# Effect of Silicon Content on Sub-critical Heat Treatment Behavior of 16%Cr-2%Mo Cast Iron

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**Abstract.** *The objective of this research is to clarify the effect of Si content on variation of hardness and retained austenite during sub-critical heat treatment of the 16 wt% Cr cast iron. The hypoeutectic 16 wt% Cr-2% Mo cast irons with 0.5-2.0 wt% Si were prepared. As-cast specimens were heated up to sub-critical temperatures at 50 K intervals from 673-923 K for 14.4, 28.8 and 43.2 ks and then, cooled to the room temperature in the air. The hardness and volume fraction of retained austenite ($V\gamma$) were measured. In the as-cast state, the hardness increased and then decreased as Si content increased. The $V\gamma$ decreased gradually with increasing the Si content to 1.5 wt% and after that, it decreased abruptly. In the sub-critically heat-treated state, the hardness increased first and subsequently decreased as the holding temperature was increased. The reason could be due to the transformation of austenite into martensite and the precipitation of secondary carbides. The degree of an increase in hardness becomes small with increasing the Si content. The $V\gamma$ decreased remarkably when the holding temperature increased over 823 K under the same holding time. The maximum hardness ($H_{STmax}$) was obtained by the treatment condition of 873 K for 14.4-18.8 ks where the $V\gamma$ was less than 15%. The highest value of $H_{STmax}$ ,745 HV30, was obtained in the 1.5 wt% Si specimen.*

## Keywords:

Sub-critical heat treatment, 16 wt% Cr-2 wt% Mo cast iron, hardness, retained austenite**,** silicon effect

## 1.Introduction

High chromium cast irons have been used as abrasion wear resistant materials more than 50 years. The heavy industries such as mine, cement, iron and steel, and thermal power plant are the main users.[1-3] These cast irons show the excellent resistance to abrasive wear because the microstructure consists of hard eutectic carbides together with a strong matrix structure. The commercial compositions are 12-30 wt% Cr (all compositions are given in %) and 2.0-3.6% C with some other alloying elements, say, Mo, Ni or Cu, to improve the hardenability. It is well known that the 15%-17% Cr cast irons with some Mo have been commonly used for rolling mill rolls in the steel plant and the components of machine in mining plant.[4,5] This is because high Cr cast irons have good wear resistance and suitable toughness.[6]

In the as-cast state, the microstructure of high Cr cast iron with hypoeutectic composition consists of primary austenite dendrites and eutectic structures of austenitic matrix and $(Cr,Fe)_7C_3$ or $M_7C_3$ carbides. However, there are many papers reported that the as-cast condition showed poor abrasive wear resistance under the high stress wear.[1,2,4,5,7] In order to get the high abrasion wear resistance, therefore, the cast iron must be heat-treated.[1-15]

The hardening of high Cr cast iron can be divided into two processes, destabilization and subcritical heat treatments. The destabilization heat treatment is that the as-cast iron is held at around 1223-1373 K to precipitate the secondary carbide in austenite and destabilize the austenite for readily transformation to martensite during cooling to room temperature. This process has been used when the high hardness over 800 HV is needed. When the medium hardness is required, the sub-critical heat treatment is introduced. Cast iron in the as-cast state is held at the subcritical temperatures, that is, below the temperature of pearlite transformation ($A_1$) and followed by air cooling. During holding, the austenite is destabilized by the precipitation of very fine secondary carbides and then transforms to martensite during cooling to room temperature. [8]

The wear resistance of high Cr cast iron depends on both the carbide and matrix structures. The third alloying elements are generally added to modify the both structures.[1-5,10-14] Powell and Randle [14] observed a reduction in the carbide interconnectivity when added 1.3% Si to 18% Cr cast iron. Laird and Powell [10] reported that Si inhibited the nucleation of the $M_7C_3$ carbide in the 18% Cr cast iron. It was also reported that the presence of Si affected the mechanical properties, the strength of matrix.[1,10] It is because Si reduced C in the austenite and promoted the transformation of austenite to martensite.

