Effect of Chromium Content on Heat Treatment Behavior of Multi-Alloyed White Cast Iron for Abrasive Wear Resistance

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The effect of chromium (Cr) content on heat treatment behavior of multi-alloyed white cast iron with basic alloy composition of 5 mass% Mo, W and V each and 2 mass% C was investigated. Cast iron with varying Cr content from 3 to 9% was prepared. Specimens were annealed at 1223 K and then hardened using fan air cooling from 1323 and 1373 K austenitizing. Hardened specimens were tempered between 673 and 873 K with 50 K intervals. In the as-cast state, the microstructure of specimens with Cr content less than 5 mass% consisted of primary austenite and eutectic structure of (γ +MC) along with (γ +M₂C). The (γ +M₇C₃) was observed in specimens with Cr content of more than 5 mass%. In as-hardened state, the hardness increased to the highest value at 5 mass% Cr and subsequently decreased with an increase in the Cr content. The volume fraction of retained austenite (V_γ) also behaved in the same way with reference to hardness. In the tempered state, evident secondary hardening was observed in all specimens. Maximum tempered hardness (H_{Tmax}) was obtained at 773–798 K tempering. The V_γ values decreased continuously as the tempering temperature increased and they were overall less than 5% at H_{Tmax} . The degree of secondary hardening (ΔH_s) increased proportionally with a rise of V_γ in as-hardened state. The H_{Tmax} increased first and then decreased as the Cr content increased. The highest values of H_{Tmax} were obtained in 5 mass% Cr specimen regardless of austenitizing temperature.

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1. Introduction

Alloyed white cast irons have been utilized for a long time as parts or components of machines in steel-making, mining, cement and thermal plant industries due to extreme hardness and excellent abrasive wear resistance.¹⁾ When minerals cause heavy abrasive damage to the surface of such parts or components during operation, the most important properties required for abrasive wear resistance are hardness and toughness. Therefore, there is a high demand for alloyed white cast iron with higher performance characteristics.

Alloyed white cast iron for rolling and pulverizing mill rolls has changed from low-alloyed white cast iron through Ni-hard cast iron and high Cr cast iron, respectively.²⁾ High Cr cast iron has been used for a long time because of hardness and better abrasive wear resistance than Ni-hard cast iron.^{1,3–5)} Nevertheless, a disadvantage of this material is that a large volume fraction of eutectic chromium carbides reduces toughness of the cast iron.

In order to improve the final product, multi-alloyed white cast iron containing several kinds of strong carbide forming elements such as chromium (Cr), molybdenum (Mo), tungsten (W) and vanadium (V) was developed.⁵⁾ These elements combine with carbon (C) to form MC, M₂C and/or M₇C₃ eutectic carbides which have very high levels of hardness and improved abrasive wear resistance.⁶⁾ Cobalt (Co) is added to improve thermal properties, especially when the alloy is serviced at high temperature like hot rolling. The rest of alloying elements after forming their eutectic carbides dissolves into matrix and promotes the precipitation of secondary carbides during heat treatment.

The basic chemical composition of multi-alloyed white cast iron is 5 mass% Cr, Mo, W, V, Co each and 2 mass% C (hereafter mass% is expressed by %).⁵⁾ Cr is not as strong a carbide former as the other elements; it is added because Cr forms discontinuous morphology of eutectic M₇C₃ carbide which improve toughness^{1,5,7–9)} and dissolves in austenite to significantly improve hardenability of the cast iron.

In reviewing the research on multi-alloyed white cast irons, systematic research on the role of Cr in the heat treatment processes is not found.^{10–12)} In this work, therefore, the effect of Cr content on heat treatment behavior (i.e., variation of hardness and volume fraction of retained austenite (V_γ) during heat treatment) was investigated using multi-alloyed white cast irons with Cr content from 3 to 9%.

2. Experimental Procedure

2.1 Preparation of test specimens

The charge materials consisting of mild-steel, pig iron, ferro-alloys and pure metals were melted and superheated to 1853 K. After being held at that temperature for 600 to 900 s, the melt was poured from 1763 to 1793 K into preheated CO₂ bonded sand molds in a round bar shape, as shown in Fig. 1. The substantial cavity size of the mold was 25 mm in diameter and 65 mm in length, together with sufficient riser. After pouring, the surface of the riser was covered instantly with dry exothermic powder to prevent the melt from cooling fast and oxidizing. The chemical compositions of the test specimens are presented in Table 1.

