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Relations of abrasion resistance and hardness of 16Cr-3C white irons with retained austenite content

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Abstract: The relationship between the retained austenite content of the matrix in 16Cr-3C white irons and the abrasion resistance was investigated. The results show that: (1) the abrasion resistance can be improved by sub-critical heat treatment, which could be attributed to the decrease of the retained austenite content; (2) both the abrasion resistance and hardness can be improved by controlling the retained austenite content below 20%-30% and arrive at the maximum when the retained austenite content is reduced to about 10%; (3) the abrasion resistance decreases abruptly once the retained austenite content is lower than 10%, which stems from both the *in situ* transformation of $(Fe, Cr)_{23}C_6$ to M_3C carbides and the formation of pearlitic matrix.

Key words: retained austenite; abrasion resistance; hardness; white iron

1 Introduction

High-chromium white irons have long been considered the candidate materials in mining and materials industry due to their excellent abrasion resistance imparted by the hard alloy eutectic carbides present in the microstructure [1, 2]. Some researchers considered that the carbides have an important influence on the abrasion resistance of high chromium white irons [3], whereas Fulcher *et al.* considered that the matrix structure has more influence [4]. Generally, the role of the matrix structure in the abrasion resistance of white iron could be envisaged by comparing the predominantly austenitic matrix with the predominantly martensitic matrix [5-11]. Sare and Arnold [2] found that the best abrasion resistance corresponds to 30%-50% austenite in the matrix, whereas Tabrett [12] indicated that the abrasion loss is independent of austenite content when the austenite content is above 20%-30%. Other researchers considered that the martensitic matrix is superior to austenitic matrix for better abrasion resistance [5, 13, 14]. While, there is an agreement that the pearlitic matrix will deteriorate the abrasion resistance, due to poor support of the carbides, and, thereby this matrix structure is generally avoided if good abrasion resistance is required [7, 11].

The purpose of this paper is to give a further insight into the relations of the hardness and abrasion resistance of 16Cr-3C white irons subjected to sub-critical heat treatment with the retained austenite content in the matrix.

2 Experimental

2.1 Materials and heat treatment

Two kinds of high chromium white irons were cast at 1500°C as ϕ80 mm balls by chilled mould, whose chemical compositions are given in **table 1**, and the balls were cut into 10 mm×10 mm×10 mm samples. The test samples of 1# were sub-critical treated at 500, 520, 540 and 560°C, respectively. The holding time was 2, 4, 6, 8 and 10 h for each temperature. The test samples of 2# were sub-critical treated at 520, 540, 560, 580 and 600°C, respectively, the holding time was from 2 to 30 h and one sample was taken out per 2 h. After sub-critical treatment, the samples were air-cooled to room temperature.

Table 1 Chemical compositions of the high chromium white iron (wt%)

Sample	C	Si	Mn	Cr	Mo	Cu	Cr/C
1#	2.88	0.95	2.68	16.42	—	—	5.70
2#	2.77	0.70	1.90	16.38	1.08	0.90	5.91

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2.2 Microstructural and microfractographic tests

The microstructure was characterized by optical microscope and scanning electron microscopy. The content of the retained austenite was measured using XRD (X-ray diffraction) combining with a self-built magnetic balance whose accuracy degree is 0.1 g, and the mean value of the computing results based on different crystal faces to eliminate the effect of the columnar structure was obtained. The results are given as the volume fraction of austenite in the matrix. The carbides and matrix structure were investigated by using an analytical electron microscopy, Philips Tecnai 20 HR-TEM (high resolution transmission electron microscopy) equipped with EDX (energy dispersive X-ray analyzer).

2.3 Hardness and abrasion wear tests

The bulk hardness was measured using Rockwell hardness meter with a load of 1.47 kN. The samples which have maximal secondary effect were selected to do dead-load sliding wear experiment using an M-200 abrasion experimental aircraft. In the wear experiment, the nether sample is ϕ50 mm $45^\#$-steel ring outer with $150^\#$-alumina (Al_3O_2) cloth and the upper sample is high chromium white cast iron sample, the load is 49 N and the rotational speed of the nether sample is 200 r/min, and it takes 3 min for each time. And such in this way, a sample was tested 3 times. The losing mass of the sample was measured by a TG328A photoelectric balance and the abrasive resistance was evaluated using the mean value of the tests. In comparison with the as-cast condition, the relative wear ratio (β) is defined as

$$\beta=\frac{\text{Mass loss of as-cast sample}}{\text{Mass loss of sub-critical treated sample}}.$$

3 Results

3.1 Microstructure

The microstructures in the as-cast condition are shown in **figure 1**. The analysis of X-ray diffraction indicates that the microstructure consists of the retained austenite, martensite and eutectic carbides, and the retained austenite contents of samples $1^\#$ and $2^\#$ are 56.2% and 64%, respectively. By quantitative analysis of metallurgical phase, the contents of eutectic carbides are 20.4% and 15.8%, respectively.