The heat treatment of hardening and tempering has been reported by many researchers. [1,3,5,6,8,10-14] However, the research on sub-critical heat treatment is quite limited.[15-17] The systematic research of Si effect on the sub-critical heat treatment behavior of high Cr cast iron has not been found. The objective of this research is to clarify the effect of Si content on the hardness and volume fraction of retained austenite (Vγ) of 16% Cr -2% Mo cast irons under the sub-critical heat treatment.

## 2. Experimental Procedures

The charge materials with target chemical composition were melted in an induction furnace and superheated to 1853 K and the melt was poured at 1773-1793 K into the $CO_2$ bonded sand mold having the cavity size of 25 mm in diameter and 65 mm in length with sufficient riser. The chemical compositions of test specimens are shown in Table 1. The round bar specimen was sectioned by wire-cutting machine to obtain the test pieces with 7 mm in thickness. The as-cast specimens were heated to the sub-critical temperatures from 673 to 923 K at 50 K interval and held for 14.4, 28.8 and 43.2 ks in each temperature. After holding, the test piece was cooled to room temperature in the air.

The bulk hardness or macro-hardness was measured using Vickers hardness tester with a load of 30 kgf and matrix hardness or micro-hardness was by the Micro-Vickers hardness tester with a load of 0.1 kgf. On the other hand, the microstructure was characterized by an optical microscope (OM) and a scanning electron microscope (SEM). The volume fraction of retained austenite (Vγ) was measured by X–Ray diffraction method using a special goniometer with automatic rotating and swinging sample stage that can cancel the texture effect of austenite dendrites. Mo-Kα characteristic x-ray beam with Zr filter was used as a X-ray source. The diffraction peaks adopted for calculation were α200, α220 for the ferrite or martensite phase and γ220, γ311 for the austenite phase, respectively. [10-18]

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

**Table 1** Chemical composition of test specimens

## 3. Results and Discussions

### 3.1 Microstructure in As-Cast State

The as-cast microstructures of all specimens consist of austenite dendrite and eutectic structure of ($\gamma$+$M_7C_3$). The matrices are mostly austenitic with some martensite except for 2.0% Si specimen of which matrix was almost pearlite. As typical example of the as-cast microstructure, the microstructure of 1.5% Si specimen is shown in Fig.1.

The effect of Si content on hardness in the as-cast state is shown in Fig. 2. The macro-hardness increases gradually to the maximum value and then decreases as the Si content increases. The micro-hardness shows similar behavior to the macro-hardness. The Vγ decreases abruptly when the Si content increases from 1.5% to 2%. An increase in hardness with increasing of Si content should be due to an increase of martensite. This is because Si decreases the solubility of carbon in austenite and increases the Ms temperature. [1,10]