In each specimen, the parameter of carbon balance (C_{bal}), which can estimate the C concentration in the matrix at equilibrium condition,^{6,13,14)} was calculated using the following equation (1),

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Table 1 Chemical composition and C_{bal} value of test specimens.

Specimen	Element (mass%)								C_{bal}
	C	Si	Mn	Cr	Mo	W	V	Co	
No.1	1.96	0.52	0.49	3.09	5.02	5.02	4.96	1.98	0.13
No.2	1.97	0.52	0.52	4.98	5.02	4.98	5.07	1.99	0
No.3	2.02	0.54	0.51	5.99	4.93	4.93	4.97	2.00	-0.21
No.4	1.98	0.50	0.49	7.01	5.09	5.05	5.03	2.01	-0.38
No.5	2.08	0.53	0.49	8.93	5.01	5.03	5.07	2.00	-0.48

Fig. 1 Schematic drawing of CO_2 bonded sand mold for test specimens.

$$C_{bal} = \%C \text{ in cast iron} - \%C_{stoich} \quad (1)$$

Here, $\%C$ is C content of specimen and $\%C_{stoich}$ is the amount of C consumed to form carbides stoichiometrically. When the M_7C_3 carbide does not crystallize during solidification, the $\%C_{stoich}$ can be calculated using eq. (2) which is available for specimens with Cr content less than 5% (No. 1 and No. 2),

$$\begin{aligned} \%C_{stoich} = & 0.060(\%Cr) + 0.063(\%Mo) + 0.033(\%W) \\ & + 0.235(\%V) \end{aligned} \quad (2)$$

In case that M_7C_3 carbide crystallizes, eq. (3) is used for calculation. This equation is available for specimens with Cr content more than 5% (No. 3 to No. 5),

$$\begin{aligned} \%C_{stoich} = & 0.099(\%Cr) + 0.063(\%Mo) + 0.033(\%W) \\ & + 0.235(\%V) \end{aligned} \quad (3)$$

2.2 Heat treatment procedures

The test ingots were coated with an anti-oxidation solution and annealed at 1223 K for 18 ks in a furnace. The annealed

ingots were sectioned using a wire-cutting machine to obtain disk-shape test pieces 7 mm in thickness. The specimens were austenitized at 1323 and 1373 K for 3.6 ks and hardened using fan air cooling (FAC). The hardened specimens were tempered at 673–873 K with 50 K intervals for 12 ks and cooled in still air.

2.3 Microstructure observation

The microstructure was observed using an Optical Microscope (OM) and Scanning Electron Microscope (SEM). The test pieces were polished using emery paper and buffered with $0.1 \mu m$ alumina powder. To reveal the microstructure, Nital, Groesbeck's and Villela's reagents were used. In this paper, lots of secondary carbides are observed in matrix. The secondary carbides are formed from austenite and martensite. The carbides from as-cast austenite while austenitizing are relatively larger in size because precipitation and growth of carbides are fast at high temperature. On the other side, the carbides from retained austenite after quenching and from martensite during tempering are fine because the reactions take place at low temperature. Then, the secondary carbides in large and small sizes co-exist in the matrix. However, it is hard to define the two kinds of carbides, because the carbides cannot be separated clearly. Therefore, authors call them as secondary carbide all together.

2.4 Measurement of hardness and volume fraction of retained austenite (V_γ)

The macro-hardness was measured using Vickers hardness tester with a load of 294.2 N (30 kgf) and micro-hardness using Micro-Vickers hardness tester with a load of 0.98 N (100 gf). The measurement was performed in five random locations and the values were averaged.

