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Effect of Silicon on Subcritical Heat Treatment Behavior and Wear Resistance of 16 wt% Cr Cast Iron with 2 wt% Mo

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Abstract

Effects of Si content on the hardness, decomposition of austenite and abrasive wear resistance during subcritical heat treatment of hypoeutectic 16 wt% Cr -2 wt% Mo cast irons were investigated. The hypoeutectic 16 wt%Cr-2wt% Mo cast irons with 0.5-2.0 wt% Si were prepared. The as-cast specimens were heated up to subcritical temperatures at 50 K intervals from 673K for 14.4 ks ,28.8 ks and 43.2 ks and then, cooled to the room temperature by fan air cooling. In the as-cast state, the hardness increased gradually as Si content increased to 1.5 wt% and then decreased rapidly. The size and the amount of eutectic carbides increased with increasing Si content. In the subcritical heat treatment state, the hardness curves showed a secondary hardening due to the transformation of austenite into martensite and the precipitation of secondary carbides. The degree of secondary hardening decreased with increasing Si content. The decomposition fraction of austenite (f) increased abruptly when the holding temperature rose over 823 K. The maximum hardness (H_{STmax}) was obtained by the condition of 873 K for 14.4-28.8 ks where the f was about 70-80%. The highest value of (H_{STmax}) 740 HV_{30} was obtained in the 1.5 wt%Si specimen. The linear relation was obtained between the wear loss and wear distance. The wear loss decreased with an increase in Si content. The highest wear resistance was obtained in the specimen with H_{STmax} and the lowest wear resistance was obtained in over-tempered specimen.

Keywords: Subcritical heat treatment, 16wt%Cr-2wt%Mo cats iron, Hardness, Decomposition fraction, Wear resistance, Si effect

Introduction

High chromium cast iron containing 12-30 wt% (as shown by %) Cr has been employed as abrasive wear resistant material for parts and components in various fields of industries because of its high abrasive wear resistance and comparatively good toughness when compared with plain white cast iron. The 15-17% Cr cast irons with Mo have been applied to liners, rollers and tables of pulverizing mills in the mining and cement industries because of their high abrasive wear resistance and suitable toughness. High chromium cast irons with hypoeutectic compositions are preferable as they avoid precipitating primary carbides that reduce their toughness. The primary purpose of Mo addition is to avoid the formation of pearlite and to improve the hardenability during heat treatment.

Practical use has shown that as-cast high chromium cast irons having austenitic matrix show poor abrasive wear resistance because it promotes spalling wear.(3) It has been reported that high chromium cast iron, which had martensitic matrix with some retained austenite, showed the greatest wear resistance to spalling.(1,3) Therefore, heat treatment of high

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chromium cast irons must be conducted so that the optimal combination of hardness and the quantity of retained austenite can be obtained from the view point of sequence abrasive wear resistance. When medium hardness is required, the most obvious advantage of using the subcritical heat treatment, which is carried out by holding the as-cast iron at the temperature below pearlite transformation point (A_1), is the cost and energy conservation that results from eliminating the high temperature heat treatment of hardening.

During holding at subcritical temperature, austenite in as-cast state is destabilized by the precipitation of secondary carbides and transforms to martensite during cooling. Sun et al[4] reported that the secondary carbides of $M_{23}C_6$ precipitated together with some molybdenum carbides, and matrix was mostly martensite after holding at 853 K in 16%Cr-1%Mo-1%Cu cast iron. However, the pearlite transformation took place when holding time increased over 22 hours. Parks[2] reported that the subcritical heat treatment could improve wear resistance of cast irons. It is considered due to the precipitation of secondary carbides as well as an increase in the amount of martensite increased the matrix strength.

It is well known that Si decreases stability of austenite. It was reported that Si promoted the transformation of austenite to martensite in high chromium cast iron.[1,3] However, the addition of 2.2% Si promoted the pearlite transformation in as-cast condition which reduced wear resistance.[2] Some research papers suggested that Si improved the toughness of the cast iron because it reduced the connectivity of eutectic carbides.[1-3] Therefore, the systematic research on the effect of Si on the hardness and wear resistance of high chromium should be investigated systematically and more in details.