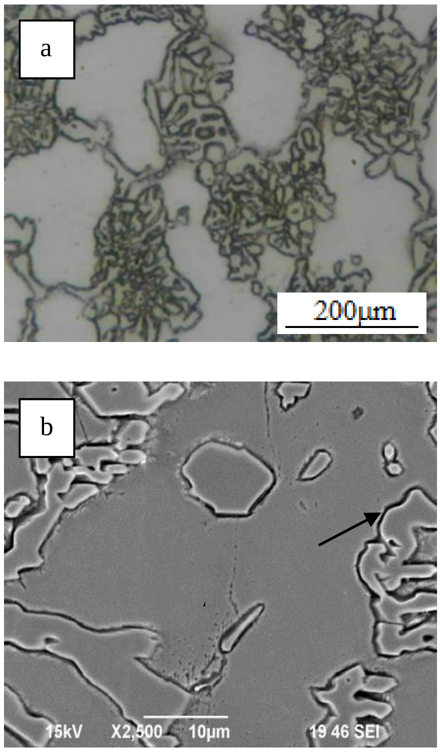



**Fig. 1** As-cast micrographs of 16%Cr cast iron with 1.5%Si. a: OM, b: SEM. (A: austenite, M: martensite)

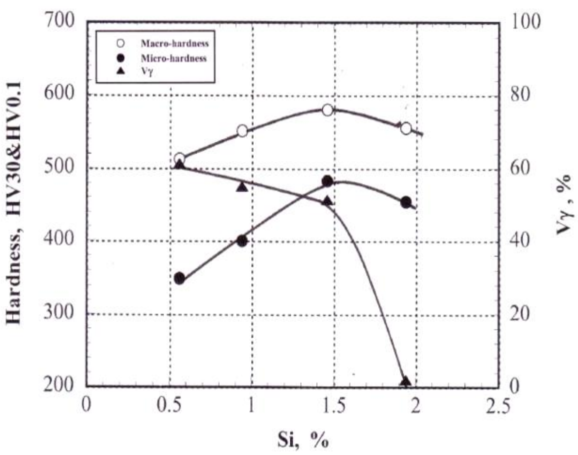



**Fig. 2** Effect of Si content on hardness and volume fraction of retained austenite (Vγ) of as-cast specimens

## 3.2 Sub-Critical Heat Treatment

Hardness and amount of retained austenite after sub-critical heat treatment vary depending on holding time, holding temperature and chemical composition of cast iron. The specimen in the as-cast state was held at a sub-critical temperature. After holding, the specimen was cooled in the air to room temperature by air. When as-cast specimen was heat-treated at a given sub-critical temperature, more austenite is decomposed as the holding temperature is increased.

In order to understand the transformation of matrix in details, the microstructures were observed using OM and SEM. As an example, the microphotographs of 1.5%Si-specimen which was held at 873 K for 14.4 ks are shown in Fig. 3. The transformation takes place at random within austenite dendrites as shown by the dark areas. It was reported that that the majority of phases in the dark areas are fine precipitated carbides, martensite and retained austenite [16-18]. In this experiment, however, it is possible that some pearlite exist there. This is because Si promotes the transformation of austenite to pearlite. When compared the specimens heat-treated at other temperatures, it was found that the austenite more decomposed more to martensite at 873 K. When the specimen is held over 873K, the transformation of austenite to ferrite and the precipitation of coarse secondary carbides occur.

The relationships between macro-hardness, Vγ and holding temperature are shown in Fig. 4 for a) 0.5%Si, b)1.0%Si and c)1.5% Si specimens, respectively. The hardness in the as-cast state is plotted for better understanding of the behavior of sub-critical heat treatment. The hardness increases to the maximum value and then decreases with an increase in the holding temperature. It can be said that this behavior is due to secondary hardening of the matrix in the same manner as obtained by the general heat treatment of hardening-tempering in alloyed steel and cast iron. It is precipitation of secondary carbides during holding and transformation of martensite in the destabilized austenite during cooling. The macro-hardness curves also show more or less the increase in the hardness and they are overall higher than the micro-hardness. This behavior tells that the macro-hardness directly reflected by the micro-hardness of matrix. The degree of secondary hardening, which is defined as the difference between the maximum hardness ($H_{STmax}$) and the hardness in the as-cast state, is shown in Table 2. It is found that the degree decreases with an increase in the Si content. This result can be explained by the fact that the Si decreases retained austenite in the as-cast state. The retained austenite plays an important role on the secondary hardening, the lower the Vγ, the smaller, the degree of secondary hardening. The degree of secondary hardening in 2% Si specimen is very less because the as-cast matrix was mostly pearlite. The $H_{STmax}$ is obtained when the specimen is treated at 873 K for 14.4-28.8 ks except for 2% Si specimen. As the holding temperature increases over a temperature which the $H_{STmax}$ is obtained, the hardness reduces remarkably due to the coarsening of precipitated carbides and a decrease of martensite. The ferrite produced finally is also one of the reasons [12-17].

