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다합금계 백주철의 탄화물 및 기지조직이 내마모성에 미치는 영향

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Effects of Carbide and Matrix Structures on Abrasion Wear Resistance of Multi-Component White Cast Iron

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Abstract The effects of carbide and matrix structures on the abrasion wear resistance of multi-component white cast irons with 3.0 mass%C have been studied in this paper. Four different heats were poured in order to obtain the specimens with different combinations of the carbide structures : a basic iron(3.0 mass%C-5.0 mass%Cr-5.0 mass%V-5.0 mass% Mo-5.0 mass%W) for the precipitation of MC, M_2C and M_7C_3 carbides, a V free iron(3.0 mass%C-5.0 mass%Cr-2.5 mass%Mo-12.5 mass%W) for M_6C and M_7C_3 carbides, a Mo and W free iron(3.0 mass%C-10.0 mass%Cr-10.0 mass% V) for MC and M_7C_3 carbides, and a Cr free iron(3.0 mass%C-5.0 mass%V-2.5 mass% Mo-12.5 mass%W) for MC and M6C carbides. A conventional high Cr white cast iron was also poured to compare its wear resistance with those of the multi-component white cast irons. In the as-cast condition, the range of abrasive wear rate(Rw = mg/min) was from 4.15 to 5.98. The lowest Rw, which means the highest wear resistance, was obtained in the basic iron with nodular MC, lamellar M_2C and cellular M_7C_3 carbides. Then, it increased in the order of Cr free iron with chunky MC and fishbone-like M_6C carbides, Mo and W free iron with nodular MC and cellular M_7C_3 carbides, and V free iron with fishbone-like M_6C and rod-like M_7C_3 carbides. On the other hand, the Rw of the high Cr white cast iron ranked between the basic iron and the Mo and W free iron. In each alloy, the Rw of air hardened or tempered specimen was lower than that of the as-cast one because of the change of matrix structures by the heat treatments. The Rw of the heat treated specimens increased in the order of Mo and W free iron, basic iron, Cr free iron, high Cr iron, and V free iron.

1. Introduction

Multi-component white cast iron is a recently developed wear resistant material for the application to the hot strip mill and mineral pulverizing mill[1,2]. It contains usually five different types of carbide forming elements such as C, Cr, V, Mo and W in order to precipitate MC, M_2C, M_6C and M_7C_3 carbides during solidification. In addition, its matrix can be also hardened by the heat treatments such as air hardening and tempering, during which the precipitation of tiny numerous secondary carbides occurrs. Properties such as wear resistance, surface roughening resistance and heat crack resistance are essentially required in the materials which are applied for the hot strip mill and mineral pulverizing mill. Among those properties, the abrasive wear resistance is reported to be dependent upon not only the type, morphology, volume fraction and distribution pattern of its carbide structures, but also the type of its matrix structures[3].

In this research, except for the basic iron, one or two alloying elements were intentionally not added in order to precipitate the specific carbides in the specimen. Heat treatments such as air hardening and tempering were employed to obtain the different types of matrix structures. Then, the effects of carbide and matrix structures on Rw have been studied with the Suga abrasive wear test machine[4]. The Rw of a conventional high Cr white cast iron was also compared with those of the multi-component white cast irons.

2. Experimental Procedure

2.1 Preparation of Specimen

Specimens were produced using a 15kg silica lined high frequency induction furnace. The charged materials were super-heated to 1650℃, and transferred into a pre-heated teapot ladle. After removal of any dross or slag, the melts were poured at 1550℃ into three Y-block molds. The chemical composition of the charged materials is listed in Table 1.

Table 1. Chemical Composition of Charge Materials

Material	Composition(mass%)							
	C	Si	Mn	Cr	V	Mo	W	Fe
Sorel Metal	4.35	0.18	0.01					bal
Steel Scrap	0.20	0.10	0.40					bal
Fe-Cr	0.03	0.68		61.68				bal
Fe-V	0.54	0.86			77.5			bal
Fe-Mo	0.03	0.72				62.0		bal
Fe-W	0.10	0.26	0.19				75.87	bal
Graphite Powder	100							

Table 2. Alloy design for the five Heats(mass%)

Alloying Elements / Heat No.	C	Cr	V	Mo	W	Carbide Type
1	3.0	5.0	5.0	5.0	5.0	MC, M_2C, M_7C_3
2	3.0	5.0	0	2.5	12.5	M_6C, M_7C_3
3	3.0	10.0	10.0	0	0	MC, M_7C_3
4	3.0	0	5.0	2.5	12.5	MC, M_6C
5	3.0	17.0	0	3.0	0	M_7C_3

2.2 Alloy Design

In order to get the various types of carbides(MC, M_2C, M_6C, M_7C_3), five different combinations of the alloying elements(C, Cr, V, Mo, W) were selected so as to make the sum being approximately 23 mass%. The alloy combination of each heat is listed in Table 2.