The researches on the usual heat treatment of hardening and tempering for high chromium cast iron have been extensively reported.[1,3,6-13] However, research on subcritical heat treatment is quite limited.[2,4,5] Particularly, the systematic research on effect of Si on the variation of hardness and the decomposition of austenite (f), during subcritical heat treatment of 16%Cr cast iron with 2%Mo, has not been found.

In this study 16%Cr-2%Mo hypoeutectic cast irons with 0.5%-2.0 Si % were prepared. The effects of holding time and Si content on the behavior of hardness and f during the subcritical heat treatment were investigated under the various holding temperatures. In addition, the abrasive wear resistance under suitable heat treatment conditions was evaluated.

Materials and Experimental Procedures

Preparation of Test Specimens

The charge materials for test specimens were melted and superheated up to 1853K using a high frequency induction furnace with alumina lining. The melt was poured from 1773- 1793 K into a preheated CO_2 mold with a capacity size of 25-mm diameter and 65-mm length through a sufficient riser. The surface of melt was immediately covered with preheated exothermic powder to prevent the riser from rapid cooling. The specimens were sectioned by a wire-cut machine to obtain disk-shaped test pieces of 7-mm thickness. The chemical composition of the test specimens are shown in Table 1.

Table 1. Chemical composition of test specimens

Specimen	Element (wt%)				
	C	Cr	Si	Mn	Mo
No.1	2.95	16.06	0.56	0.56	2.00
No.2	2.92	15.93	0.94	0.56	2.03
No.3	2.95	15.94	1.46	0.57	1.98
No.4	2.94	15.93	1.94	0.54	1.96

Heat treatment procedure

The as-cast specimen was heated up to subcritical temperatures at 50 K intervals from 673 K for 14.4 ks, 28.8 ks and 43.2 ks and then, cooled to the room temperature by fan air cooling.

Measurement of Hardness and Observation of Microstructure

Measurement of macro-hardness and micro-hardness were performed by a Vickers hardness tester with the loads of 300 N (30kgf) for macro-hardness and 1N(0.1kgf) for micro-hardness, respectively. To observe the microstructures, specimens were polished using emery papers and then finished by a buff cloth with extremely fine alumina powder of

0.3 µm in diameter. The microstructures were revealed using Vilella's reagent. The investigation was performed by an optical microscope (OM) and a scanning electron microscope (SEM). Measurement of decomposition fraction of austenite (f) was performed by an imaage analysis system. In each specimen the images were carefully taken around the center of the test piece, and more than 50 fields at magnification of 200 times were adopted for calculation.(3) The decomposition fraction of austenite (f) was calculated using the following equation;

$$f(\%) - (\frac{Ad}{Am}x100)$$

f = Decomposition fraction of austenite
Ad = Area fraction of transformation
Am = Area fraction of matrix

Abrasive Wear Test

A schematic drawing of an abrasive wear tester is illustrated in Figure 1. Under the load of 5 N (0.5kgf), the abrading wheel (44 mm in diameter and 12 mm in thickness) with a 180 mesh SiC abrasive paper on the circumference was revolved intermittently while moving back and forth by 35 mm traveling stoke on a same area of the test piece in dry condition. The revolving speed of the abrading wheel was 0.345 mm/s and the worn area was 420 (12x35) mm^2. The abrasive wear loss of the test piece was measured using an electronic balance after one cycle test, which takes 400 s, and the test was repeated up to eight times for one test piece.