As seen in **figure 2**, the eutectic carbides appear unchanged, while most retained austenite has transformed into martensite after sub-critical treatment. There is a small quantity of retained austenite in the matrix for alloys $1^\#$ and $2^\#$. As seen in **figure 3**, the retained austenite contents in the matrix of the two white irons decrease with the holding time prolonging. The transforming ratio of retained austenite differs for different temperatures. The transformation of retained austenite into martensite causes secondary hardening because the hardness of martensite is higher than that of austenite.

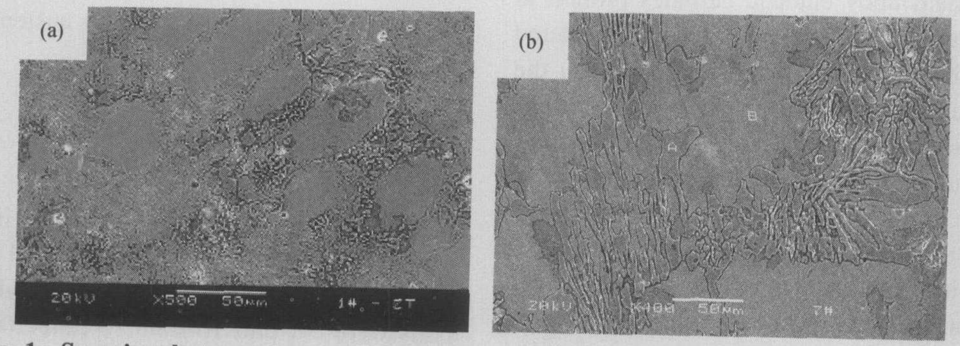

Figure 1 Scanning electron micrographs of the two alloys in as-cast condition: (a) alloy $1^\#$; (b) alloy $2^\#$.

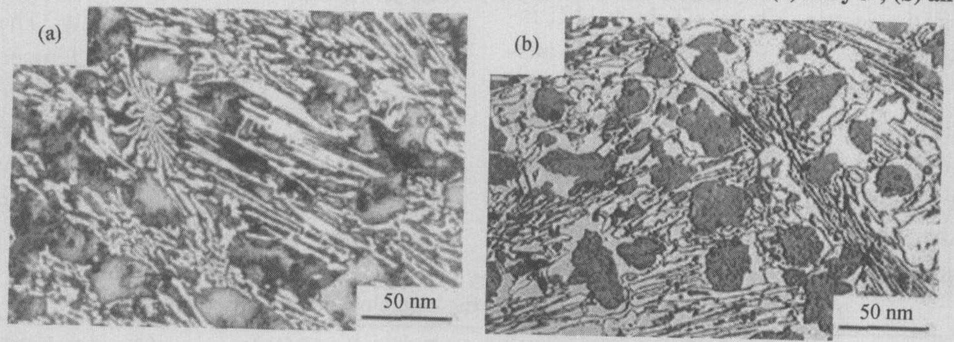

Figure 2 Optical micrographs of the alloys subjected to sub-critical heat treatments at various temperatures: (a) alloy $1^\#$ sub-critical treated at 520°C for 8 h; (b) alloy $2^\#$ sub-critical treated at 580°C for 10 h.