The volume fraction of retained austenite (V_γ) was measured using a X-ray diffraction method developed for alloyed white cast iron.^{11,14,15} The goniometer with special sample stage enabled the test piece to rotate and swing simultaneously and cancel the effect of preferred crystal orientation of austenite. $Mo-K_\alpha$ characteristic line with a wavelength of 0.0711 nm was used as a source of X-ray

beam. The scanning range was from 24 to 44 degree by 2θ . For quantitative calculation, $(200)_\alpha$ and $(220)_\alpha$ planes for ferrite (α) or martensite as $(220)_\gamma$ and $(311)_\gamma$ planes for austenite (γ) were adopted, respectively. The integrated area of the inner side of every peak was measured using an image analyzer. The calculation of V_γ was done for three combinations of peaks, $(220)_\alpha$ – $(311)_\gamma$, $(200)_\alpha$ – $\Sigma(220,311)_\gamma$ and $\Sigma(200,220)_\alpha$ – $(311)_\gamma$ and the average value was adopted.

3. Results and Discussions

3.1 As-cast microstructure of specimens

The typical as-cast microstructures of test specimens were observed using OM and are shown in Fig. 2. All the specimens showed hypoeutectic composition consisting of primary austenite dendrite (γ_p) and eutectic structure (γ +eutectic carbide). The type and morphology of phase exist in multi-alloyed white cast iron was clarified by Wu *et al.*⁶⁾ and Hashimoto *et al.*¹⁶⁾ They reported that the eutectic carbides in multi-alloyed white cast iron with basic alloy composition are mostly MC and M_2C types but very small amount of M_7C_3 type co-exists. The morphology of MC carbide is modular while the M_2C carbide is fine lamellar. The eutectic M_7C_3 carbide is rod-like or ledeburitic. The type of carbide can be distinguished by etching with Groesbeck's reagents, that is, the M_2C and M_7C_3 carbides are colored but MC carbide is not.⁶⁾ From the color etching, it

Fig. 2 Microstructures of as-cast specimens with different Cr contents (by OM).

Fig. 3 Relationship between area fractions of primary austenite (γ_p), kind of eutectic structure and Cr content in the as-cast specimens.

is found that eutectics of (γ +MC) and (γ + M_2C) exist in the specimens with 3 and 5%Cr. In the specimen with 6%Cr, the eutectic of (γ + M_7C_3) began to crystallize, taking the place of (γ + M_2C) eutectic. In the specimen with 7%Cr, the (γ + M_2C) eutectic was much less. In the specimen with 9%Cr, the eutectic structures were mostly (γ +MC) and (γ + M_7C_3).

In order to identify how Cr content affects the fraction of phases crystallizing from liquid, the area fraction of primary austenite dendrite (γ_p) and each type of the eutectic in the as-cast specimens were measured and the relationship is shown in Fig. 3. The amount of γ_p decreased very slightly and (γ +MC) eutectic did so gradually. On the contrary, (γ + M_2C) and (γ + M_7C_3) eutectics increased as Cr content rose, except for specimen No. 3 with 6%Cr in which (γ +MC), (γ + M_2C) and (γ + M_7C_3) eutectics co-exist. At 6%Cr, the Cr began to display inhibition of (γ + M_2C) crystallization and instead promoted the nucleation of (γ + M_7C_3) eutectic, respectively. It was observed that the (γ + M_7C_3) eutectic started to crystallize in 6%Cr cast iron.

3.2 Behavior of hardness and V_γ in as-hardened state

It was reported that the eutectic carbide changed little during austenitizing except for M_2C carbide which might decompose when being held at high temperature for long time.¹⁷⁾ On the other hand, the matrix changed widely depending on the heat treatment condition. During austenitizing, the retained austenite in the as-cast state is destabilized by the precipitation of secondary carbides. This reduces the stability of austenite and allows the transformation of austenite into martensite during post cooling.

SEM microphotographs of all as-hardened specimens are shown in Fig. 4. The matrix of each specimen is composed of martensite (M), retained austenite (γ_R) and fine secondary carbides (SC). It is evident that the secondary carbide precipitated during austenitizing. However, the variation of the amount could not be made clear in the microphotographs. Also, the types of secondary carbides could not be identified using SEM but only TEM analysis because the sizes are too fine to analyze alloy concentration quantitatively. However, Hashimoto *et al.*¹⁸⁾ reported using XRD and TEM that the secondary carbides in as-hardened state were MC, M_6C and

Fig. 4 Typical matrix microstructures of as-hardened specimens with different Cr contents (by SEM).