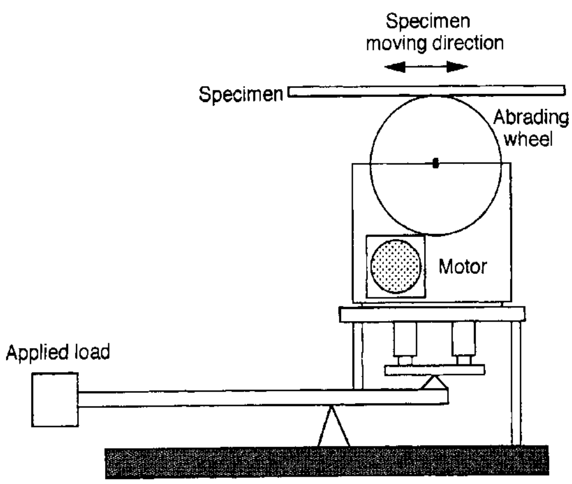


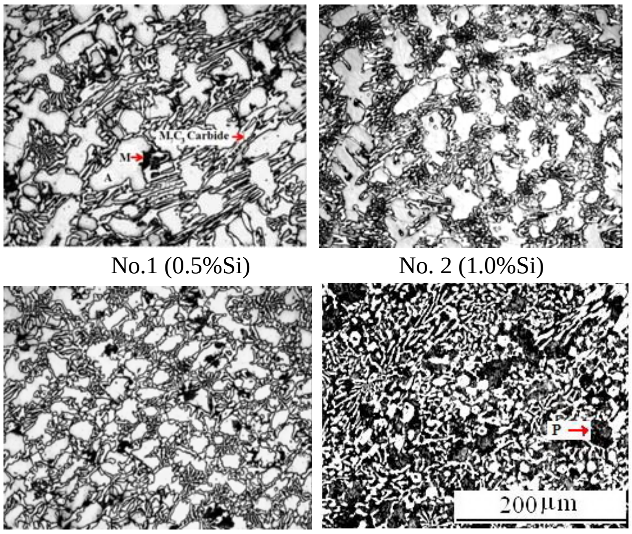
Figure 1. A schematic drawing of abrasive wear testing machine.

Results and Discussions

As-cast State

The typical as-cast microstructures of 16% Cr- 2%Mo specimens with Si taken by OM are shown in Figure 1. Each specimen had similar microstructure consisting of primary dendrites austenite and eutectic structures. The matrix structures were austenitic with some martensite except for 2.0% Si specimen which was pearlitic.
It was found that the size of the eutectic carbides was more equiaxed and the volume fraction of carbide increased with rising Si content. This is because Si decreases the austenite and eutectic start temperatures. It is well known that Si has significant effect on the eutectic composition that it shifts the eutectic point to the lower carbon side.(3) Therefore, it is natural that the microstructure of 2%Si specimen was close to the eutectic composition.(13)

Effect of Si content on macro-hardness and micro-hardness in as-cast state is shown in Figure 2. The macro-hardness increased gradually to the maximum value and then decreased remarkably as Si content increased. The micro-hardness shows similar behavior to the macro-hardness. An increase in the hardness by Si addition is due to an increase in volume fraction of eutectic carbides. It is possible that the amount of martensite increases with increasing Si content because Si decreases the solubility of carbon in austenite, thereby rising the Ms temperature.(1)



No.1 (0.5%Si) No. 2 (1.0%Si)
No. 3 (1.5%Si) No. 4 (2.0% Si)

Figure 2. As-cast microphotographs of 16% Cr-2%Mo cast irons with Si. (A: Austanite, M: Martensite, P: Pearlite)

Subcritical Heat Treatment State

The hardness after subcritical heat treatment depends on the transformation of austenite. During holding at a subcritical temperature, the secondary carbides precipitate in austenite. Resultantly, C and Cr contents in the residual austenite were reduced, and this can make the austenite transform into martensite during cooling.

As a typical example, the microstructures of the 16%Cr-2%Mo with 1.5%Si specimen held at 14.4 ks for various temperature are shown in Figure 3. As the holding temperature increases, the dark area where austenite transformed into martensite increases. This proves that the decomposition of austenite proceeds isothermally with an increase in holding temperature. It was found that most of the austenite transformed to martensite at the holding temperature of 873 K. Some papers reported that the majority of the matrix in the dark areas is martensite.[1,4,5] However, it is possible that some pearlite also exists within these dark areas. The precipitation of secondary carbides in the dark area was nonuniform and the size of secondary carbides was less than 5 um.[1] When the specimen was held over 873K, however, the transformation of austenite to pearlite occurred. This is because Si promotes the pearlite transformation.