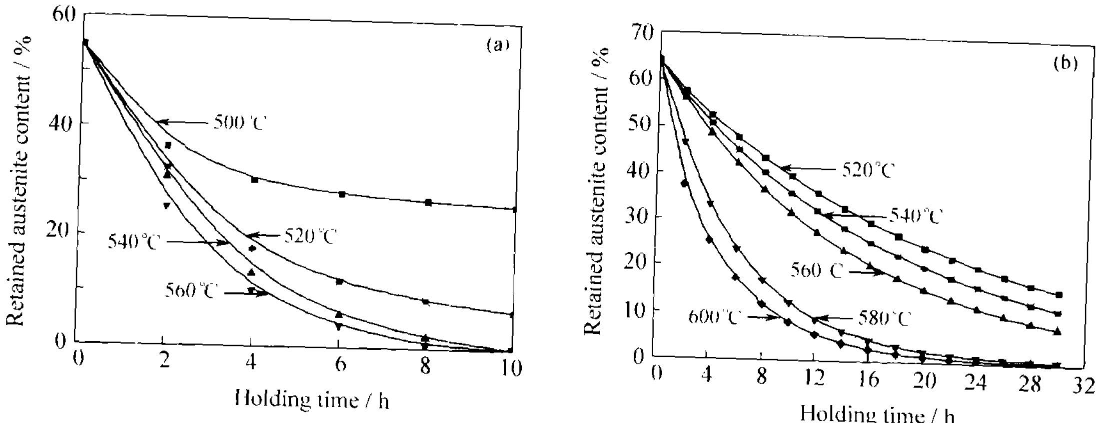

Figure 3 Changes of the retained austenite content (wt%) in the matrix of the two alloys in sub-critical heat treatment: (a) alloy $1^{\#}$; (b) alloy $2^{\#}$.

3.2 Hardening behavior

Figure 4 illustrates the hardening behavior of the alloys subjected to sub-critical heat treatment at different temperatures. It can be elicited that alloy $1^{\#}$ which being sub-critical treated at 520, 540 and 560°C and alloy $2^{\#}$ which being sub-critical treated at 560, 580 and 600°C have obvious secondary hardening behavior. And the hardness arrives at the maximum at a proper temperature and a holding time.

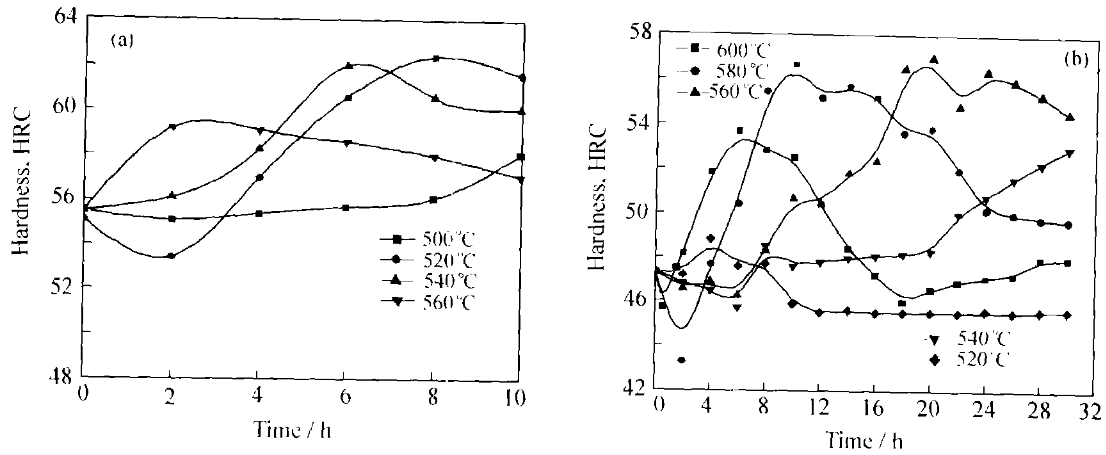

Figure 4 Hardening behavior of the alloys subjected to sub-critical heat treating at different temperatures: (a) alloy $1^{\#}$; (b) alloy $2^{\#}$.

3.3 Abrasive wear behavior

An example of white iron wear surface following abrasion 150-girt Al_2O_3 is provided in **figure 5**. For all of the white irons, wear is relatively mild, primarily involving plastic deformation in the form of grooving and wear sheet formation (figure 5(a)). Composed of the compacted debris generated by abrasion-surface interactions, the wear sheet formed at the surface of white irons is usually deformed heavily. Fracture of the wear sheet occurs primarily at the edges of grooves, where heavily deformed materials pile up. Subsurface fracture, which is the principal mechanism of material removal, occurs primarily at microstructural heterogeneities, and is usually not extensive (figure 5(b)). Under a definite pressure, Al_2O_3 granules would penetrate into the sample surface and plough the material with shearing stress. In course of abrasion, the abrasive grains would gradually dull due to wear abrasion pushing materials to both sides of abrasion grooves forming ridge. The materials drop out for plasticity exhausted during ploughing and pushing again and again.