M_7C_3 types. In as-hardened matrix, martensite phases transformed from destabilized austenite are clearly observed in all of specimens (Fig. 4). In addition, the amount of retained austenite seems to be greater in the specimens hardened from higher temperature.

Fig. 5 Relationship between macro-hardness, volume fraction of retained austenite (V_γ) and Cr content in as-hardened state.

The effect of Cr content on macro-hardness and V_γ in as-hardened state is shown in Fig. 5. The macro-hardness increased a little to the maximum value at 5%Cr and afterward decreased gradually as Cr content rose. The slight increase in hardness in the former stage from 3 to 5%Cr could be because Cr dissolved in the matrix not only improved the hardenability, but also strengthened the matrix. In addition, an increase in Cr content promoted the precipitation of secondary carbides. A decrease in the hardness in the latter stage over 5%Cr shows in Fig. 3 that the amount of $(\gamma+M_7C_3)$ eutectic with low hardness increased and those of $(\gamma+MC)$ and $(\gamma+M_2C)$ eutectics with high hardness decreased as Cr content rose. Besides, as the C_{bal} of specimen falls, the hardness of martensite decreases due to reduction of C in martensite. On the other hand, the V_γ increased gradually to the highest value at 5%Cr and then decreased slowly. At the former stage, the Cr dissolved in austenite lowered M_s temperature and consequently, the V_γ increased. At the latter stage, the V_γ continued to decrease. This is because M_s temperature in multi-alloyed white cast iron increases as the Cr content rises over 5%.¹⁹⁾ The V_γ value is overall high in the case of high austenitizing temperature like 1373 K, and there, the solubility of C and alloying elements in austenite was increased. These elements, dissolved more in austenite, made M_s temperatures lower. At 3%Cr, the V_γ values of specimens hardened from each austenitizing temperature were nearly the same.

The hardness of specimens hardened from 1323 K are greater than those hardened from 1373 K, regardless of Cr content. The reason is that the low austenitizing temperature produces less V_γ than high austenitizing temperature does.

As mentioned previously, the eutectic carbides change little during heat treatment; that is, the variation of macro-hardness is mainly caused by matrix microstructure. The effect of V_γ on micro-hardness in the as-hardened state is shown in Fig. 6. The micro-hardness rose gradually in proportion to the V_γ in the case of 1323 K austenitizing, and slightly in 1373 K austenitizing. The maximum micro-hardness was obtained at 17% in the specimen hardened from

Fig. 6 Relationship between micro-hardness and volume fraction of retained austenite (V_γ) in as-hardened state.

1323 K, and 24% V_γ in hardening from 1373 K. The reason for the increase is that an increase in V_γ is equivalent to the increase of C_{bal} of specimen. When C_{bal} rises, therefore, the precipitation of secondary carbides increases.

3.3 Behavior of hardness and V_γ in a tempered state

In general, the V_γ decreases as tempering temperature is elevated because the retained austenite is destabilized by precipitation of secondary carbides. It is difficult to identify the type and morphology of secondary carbides in tempered state using SEM analysis. However, it is reported that the secondary carbides in heat-treated multi-alloyed white cast iron with basic composition were mostly MC , M_6C and M_7C_3 types based on TEM analysis.¹⁶⁾ Due to the precipitation of secondary carbides, C concentration, as well as alloying elements in austenite, decreases, and this makes M_s temperature rise. This result enables the residual austenite to transform into bainite or martensite during cooling.