2.3 Heat Treatment

Before air hardening, the specimens were homogenized at 950℃ for 3 hrs. under the nitrogen atmosphere, and subsequently furnace cooled to the room temperature. With respect to the air hardening, the homogenized specimens were austenitized at 1050℃ for 1.5 hrs. under the nitrogen atmosphere, and followed by fan air cooling to the room temperature. In the tempering, the air hardened specimens were held at 500℃ for 3 hrs., and then cooled to the room temperature in the air. A schematic diagram of furnace for the heat treatments is shown in Fig. 1.

2.4 Metallographic Examination

The specimens were ground, polished, etched and examined metallographically by a SEM. The etching solution used was Villela's etchant(1g of picric acid, 5mℓ of hydrochloric acid and 94mℓ of methyl alcohol).

2.5 Austenite measurement

The vol.% of austenite was calculated from the peak areas of (200) and (220) for ferrite and those of (220) and (311) for austenite. The diffraction patterns were obtained by rotating and swinging the sample stage of X-ray diffractometer simultaneously in order to minimize the effect of crystal orientation. X-ray diffraction conditions in the measurement of austenite are summarized in Table 3.

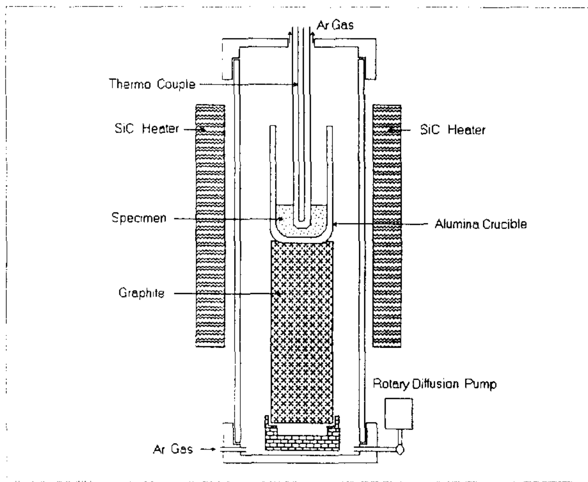

Fig. 1. A schematic diagram of furnace for the heat treatments

2.6 Wear Test

Under the load of 3kgf, the abrasive wheel(size : 44

Table 3. X-ray diffraction condition in the measurement of austenite

Parameter	Values	Parameter	Values
Acc Voltage(kv)	45	Divergence Slit(°)	1/2
Prove Current(mA)	60	Goniometer Receiving Slit(mm)	0.3
Characteristic X-ray	Mo-Kα	Scattering Slit(°)	1
Filter	Zr	Monochromator Receiving Slit(mm)	-
Gonio Speed(°/min)	1/4	Chart Speed(mm/min)	10
Time Constant(sec)	1	2θ range(°)	31~40