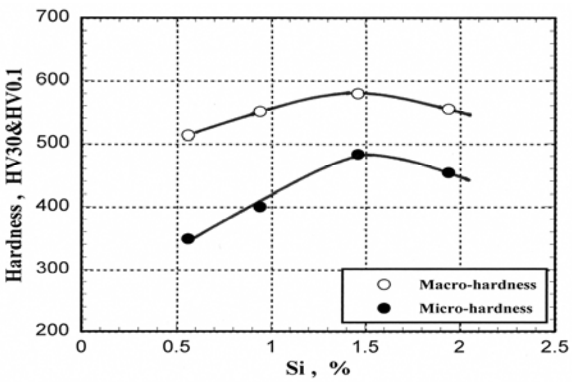


Figure 3. Effect Si content on the macro-hardness and micro-hardness of 16% Cr -2% Mo cast irons in the as-cast state.

The effects of holding time on the macro-hardness and micro-hardness are representatively shown in Figure 4. In each diagram, as-cast hardness are plotted for a better understanding. Regardless of Si content, the variation of hardness curves shows more or less a secondary hardening due to the precipitation of secondary carbides during holding and the martensite transformation from destabilized austenite during cooling. The variation of micro-hardness was similar to the macro-hardness. The degree of secondary hardening, which is defined as the difference between the maximum hardness (H_{STmax}) and the as-cast hardness, decreased with an increase in Si content. The degree was much less in the 2.0% Si specimens because the matrix in the as-cast state was mostly pearlite. Therefore, it can be said that the difference in the as-cast matrix structure is closely related to be the difference in the degree of the secondary hardening. The f increased greatly as the holding temperature rose over 823 K, and the transformation was complete at 923 K except for the 2.0% Si specimen. The f was high in the case of higher holding time. Except for 2.0% Si specimen, the H_{STmax} values were obtained when the specimens were held at 873K for 14.4-28.8 ks. When the holding temperature exceeds 873K, the hardness reduced remarkably due to the coarsening of precipitated carbides and ferrite transformation. As presented in Figure 4, it can be found that the shortest holding time, 14.4 ks, to get the H_{stmax} value was obtained in the 1.5% Si specimen. It can be explained by the fact that Si reduces the solubility of carbon in austenite and promotes the precipitation of secondary carbides; these increase the rate of transformation of austenite to martensite.[1,2,13]