The relationship between macro-hardness, V_γ and the tempering temperature of all specimens is shown in Fig. 7. The secondary hardening is observed in all the hardness curves and occurs due to the precipitation of secondary carbides and martensite transformation from the residual austenite during cooling after tempering. The hardness specifically drops from as-hardened state at the lowest tempering temperature of 673 K. Then, it increases to the maximum point or the maximum tempered hardness (H_{Tmax}) as the temperature is evaluated and after that, it decreases remarkably. In most of specimens, the H_{Tmax} are obtained at 773 and 798 K tempering. The higher austenitizing temperature provides greater H_{Tmax} value. On the other side, the V_γ decreases gradually as the temperature increases to 723 K and it continues to drop steeply when the temperature rises over 723 K. The V_γ value at H_{Tmax} is less than 5% regardless of both the Cr content and austenitizing temperature. At each austenitizing temperature, the tempering temperature obtained H_{Tmax} shifts to the low temperature side as Cr content increases over 6%. The reason is that the C concentration in austenite reduces with an increase in Cr content. In such specimens, therefore, the lower tempering temperature is enough to complete the precipitation of secondary carbides

which are necessary to get H_{Tmax} . The decrease in hardness over the temperature at the H_{Tmax} could be due to coarsening of fine carbides, tempering of martensite, as well as the simultaneous reduction of V_γ . Powell and Laird²⁰⁾ suggested that the precipitation of secondary carbides in high Cr cast iron occurs in the short time during tempering and, after that, the carbides begin to agglomerate. This behavior could lead to the coarsening of secondary carbides.

Based on the above results, it is clear that the hardness of specimen or macro-hardness varies depending on the type and amount of eutectic carbide and the matrix structure. It is also known that the hardness of eutectic carbide changes little at room temperature, even if heat treatment was involved. In the same cast iron, therefore, the variation of macro-hardness depends on the matrix hardness. The relationship between V_γ and macro-hardness and micro-hardness in tempered state are shown in Fig. 8(a) and (b), respectively. Of course, the distribution of macro-hardness lies at higher hardness than that of micro-hardness, however, there is a little variation in both types of hardness. The hardness increases markedly to the maximum value at about 4% V_γ and then decreases gradually as the V_γ increases. The reason for the decrease is that an excess of soft retained austenite remains in the matrix together with a decrease in martensite. At the same V_γ value, the specimens hardened from 1373 K have greater hardness on the whole than those hardened from 1323 K. The fact is that greater secondary hardening is obtained in the specimens hardened from high temperature. The greatest hardness is obtained in the specimen No. 2 with 5%Cr. Regardless of the austenitizing temperature, the macro-hardness of more than 900 HV30 and micro-hardness over 800 HV0.1 are obtained between 1 to 10% V_γ and 1 to 18% V_γ , respectively. As shown in Fig. 8(b), in the region of less than 2% V_γ , the micro-hardness is scattered broadly from a very low value of 540 to 860 HV0.1. In order to make this reason clear, the relation of micro-hardness vs. tempering temperature is arranged and shown in Fig. 9. It is found that the hardness decreases as the tempering temperature increases. This evidence illustrates that a decrease in hardness is due to the coarsening of secondary carbides and transformation of austenite to ferrite or pearlite with an increase in tempering temperature. At the highest tempering temperature of 873 K, however, the micro-hardness is very low and still lie widely. This broad dispersion of hardness comes from the Cr content in specimen. As Cr content increases, more Cr carbide which has lower hardness, precipitates in the matrix and causes the micro-hardness to be very low. Moreover, the hardness tempered at 873 K decreases in the order of Cr content of specimens even if the hardening temperature is different.

The effect of Cr content on maximum tempered macro-hardness (H_{Tmax}) and V_γ at H_{Tmax} ($V_{\gamma-HTmax}$) is shown in Fig. 10. As the Cr content rises, the H_{Tmax} increases to the highest value at 5%Cr and decreases progressively with a rise of the Cr content over 5%. The H_{Tmax} values of 913 and 932 HV30 were obtained in the cases of austenitizing temperatures at 1323 and 1373 K, respectively. The former is caused by an increase in the amount of precipitated secondary carbides and martensite transformed from destabilized austenite. In addition to this, an increase in total amount of eutectics of $(\gamma+MC)$ and $(\gamma+M_2C)$ can boost the hardness.

Fig. 7 Relationship between macro-hardness, volume fraction of retained austenite (V_γ) and tempering temperatures of specimens with different Cr contents.

The latter behavior is due to an increase in eutectic M_7C_3 carbide, which has lower hardness than MC and M_2C carbides together with a decrease in the hardness of martensite with low C concentration. As for the V_γ at H_{Tmax} ($V_{\gamma-HTmax}$), it is clear the difference in V_γ values among the specimens are small and overall are less than 5% regardless of Cr content. This proves that a certain amount of austenite remains in the specimens with H_{Tmax} even after tempering.

