of toughness. It is noted that similar results were also obtained by Tabrett[17], which gives a strong support to the theory. With the increase of annealing temperature and the longer holding time, $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides are uniformly precipitated in the grain, but the carbides at grain boundaries are disappeared. And the support of the matrix is strengthened. In addition, the formation of the new carbides is helpful to the formation of the grinding layer, which can effectively reduce the wear and tear of the material. Therefore, with the increase of annealing temperature, the wear resistance of high chromium cast steel in Cr25 system is gradually increased, as shown in Figure 6(c,d). The wear mechanism is changed from abrasion wear to abrasive and adhesive wear.

4. Conclusions

1) The microstructure of annealing Cr25 cast steels at 1180-1200 °C for 5-10 h, it is composed of ferrite + $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ phase. The $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides are firstly precipitated from ferrite matrix at 1800-1200 °C for 10 h and 5 h, respectively. And then the $(\text{Cr}\cdot\text{Fe})_{23}\text{C}_6$ carbides are dissolved in the ferrite matrix at 1200 °C for 10 h.

2) The hardness of annealing Cr25 cast steels is not improved with the increase of annealing temperature and the longer holding time. But the impact toughness compared with the cast state slightly is increased from 6 J/cm² to 8 J/cm².

3) The wear-resistant of the high Cr ferrite cast steel is increased and improved with annealing temperature and holding time at 260 °C. The wear mechanism is changed from abrasion wear to abrasive and adhesive wear. The good wear-resistant of the high Cr ferrite cast steel is mainly attributed to the fine uniformly dispersed carbides.

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