Figure 6 shows the relationship between the relative wear ratio and the retained austenite contents. As shown in figure 6, the relative wear ratio of the alloys has no notable change if the retained austenite contents are higher about 15% for alloy $1^{\#}$ and 30% for alloy $2^{\#}$. The relative wear ratio increases when the retained austenite contents are less than about 15% for alloy $1^{\#}$ and 30% for alloy $2^{\#}$ and obtains the maximum when retained austenite contents are about 10% for the two alloys. It decreases sharply when the retained austenite contents are less than 10%.

3 Discussion

In an attempt to rank materials based on intrinsic properties, several models have been developed which assume that the subsurface lateral fracture is responsible for much of the materials removed during abrasion wear [15-18]. Most of these models fit the following equation to predict the volume wear loss developed by Evans and Marshall [15]:

$$V=\alpha\frac{P_N^{9/8}}{K_c^{1/2}H^{5/8}}\left(\frac{E}{H}\right)^{4/5}L,$$

where α is the material-independent constant, P_N is the normal load, K_c, H and E are the fracture toughness, hardness and Yong's modulus of the abraded material respectively, and L is the sliding distance. For a material given the composition and experiment condition, α, P_N and E are delimited. Only improving K_c and H can improve the abrasion resistance. In the previous research [19] the fracture toughness of white iron has little change after sub-critical heat treatment. Thereby the abrasion resistance of alloys depends on the hardness of the alloys.

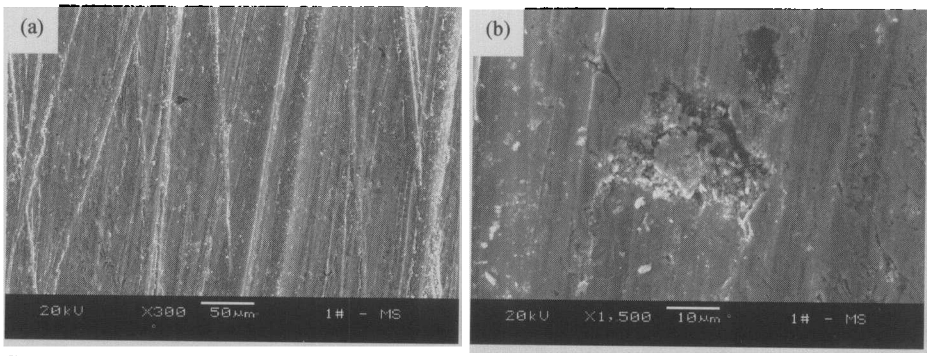

Figure 5 Scanning electron micrographs of an abrasion sample: (a) low magnification; (b) high magnification.

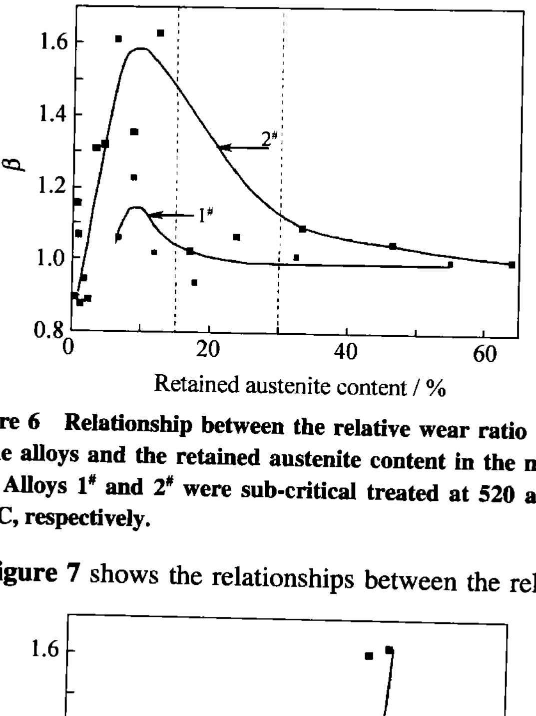

Figure 6 Relationship between the relative wear ratio (β) of the alloys and the retained austenite content in the matrix. Alloys 1# and 2# were sub-critical treated at 520 and 580°C, respectively.

Figure 7 shows the relationships between the relative abrasion ratio β and the hardness of the alloys. As it shows, the relative abrasion ratio β is proportional to the hardness, it increases with the hardness increasing, and it has no notable change when the hardness is lower than one value. The values are about HRC 56 for alloy 1# and HRC 53 for alloy 2#.