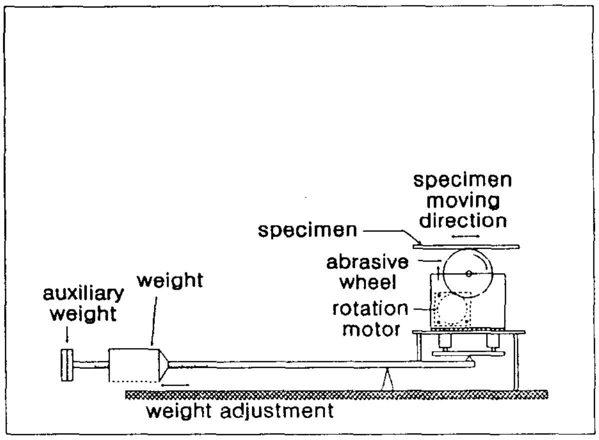

Fig. 2. A schematic diagram of Suga abrasive wear test machine

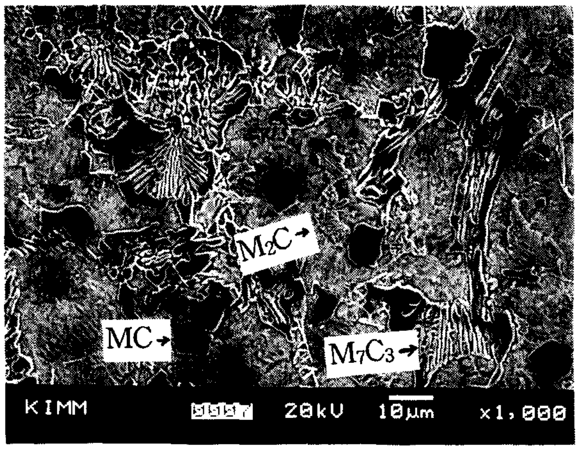

Photo. 1. SEM microstructure of the as-cast specimen of Heat 1

Table 4. Alloy concentrations of each phase in the four specimens by EPMA

Heat No.	Phase	Element(mass %)					Heat No.	Phase	Element(mass %)				
		Cr	V	Mo	W	Fe			Cr	V	Mo	W	Fe
1	MC	5	56	13	22	4	3	MC	8	89	0	0	3
	M_2C	12	10	30	18	30		M_7C_3	33	15	0	0	52
	M_7C_3	13	3	3	1	80		Matrix	11	4	0	0	85
	Matrix	5	1	1	1	92							
2	MC	3	0	31	36	30	4	MC	0	44	24	28	4
	M_7C_3	11	0	7	4	78		M_6C	0	22	27	24	47
	Matrix	2	0	2	3	93		Matrix	0	6	9	7	78

mm diameter x 12 mm thickness) wound with 120 mesh SiC paper(size : 12 mm×158 mm) was rotated intermittently while scratching on the same surface of the test piece(size : 50 mm×50 mm×4 mm thickness) in the dried condition. The rotating speed of the abrasive wheel was 0.345mm/sec and the contacted area in the specimen was(12×35)mm^2. The wear loss of the test piece was measured after every cycle(360 revolution), and this procedure was repeated upto 8 cycles. A schematic diagram of Suga abrasive wear test machine is depicted in Fig. 2.

3. Experimental Results and Discussions

3.1 Carbide structures observed in the as-cast specimens

3.1.1 3.0 mass%C-5.0 mass%Cr-5.0 mass%V-5.0 mass%Mo-5.0 mass%W iron (Heat 1)

Three different carbide structures were observed in the as-cast specimen of Heat 1. As shown in Photo. 1, this specimen consisted of MC carbides with nodular morphology, M_2C carbides with lamellar one and M_7C_3 carbides with cellular one.

EPMA was also conducted to reassure the identification of each carbide present and matrix, and the alloy concentrations of each phase determined by it are listed in Table 4. From this table, it can be known that nodular MC carbide contained mainly V and some of other alloying elements, and cellular M_7C_3 carbide was mostly composed of Fe and Cr. While lamellar M_2C carbide was rich in Mo, W and Fe contents, the matrix was a iron-base solid solution.

3.1.2. 3.0mass%C-5.0 mass%Cr-2.5 mass%Mo-12.5 mass%W iron(Heat 2)

The SEM microstructure of the as-cast specimen of Heat 2 is shown in Photo. 2. There existed two different carbide structures, M_7C_3 carbide with rod-like morphology and M_6C carbide with fishbone-like one. Both of them were also identified by EPMA and the result of which are listed in Table 4.