Looking back at Fig. 8, it is clear that the V_γ in as-hardened state is closely connected to the tempered hardness of specimens. So, the relation between H_{Tmax} vs. V_γ values was clarified and is shown in Fig. 11. The H_{Tmax} increased roughly in proportion to the V_γ in the range of 5–25%; the greater amount of V_γ in the as-hardened state, the higher H_{Tmax} . It is known that the V_γ in as-hardened state depends on the amount of C and alloying elements dissolving in

Fig. 8 Relationship between hardness and volume fraction of retained austenite (V_γ) in tempered state. (a) Macro-hardness, (b) Micro-hardness.

Fig. 9 Relationship between micro-hardness and tempering temperature of specimens with volume fraction of retained austenite (V_γ) less than 2%.

matrix. In as-hardened state, more C and other alloying elements are supersaturated in the austenite and it promotes more precipitation of secondary carbides. At the same time, the martensite is also supersaturated with C and alloying elements and it precipitates secondary carbide with high

Fig. 10 Relationship between maximum tempered hardness (H_{Tmax}), volume fraction of retained austenite (V_γ) at H_{Tmax} and Cr content.

Fig. 11 Relationship between maximum tempered hardness (H_{Tmax}) and volume fraction of retained austenite (V_γ) in as-hardened state.

hardness during tempering. Therefore, it can be said that the more V_γ , the more precipitation of secondary carbides. Here, it can be seen that V_γ of more than 17% in as-hardened state is needed to get the H_{Tmax} over 900 HV30 by tempering.

As illustrated in Fig. 7, the hardness curves showed greater or lesser secondary hardening, depending on the Cr content and austenitizing temperature. In order to clarify how Cr content affects secondary hardening, the degree of secondary hardening (ΔH_s), which is expressed by the difference in the hardness between H_{Tmax} and the hardness where the secondary hardening begins, is calculated. The relationship between ΔH_s and Cr content is shown in Fig. 12. In the region of Cr content more than 5%, the ΔH_s decreased in proportion to the Cr content in each case of austenitizing temperature. However, the ΔH_s values are more in 1373 K austenitizing than those in 1323 K. In spite of a decrease in Cr content, the ΔH_s of 3%Cr specimen was low. This is because M_s temperature is higher than that of the 5%Cr specimen.¹⁹⁾ So, it is reasonable that the V_γ value and ΔH_s in 3%Cr specimen decreased more than those of 5%Cr specimen. From such a remarkable change in the ΔH_s , it was determined that the ΔH_s could also be closely related to

Fig. 12 Effect of Cr content on degree of secondary hardening (ΔH_s). Fig. 14 Relationship between maximum tempered hardness (H_{Tmax}) and degree of secondary hardening (ΔH_s). Fig. 13 Relationship between degree of secondary hardening (ΔH_s) and volume fraction of retained austenite (V_γ) in as-hardened state. Fig. 15 Relationship between degree of secondary hardening (ΔH_s) and difference between volume fraction of retained austenite in as-hardened state and that at H_{Tmax} ($\Delta V_{\gamma-HTmax}$).

the V_γ in as-hardened state. The relationship is shown in Fig. 13. The ΔH_s increased proportionally to an increase of V_γ in as-hardened state, regardless of austenitizing temperature. This figure supports the result in Fig. 11 that the greater the amount of V_γ in as-hardened state provided the higher the H_{Tmax} . It is because more V_γ causes more reactions to increase the hardness by the secondary hardening mechanism. However, it should be noted that too much V_γ in the as-hardened state may lead a reduction of hardness in the tempered state because a great amount of austenite may be left in the matrix, even after tempering.

As described before, the ΔH_s is closely related to the H_{Tmax} . Therefore, the relationship between H_{Tmax} and the ΔH_s is summarized and shown in Fig. 14. The H_{Tmax} rose to 900HV30 at ΔH_s of 50HV30, and then the H_{Tmax} increased slightly as the ΔH_s rose. The result shows that a larger amount of ΔH_s provides higher H_{Tmax} , similar to the relationship between H_{Tmax} vs. V_γ in as-hardened state.