Figure 8 shows the relationships between the hardness and the retained austenite content of the alloys. It can be found that the hardness increases with the retained austenite content decreasing. In the sub-critical heat treatment process, the precipitation of (Fe, Cr)$_{23}$C$_6$ in austenite destabilizes due to the reducing Cr and C content of austenite (see **figure 9**). This destabilized austenite has a higher M_s temperature than the as-cast structure and is, therefore, more likely to transform into martensite during air-cooling to room temperature. This causes the hardness increasing. And, at

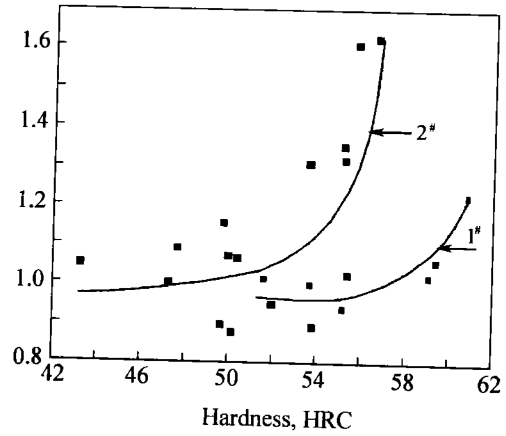

Figure 7 Relationships between the relative wear ratio and hardness of the alloys. Alloys 1# and 2# were sub-critical treated at 520 and 580°C, respectively.

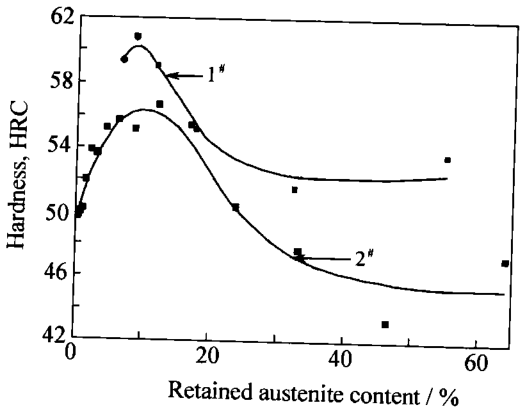

Figure 8 Relationships between the hardness of the alloys and retained austenite content in the matrix. Alloys 1# and 2# were sub-critical treated at 520 and 580°C, respectively.

the same time, there are ε-carbide precipitates from the supersaturated martensite obtained in the solidifying process (see **figure 10**). This causes the hardness of martensite decreasing. As a result of the two effects, the hardness increases by slow degrees. Thereby the relative abrasion ratio does not be improved markedly. Prolonging the holding time, more secondary carbides precipitate and more retained austenite transforms into martensite during air-cooling to room temperature. The increasing of hardness caused by these reasons above exceeds the decreasing of hardness caused by the decreasing of martensite hardness when about more than 40% of the retained austenite for alloy 1# and 65% for alloy 2# have transformed into martensite. This causes the hardness and relative wear ratio increasing sharply. That is to say, the hardness and abrasion resistance can be improved if the relative percentage transforming is in 40%-65% for 16Cr-3C white irons. And the hardness and relative wear ratio obtain the maximum when the retained austenite content is about 10%.

Prolonging the holding time the austenite level can be ulteriorly reduced, but an *in situ* transforming to M_3C carbides happens to $(Fe, Cr)_{23}C_6$ (see **figure 11**) when the retained austenite content reaches about 10%. Synchronously the matrix begins to transform to pearlitic matrix. These decrease the hardness of the alloys, as a result, the abrasion resistance decreases sharply. Moreover, an amount of retained austenite in the matrix can inactivate crack tip and inhibit the crack developing for better microplasticity of retained austenite [20]. Thereby too less retained austenite makes against the improving of abrasion resistance.