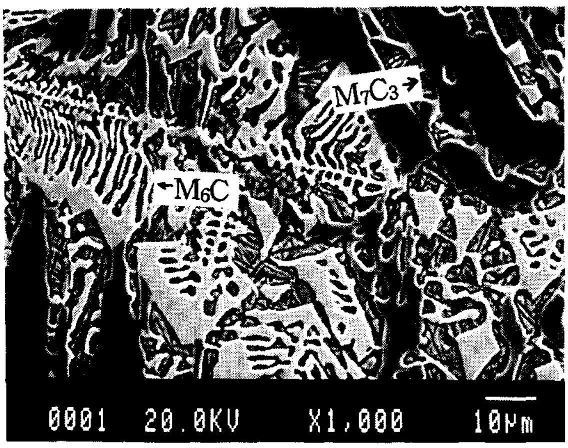

Photo. 2. SEM microstructure of the as-cast specimen of Heat 2

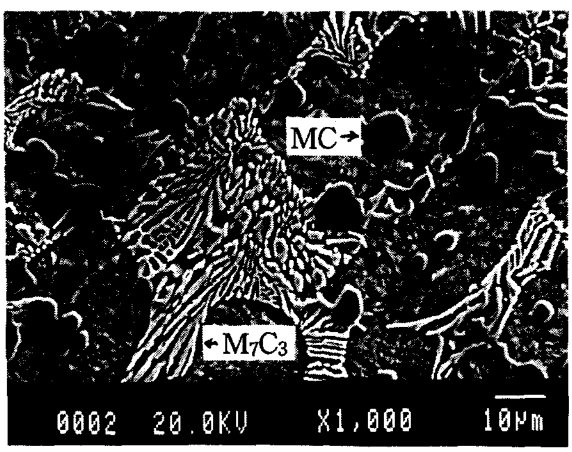

Photo. 3. SEM microstructure of the as-cast specimen of Heat 3

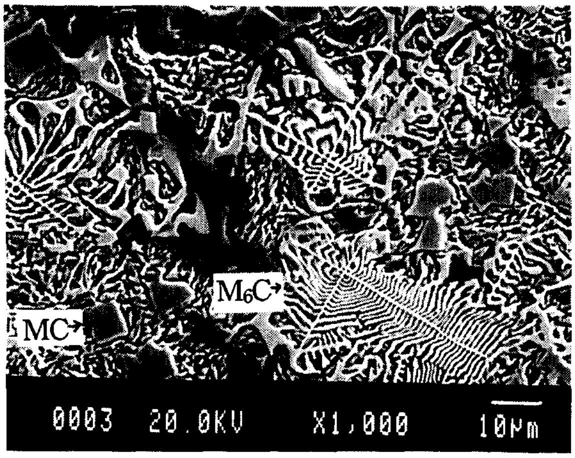

Photo. 4. SEM microstructure of the as-cast specimen of Heat 4

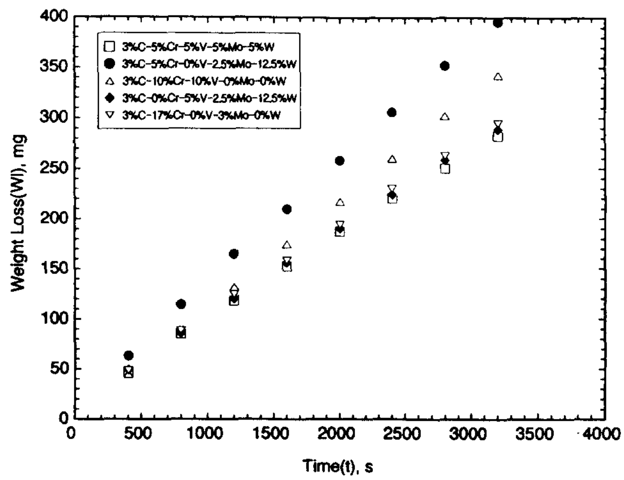

Fig. 3. The relationship between wear loss and wearing time in the as-cast specimens

3.1.3 3.0 mass%C-10.0 mass%Cr-10.0 mass%V (Heat 3)

As has been expected from the alloy composition, only MC and M_7C_3 carbide structures were observed in this specimen. As shown in Photo. 3, the morphology of each carbide was similar to that observed in Photo. 1. The alloy concentrations of each phase determined by EPMA are listed in Table 4.

3.1.4 3.0 mass% C-5.0 mass%V-2.5 mass%Mo-12.5 mass%W iron(Heat 4)

As shown in Photo. 4, chunky MC and fishbone-like M6C carbides were coexisted in this specimen. EPMA of each phase is also listed in Table 4.

3.2 Abrasion Wear Test

3.2.1 As-cast specimens

The results of abrasion wear test on the as-cast specimens are shown in Fig. 3.

As shown in this figure, a linear relationship was ob-

Table 5. Summary of various properties in the as-cast specimens

Property / Heat No.	Volume Percent(%)					Matrix Structure	Hardness (HRc)
	MC	M_7C_3	M_3C	M_6C	Total carbides		
1	17.4	11.0	2.7	*	31.1	pearlite+γ(1.41%)	57.2
2	*	38.6	*	32.0	70.6	pearlite	64.2
3	21.6	15.3	*	*	36.9	pearlite	47.0
4	22.5	*	*	13.4	35.9	pearlite+γ(5.38%)	55.6
5	*	30.0	*	*	30.0	pearlite+γ(66.8%)	49.8