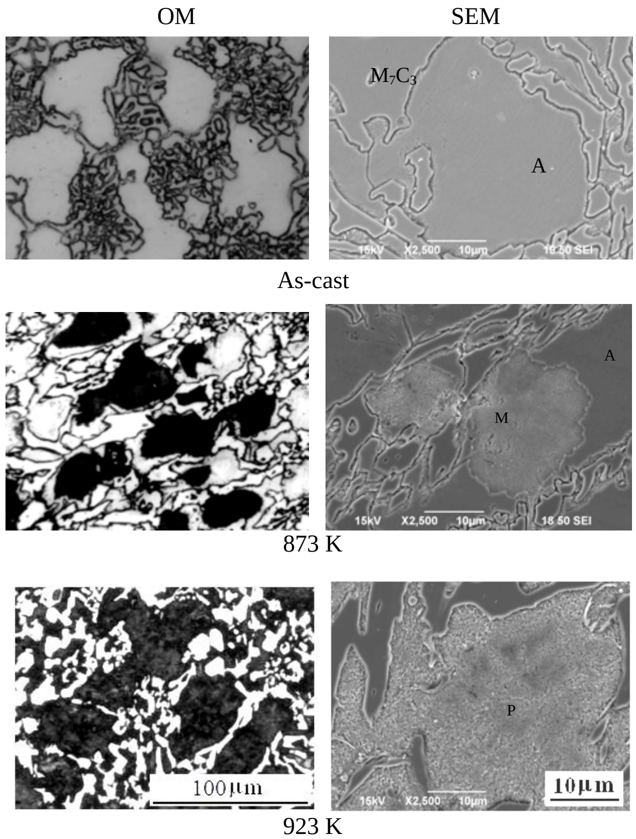
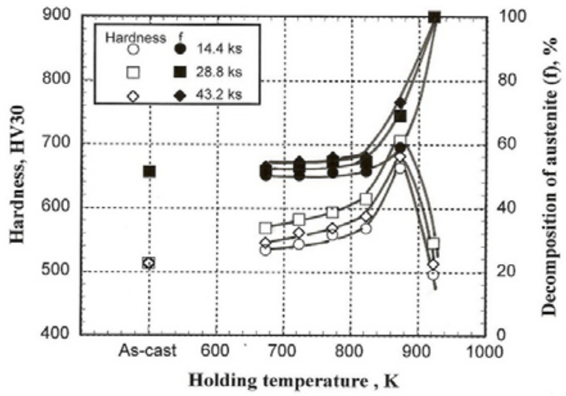
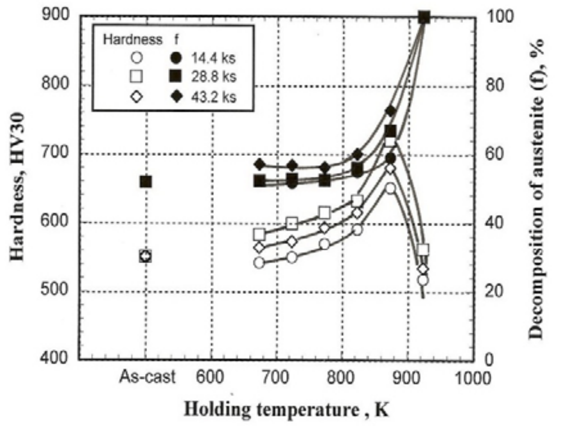


Figure 4. Effect of holding temperature on matrix transformation of16%Cr cast iron with 1.5%Si. Holding time: 14.4 ks; (A: Austanite, M: Martensite, P: Pearlite)

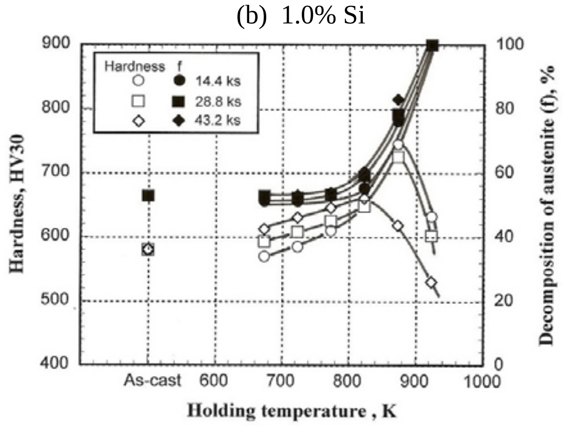
Here, the hardness obtained from all specimens was connected to a parameter of the f; it is shown in Figure 5. It was found that the hardness rises greatly to maximum value and then decreased remarkably as the decomposition fraction increased. The highest value of hardness was obtained at about 70-80% f. It is considered that an increase in the hardness was due to the precipitation of secondary carbides and following the martensite transformation of destabilized austenite. The remarkable decrease in the hardness at high decomposition fraction is also considered due to a decrease in amount of martensite together with the aggregation and coarsening of secondary carbides.



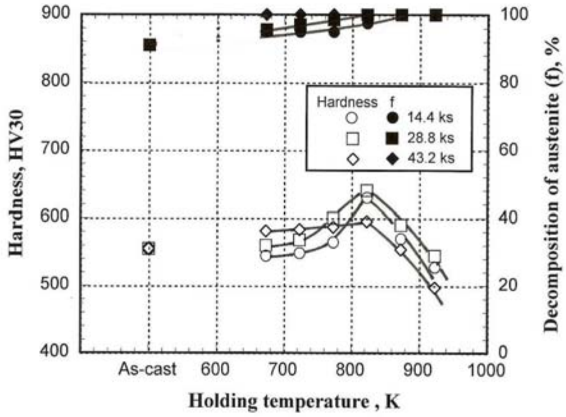
(a) 0.5%Si



(b) 1.0% Si



(c) 1.5% Si



(d) 2.0% Si

Figure 5. Effect of holding temperature on the hardness and decomposition of austenite (f) of 16%Cr cast iron with 1.5%Si.