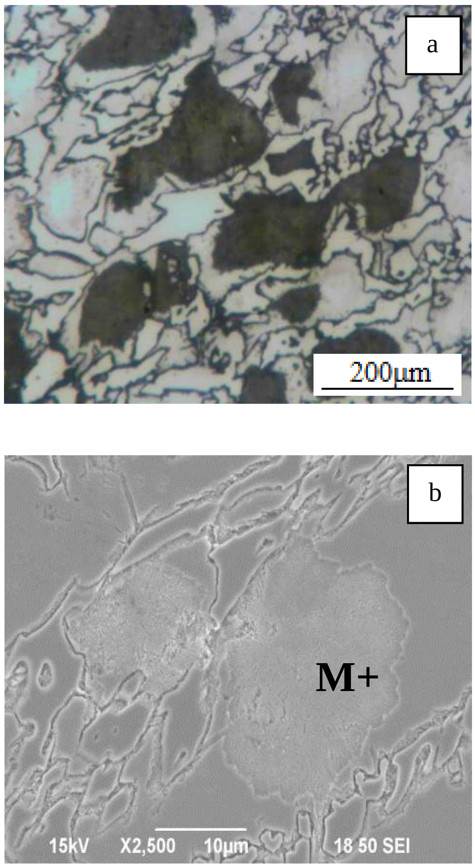
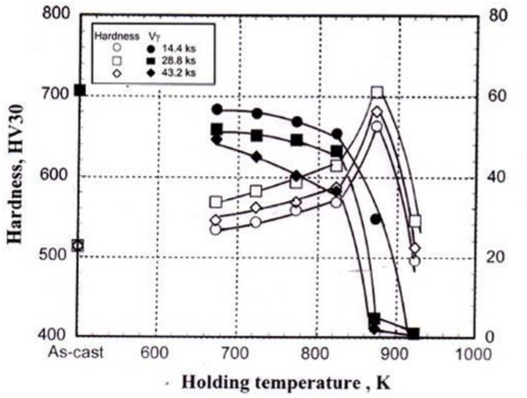
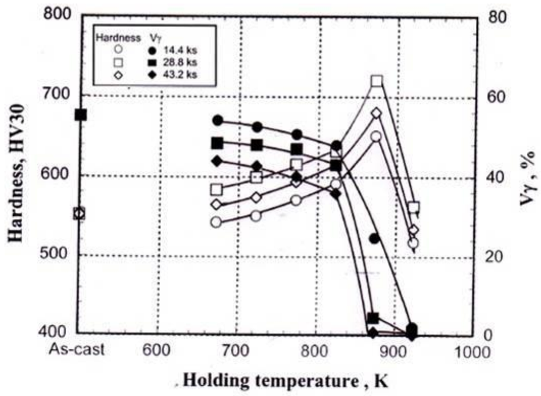


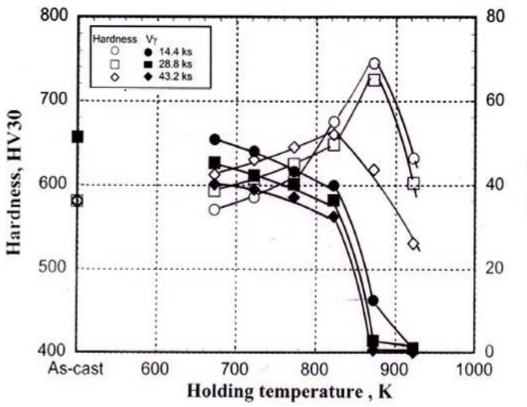

**Fig. 3** Transformation of matrix during sub-critical heat treatment of 1.5%Si specimen after holding at 873 K for 14.4 ks. a: OM, b: SEM. A: austenite, M: martensite, SC: secondary carbide




**a) 0.5% Si**




**b) 1.0% Si**




**c) 1.5% Si**

**Fig.4** Relationship between macro-hardness, volume fraction of retained austenite (Vγ) and holding temperature of 0.5%, 1.0% and 1.5% Si specimens.

| Specimen | An increase in hardness (HV30) | | |
|---|---|---|---|
| | 14. ks | 28.8 ks | 43.2 ks |
| 0.5% Si | +150 | +192 | +168 |
| 1.0% Si | +110 | +159 | +129 |
| 1.5% Si | +135 | +125 | +80 |
| 2.0% Si | +59 | +65 | +40 |

**Table 2** The degree of an increase in hardness of test specimen

In each specimen, the Vγ decreases as the holding time and holding temperature increase. Here, it is understood that longer holding time and higher holding temperature are needed to decompose a large amount of austenite in the as-cast state. At the same holding time, the Vγ decreases remarkably when the holding temperature is elevated over 823 K and becomes nil between 873K and 973 K. The Vγ value that gives $H_{STmax}$ exists in less than 15%.