served between wear loss and wearing time. When the wear loss varies linearly with the wearing time, it is convenient to adopt the term, wear rate(Rw : mg/min) which corresponds to the slope of each line in Fig. 3. In the as-cast specimens, the range of Rw was from 4.15 to 5.98 mg/min. The smallest Rw which means the highest wear resistance, was obtained in Heat 1 containing nodular MC, lamellar M_2C and cellular M_7C_3 carbides. Then, the Rw increased in the order of Heat 4 with chunky MC and fishbone-like M_6C carbides, and Heat 3 with nodular MC and cellular M_7C_3 carbides. The worst sample for the Rw was Heat 2 with fishbone-like M_6C and rod-like M_7C_3 carbides. On the other hand, the Rw of the high Cr white cast iron ranked between Heat 3 and 4. Various properties of each specimen such as volume percent of each carbide, type of matrix structure and HRc hardness are summarized in Table 5. Except for Heat 2(70.6 vol.%), the amounts of carbides present in the four Heats averaged 33.5 vol.% . And, the matrixes were almost fully pearlitic except for Heat 5, where 66.8 vol.% of the matrix structure was austenite (γ). The range of HRc hardness in the five Heats was from 47.0 to 64.2.

As mentioned earlier, the abrasive wear resistance of multi-component white cast iron depends upon the type, morphology, volume fraction of carbide structures, and the type of matrix structures. The smallest Rw obtained in Heat 1 could be attributed to the fact that;1) it contains 17.4 vol.% MC carbide which is hardest among the carbides present in the multi-component white cast irons 2) the three different types of carbides are uniformly dispersed in the matrix 3) the iron has a relatively high hardness. On the other hand, Heat 2 shows the highest Rw in spite of its highest hardness due to the fact that;1) the presense of 70.6 vol.% carbides makes the iron brittle 2) hardest MC carbide is not present 3) fishbone-like M6C carbide with continuously connected morphology is brittle 4) in case of the fact 3), the initiated cracks during the wear test can easily propagate. The Rw values of Heat 1 and 4 were almost same. The reason could be postulated from both microstructures that although the fishbone-like M6C carbide existing in Heat 4 is less wear resistant as explained in the case of Heat 2, the presence of more MC carbide(22.5 vol.%) may probably compensate the existence of M_2C and M_7C_3 carbides in Heat 1. The Rw of the high Cr white cast iron ranked third among the five specimens. Cellular M_7C_3 carbide is usually harder than M_3C(which appears in low Cr white cast iron) carbide, and has a deep root and interconnected in the matrix. Therefore, it shows a good resistance against an abrasion wear like scratching by hard ore or ceramics.

3.2.2 Air hardened specimens

The results of abrasion wear test in the air hardened specimens are shown in Fig. 4 which shows that Rw ranges from 1.67 to 4.45 mg/min.

The smallest Rw was obtained in Heat 3 which ranked fourth out of the five in the as-cast condition. And then, Rw increased in the order of Heats 1, 4, 5 and 2. Various properties of each specimen after air hardening treatment are shown in Table 6. As listed in this table, the matrix

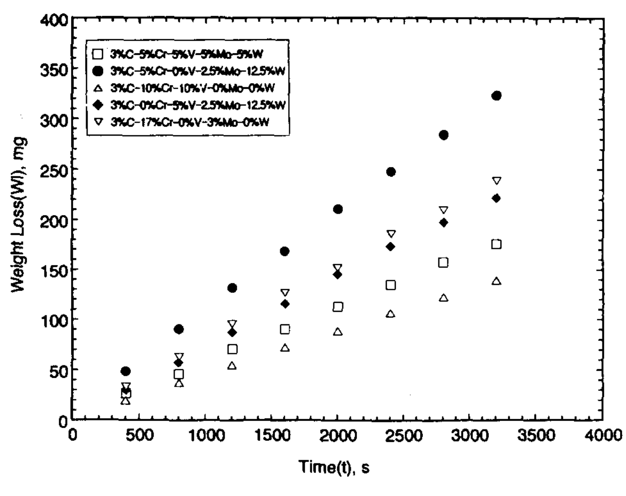

Fig. 4. Relationship between wear loss and wearing time in the air hardened specimens

Table 6. Summary of various properties in the heat treated specimens

Heat No. \ Property	Air Hardening		Air Hardening+ Tempering(500℃)	
	matrix structure	hardness (HRc)	matrix structure	hardness (HRc)
1	martensite + γ(6.24%)	64.4	martensite + γ(1.11%)	63.9
2	martensite + γ(27.33%)	64.7	martensite + γ(2.33%)	64.9
3	martensite + γ(2.23%)	67.7	martensite	60.3
4	martensite + γ(21.31%)	66.0	martensite + γ(5.18%)	60.9
5	martensite + γ(20.97%)	67.8	martensite + γ(1.36%)	65.3