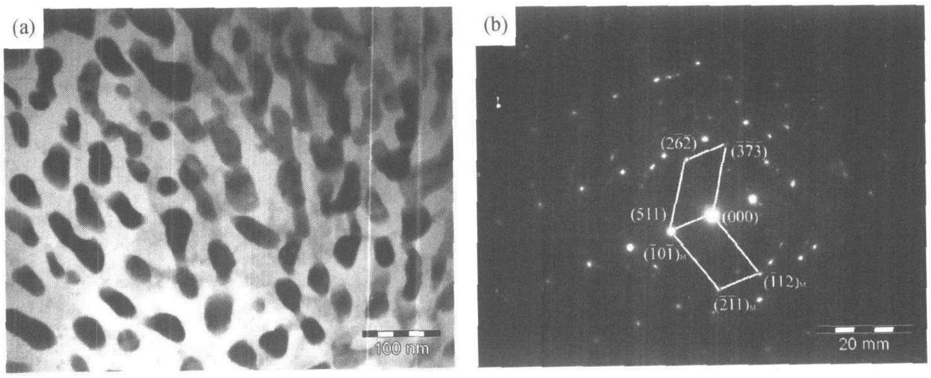

Figure 9 TEM showing $(Fe, Cr)_{23}C_6$ precipitated in the austenite grains (a) and its SADP (b).

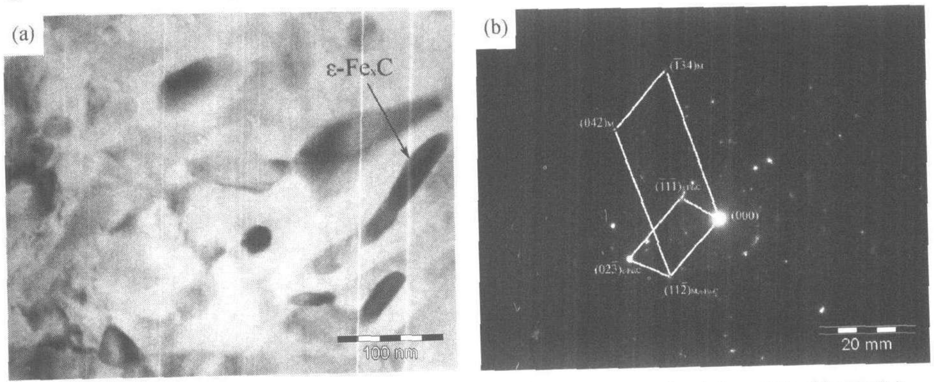

Figure 10 TEM showing ε-carbide precipitated from martensite (a) and its SADP (b).

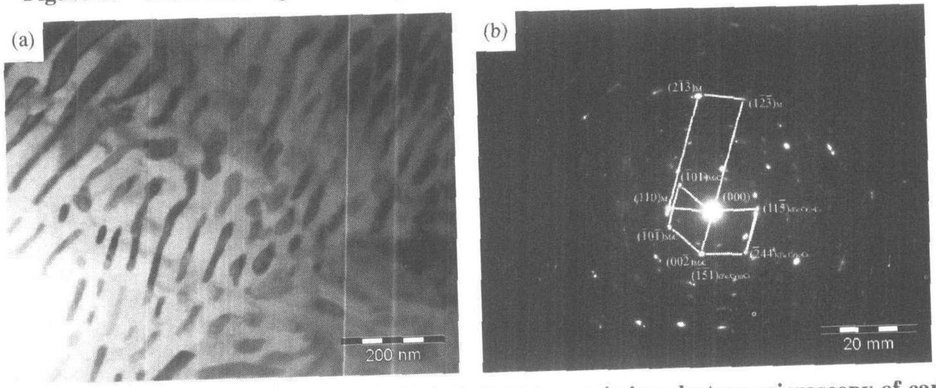

Figure 11 *In situ* transformation of $(Fe, Cr)_{23}C_6 \rightarrow M_3C$: (a) bright-transmission electron microscopy of carbides; (b) SADP of (a).

4 Conclusions

(1) The retained austenite can be reduced effectively to a very low level through sub-critical heat treatment. The abrasion resistance can be improved because of the hardening of the alloys induced by the retained austenite transforming into martensite. The relative wear ratio is proportional to the hardness.

(2) The hardness and abrasion resistance can be improved greatly when the retained austenite contents are lower than about 15% for alloy $1^{\#}$ and 30% for alloy $2^{\#}$ under the experiment condition. The hardness and abrasion resistance can be improved if the relative percentage transforming is in 40%-65% for 16Cr-3C white irons.

(3) The alloys obtain the best abrasion resistance when the retained austenite content is reduced to about 10%.

(4) The abrasion resistance decreases sharply when the retained austenite content is lower than 10% because of the hardness decreasing of secondary carbides and matrix caused by the *in situ* transformation of $(Fe, Cr)_{23}C_6$ to M_3C and pearlitic transformation.

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