Here, it should be of interest to note how closely the net value of austenite is directly connected to ΔH_s . The difference between the V_γ in as-hardened state and that

at H_{Tmax} ($\Delta V_{\gamma-HTmax}$) is calculated for each specimen and the relationship is shown in Fig. 15. The ΔH_s increased proportionally to increase in $\Delta V_{\gamma-HTmax}$. It is clear that the net amount of austenite ($\Delta V_{\gamma-HTmax}$) is directly related to the H_{Tmax} . Figure 14 also shows that the ΔH_s value above 50HV30 is necessary to achieve H_{Tmax} over 900HV30. Figure 15, on the other hand, demonstrates that $\Delta V_{\gamma-HTmax}$ greater than 12% is required and this value is near to 14% V_γ in the as-hardened state shown in Fig. 13.

4. Conclusions

The effect of chromium (Cr) content on the heat treatment behavior of multi-alloyed white cast iron was investigated, varying Cr content from 3 to 9% under the basic chemical composition. Test pieces were hardened in a range of different austenitizing temperatures of 1323 and 1373 K after annealing, then, they were tempered between 673 and 873 K. The results are summarized as follows:

As-cast state

- (1) The microstructure of each specimen consisted of primary austenite dendrite (γ_p) and (γ +MC) and (γ +M₂C) eutectics in specimens with 3 and 5%Cr. By contrast, (γ +M₇C₃) eutectic appeared in specimens with 6%Cr and more.
- (2) With regard to the chemical composition of specimens in this study, the area fraction of γ_p decreased slightly, and (γ +MC) eutectic decreased progressively. On the other hand, (γ +M₂C) and (γ +M₇C₃) eutectics increased as Cr content went up, except for the 6%Cr specimen. When the Cr content increased to 6%, the crystallization of (γ +M₂C) eutectic was inhibited and that of (γ +M₇C₃) eutectic was promoted.

As-hardened state

- (1) The hardness increased slightly to the highest value at 5%Cr, and then decreased continuously as the Cr content increased. The low austenitizing temperature 1323 K resulted in greater hardness than high austenitizing temperature of 1373 K.
- (2) The volume fraction of retained austenite (V_γ) in as-hardened state increased gradually to the highest value at 5%Cr and, after that, it decreased progressively as Cr content rose. The higher austenitizing temperature showed a greater amount of V_γ when the Cr content was over 5%.
- (3) The micro-hardness increased proportional to the V_γ . The maximum micro-hardness was obtained at 17% and 24% V_γ in specimens hardened from 1323 K and 1373 K, respectively.

Tempered state

- (1) The secondary hardening was clearly found in all the tempered hardness curves. The maximum tempered hardness (H_{Tmax}) was obtained at tempering between 773 and 798 K and it shifted to the lower temperature side when Cr content was over 6%. Higher H_{Tmax} value was obtained by hardening from higher austenitizing temperature.
- (2) The V_γ decreased as the temperature increased, and it dropped steeply when the temperature got over 723 K. The V_γ value in the tempered specimen at the H_{Tmax} was overall less than 5%.
- (3) The hardness increased to the maximum value at about 4% V_γ and decreased gradually as the V_γ increased. Macro-hardness over 900 HV30 and micro-hardness over 800 HV0.1 were at V_γ up to 10% and up to 18%, respectively. At the V_γ value of less than 2%, the micro-hardness scattered broadly from 540 to 860 HV0.1 due to an increase in Cr carbide with lower hardness.
- (4) The H_{Tmax} value increased proportionally as the V_γ value in the as-hardened state rose. A value of more than 17% V_γ was found to be necessary to achieve the H_{Tmax} over 900 HV30.

- (5) The degree of secondary hardening (ΔH_s) decreased progressively as Cr content increased. The ΔH_s rose with an increase in the V_γ value in as-hardened state. It was found that the ΔH_s more than 50HV30, which was necessary to obtain H_{Tmax} value over 900HV30, was provided when the V_γ in as-hardened state rose above 14%.

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