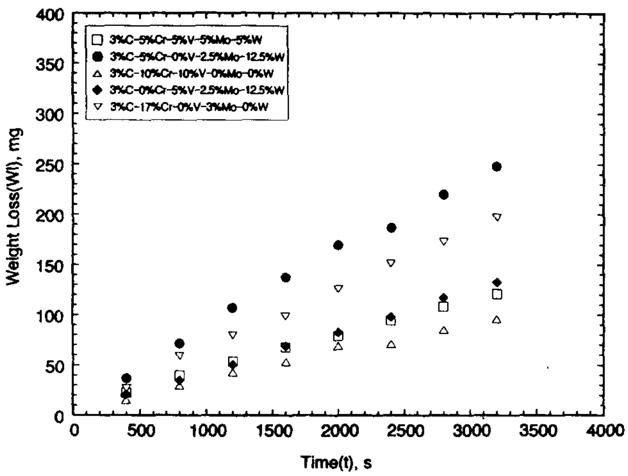

Fig. 5. Relationship between wear loss and wearing time in the tempered specimens

structures of all the specimens were composed of martensite and austenite with different vol.% depending on the chemical composition of each specimen. The variation of the matrix structures were also manifested as higher hardness compared with that measured in the as-cast specimens. Because the abrasion wear resistance of multi-component white cast iron is a fuction of both carbide and matrix structures, it is clear that the Rw decreased when the specimens were air hardened. Therefore, the change in Rw and the decreasing ratio of the Rw(air hardened) over Rw(as-cast) were as follows;Heat 1(4.15→2.07, 50.1%), Heat 2(5.98→4.45, 25.6%), Heat 3(5.13→1.67, 67.4%), Heat 4(4.22→2.40, 43.1%), Heat 5(4.59→3.57, 22.2%). In Heat 3, the vol.% of austenite was negligibly small compared with those of other specimens, which could account for the smallest Rw. Because the vol% of the matrix in Heat 2 was relatively small in comparison with those of other specimens, the decreasing ratio of the Rw(air hardened) over Rw(as-cast) was only 25.6%, while those of other multi-component specimens were more than 40%.

3.2.3 Tempered specimens

The relationship between wear loss and wearing time in the tempered specimens is shown in Fig. 5 in which Rw ranges from 2.57 to 5.86 mg/min. The order of the wear resistant ranking was same as that obtained in the air hardened specimens. The Rw of each iron lowered compared with that of each as-cast specimen, but increased more than that of the air hardened specimens. The changes of Rw and decreasing ratio of Rw (tempered) over Rw(as-cast) were as follows ; Heat 1 (4.15→3.25, 21.7%), Heat 2(5.98→5.86, 2.0%), Heat 3 (5.13→2.57, 50%), Heat 4(4.22→4.17, 1.2%), Heat 5 (4.59→4.41, 4.0%). In this research, all the specimens which were air hardened were tempered at the same temperature of 500℃, though this temperature may not be optimum depending on the specimen. The decreasing ratios of γ(tempered) over γ(air hardened) were from 75 to 100%. This can contribute to an increment of the toughness of the matrix due to the transformation of austenite into the tempered martensite, that is, sorbitic pearlite(α+Fe_3C or M_3C), and at the same time, to the precipitation of hard secondary special carbides for the improvement of the wear resistance.

4. Conclusion

1) By changing the content and combination of carbide forming elements, it was possible to control the microstructure with different type and morphology of carbide.

2) In the as-cast condition, the abrasive wear was lowest in the basic iron with nodular MC, lamellar M_2C and cellular M_7C_3 carbides. Then, it increased in the order of the Cr free iron with chunky MC and fishbone-like M_6C carbides, the high Cr white cast iron, the Mo and W free iron with nodular MC and cellular M_7C_3 carbides, and the V free iron with fishbone-like M_6C and rod-like M_7C_3 carbides.

3) The abrasive wear resistance of each air hardened

and tempered irons was generally lower than that of each as-cast iron. The order of abrasive wear resistance went up from the Mo and W free iron, the basic iron, the Cr free iron, and the V free iron. In comparison with as-cast irons, the difference in abrasive wear resistance among the specimens enlarged because of the structural change in the matrix by the heat treatment.

Acknowledgements

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