The effect of Si content on the H_{stmax} obtained from all specimens is shown in Figure 6. The H_{STmax} rises to the maximum value at 1.5% Si. After that, it decreases abruptly. The reasons are described as above. The highest values of H_{STmax} are 740 HV_{30} for macro-hardness and 620 $HV_{0.1}$ for micro-hardness, respectively.

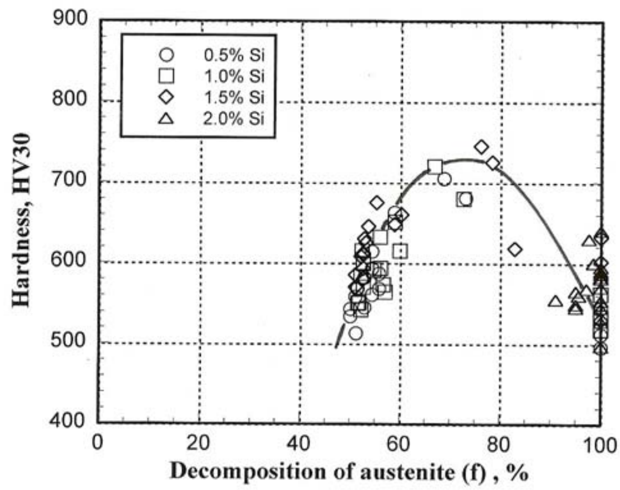


Figure 6. Effect of decomposition of austenite (f) on the hardness of 16% Cr-2%Mo cast irons with Si.

Abrasive Wear Test

Figure 7 shows the results of the abrasive wear test of 0.5% and 1.5% Si under suitable heat treatment conditions as shown in Figure 4. It was found that the wear loss increases in proportion to the wear distance in each specimen. The total wear loss in 1.5 % Si specimen was lower than that in 0.5% Si specimen. The highest wear resistance or lowest wear loss was obtained in the specimen treated at 873 K which has H_{STmax}. The lowest wear resistance or highest wear loss was obtained the specimen treated at 923 K which has over-tempering in both series of cast irons. Therefore, it can be said that Si improves the wear resistance of cast iron in the subcritical heat treatment process. It can be explained that the addition of Si up to 1.5% has an effect on increasing the size and volume fraction of carbide and increasing the matrix hardness leading to improve the wear resistance.