The relationship between macro-hardness and Vγ in the sub-critical heat treatment state is shown in Fig. 5. The hardness increases and then decreases after reaching the maximum value. Such high hardness appears at the Vγ values less than 15%. The highest hardness is obtained in the 1.5 % Si specimen. It is concluded that Si promotes both the precipitation of secondary carbides and the transformation of martensite in the matrix during subcritical heat treatment.

In all the specimens, the $H_{STmax}$ is connected to the Si content and the relation is shown in Fig.6. The $H_{stmax}$ increases to be the maximum value at 1.5% Si as the Si content rises. After that, it decreases greatly. The highest values of $H_{stmax}$ are 745HV30 for macro-hardness and 644HV0.1 for micro-hardness, respectively.

In this subcritical heat treatment, the highest improvement of hardness by the addition of Si is obtained at 1.5%Si. This is because Si acted to destabilize the austenite and increased Ms temperature [1,14]. As mentioned previously, more precipitation of secondary carbides occurs as well as more retained austenite decomposes to martensite, as the holding time or temperature increases. As a result, the high hardness is obtained but too much addition of Si getting over 1.5% gives a negative influence because it promoted the pearlite transformation in the as-cast state.

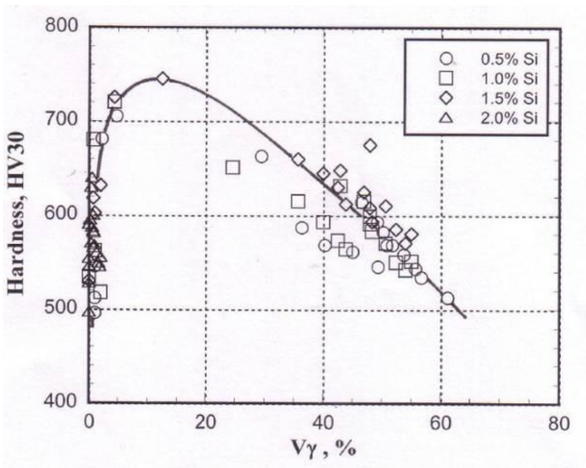



**Fig.5** Relationship between macro-hardness and retained of austenite (Vγ) of specimens.

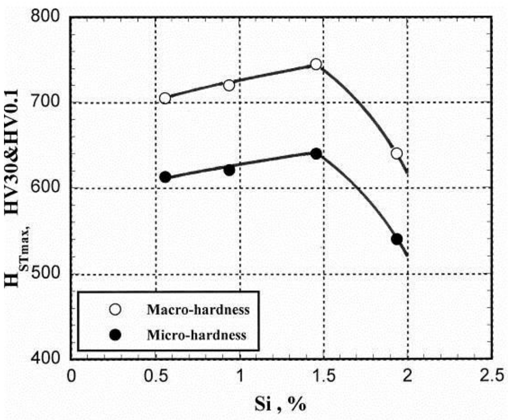



**Fig.6** Effect of Si content on maximum hardness ($H_{STmax}$) in sub-critical heat treatment

## 4. Conclusions

Effects of Si content on the hardness and volume fraction of retained austenite (Vγ) during sub-critical heat treatment were investigated using hypoeutectic 16%Cr - 2%Mo cast irons. The results are summarized as follows;

1. In the as-cast state, the hardness increased gradually as the Si content increased to 1.5% and then decreased. The Vγ decreased greatly as the Si content increased over 1.5 %.

2. In sub-critical heat treatment, the hardness curves showed a secondary hardening due to the precipitation of secondary carbides and the transformation of destabilized austenite to martensite. The degree of secondary hardening was decreased with increasing the Si content. The Vγ decreased greatly when the holding temperature gets over 823 K. The maximum hardness($H_{STmax}$) was obtained by the treatment of 873 K for 14.4 ks where the Vγ was less than 15%. The highest value of $H_{STmax}$ , 745HV30, was obtained in the 1.5%Si specimen.

3. The addition of Si up to 1.5% could improve the hardness of 16% Cr -2% Mo cast iron subject to sub-critical heat treatment

## Acknowledgements

The authors would like to thank the Faculty of Engineering, Mahasarakham University for research funding and Thai Parkerizing Company for providing the opportunity to use the experimental devices.

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