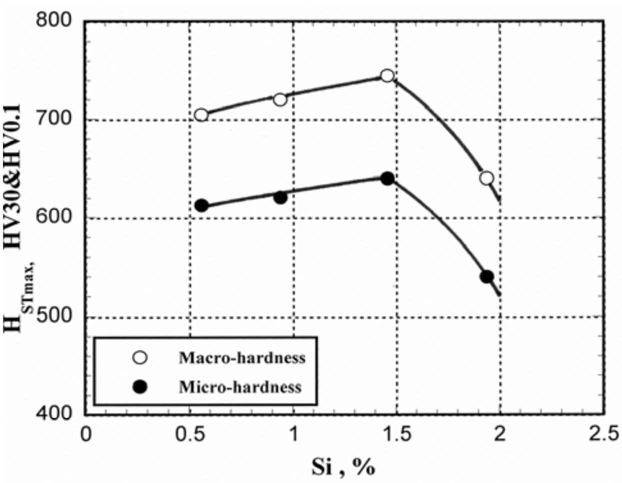
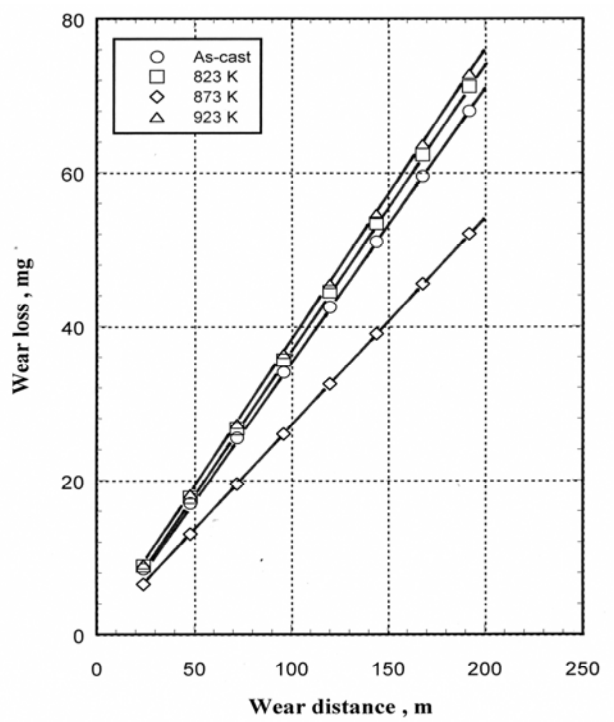
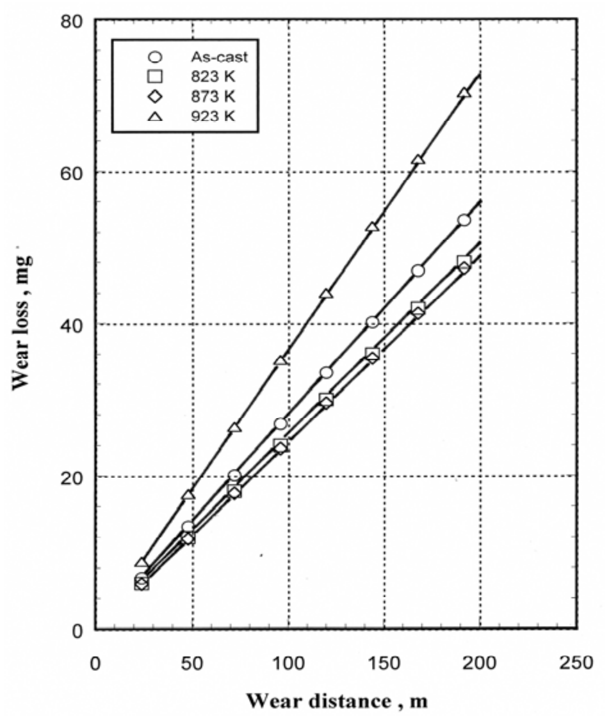


Figure 7. Effect of Si content on the maximum hardness in the subcritical heat treatment(H_{stmax}) of 16% Cr -2% Mo cast irons.



a) 0.5% Si



b) 1.5% Si

Figure 8. Relationship between wear loss and wear distance of 16% Cr-2% Mo cast irons with different heat treatment. Load: 5 N

Conclusions

Effects of Si content on the hardness, decomposition of austenite (f) and abrasive wear resistance during subcritical heat treatment of hypoeutectic 16%Cr -2%Mo cast irons were investigated. The results are summarized as follows;

(1) In an as-cast state, the hardness increased gradually as the Si content increased to 1.5%wt and then decreased rapidly. The size and volume fraction of eutectic carbides increased with increasing Si content.

(2) In the subcritical heat treatment state, the hardness curves showed a secondary hardening due to the transformation of austenite into martensite and the precipitation of secondary carbides. The degree of secondary hardening decreased with increasing Si content. The decomposition fraction of austenite (f) increased abruptly when the holding temperature rises over 823 K. The maximum hardness (H_{STmax}) was obtained by the condition of 873 K for 14.4-28.8 ks where the f was about 70-80%. The highest value of (H_{STmax}) 740 HV_{30} was obtained in the 1.5%Si specimen.

(3) The linear relation was obtained between the wear loss and wear distance. The wear loss

decreased with an increase in Si content. The highest wear resistance was obtained in the specimen with H_{STmax} and the lowest wear resistance was obtained in the over-tempered specimen.

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