CHAPTER IV

EXPERIMENTAL RESULTS

The hypoeutectic 16% Cr cast irons without and with Mo are prepared, and heat treatment of hardening after annealing and three levels of tempering were conducted to the specimens. The wear resistance of heat-treated cast irons is evaluated using Suga abrasion wear tester and Rubber wheel abrasion wear tester. Particularly, the investigations are focused on the effects of hardness and volume fraction of retained austenite (V_γ), which are varied depending on heat treatment conditions and Mo content, on the wear behavior.

4.1 Microstructure of Test Specimens

4.1.1 As-cast State

Typical as-cast microstructures of Mo-free and Mo containing specimens taken by OM and SEM are shown in Fig.4-1. In each specimen, the microstructure consists of primary dendrite and eutectic structure. According to the work by Matsubara et al [2], the eutectic carbides are M_7C_3 type in these chemical compositions of the specimens. As for the morphology of eutectic structure, the (γ+M_7C_3) eutectic shows a colony shape because it grows with a cellular interface [2]. The eutectic colony consists of fine rod-like M_7C_3 carbides in the central region and coarse string-like M_7C_3 carbides at the boundary region. It is well known that the eutectic carbide in the colony is three-dimensionally interconnected [1]. The morphology of (γ+M_7C_3) eutectic in specimens with Mo is similar to that in the Mo-free specimen but the sizes of eutectic carbide particles and eutectic colony are coarser in the specimens containing Mo. It was also found that the carbide size seemed to be increased with an increase in Mo content.

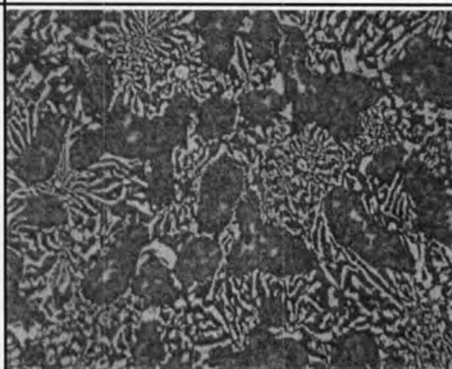
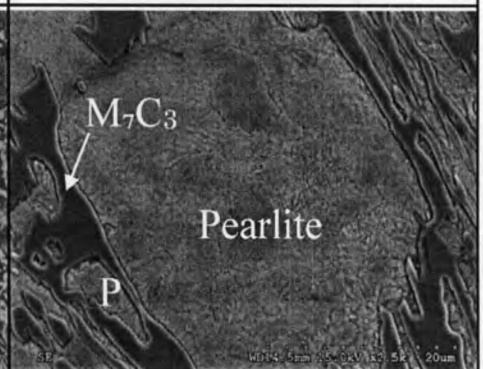
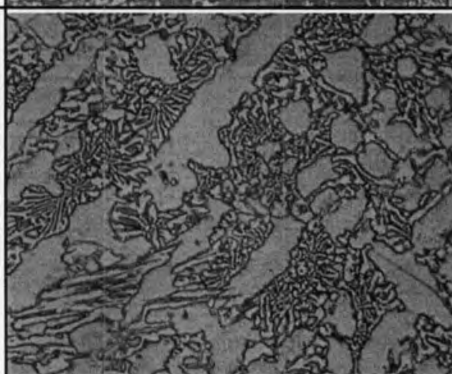
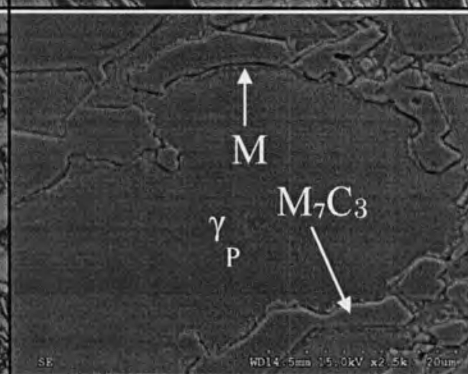
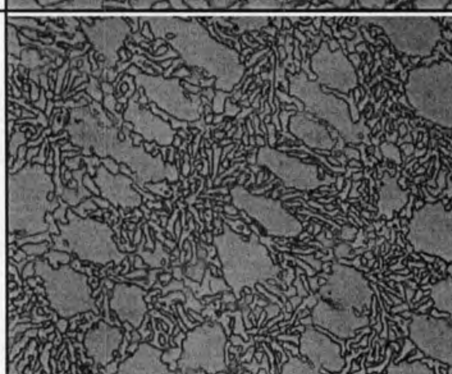
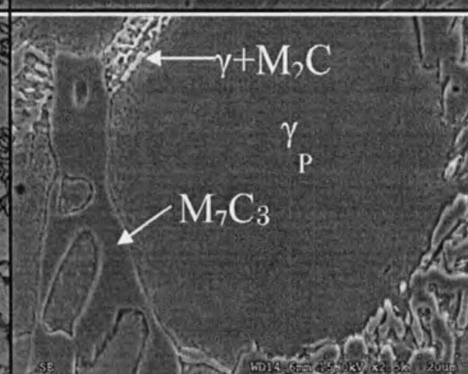
Specimen	By OM	By SEM
No.1 (0%Mo)		
No.2 (1%Mo)		
No.3 (3%Mo)		
	100μm	10μm

Fig. 4-1 Microphotographs of as-cast specimens, without and with Mo by OM and SEM.

Though molybdenum carbide of Mo_2C cannot be found out in the microphotograph of specimen No.3 with 3% Mo taken by an optical microscope (OM), it can be seen apparently in that taken by a scanning electron microscope (SEM). The M_2C carbide could be precipitated as a eutectic. This is because Mo is a strong carbide former and segregates to the final liquid to form the binary or ternary eutectic by combining with carbon. The type of molybdenum carbide precipitated from liquid during solidification should be Mo_2C (M_2C).

Mo is also distributed into matrix during solidification and it affects the transformation of matrix. The matrix of Mo-free specimen is mostly pearlite, as shown in Fig.4-1. In contrast, the matrices of specimens with Mo are austenitic and there some martensite exists possibly near eutectic carbides. This explains the fact that Mo delays the pearlite transformation and decreases the Ms temperature in the as-cast state.

4.1.2 Alloy distribution in as-cast specimens

During solidification, the alloying elements are distributed to both of austenite and eutectic carbide according to their distribution coefficient. The kind and amount of alloying element distributed to the austenite determine the matrix structure in both the as-cast and heat-treated states. The element remaining in the melt is consumed by formation of eutectic carbide. Distribution of alloying elements in the as-cast specimens is revealed using Mapping of characteristic X-ray emitted from each element in the structure. That work is accomplished by EPMA and the results are shown in Fig.4-2. It can be qualitative said that the concentrations of C and Cr are relatively high in the eutectic carbides compared with those in the austenite dendrite or matrix. By contrast, the concentration of Fe is comparatively high in the matrix. These results suggest that the growing primary austenite rejects C and Cr into the liquid and they are consumed to form

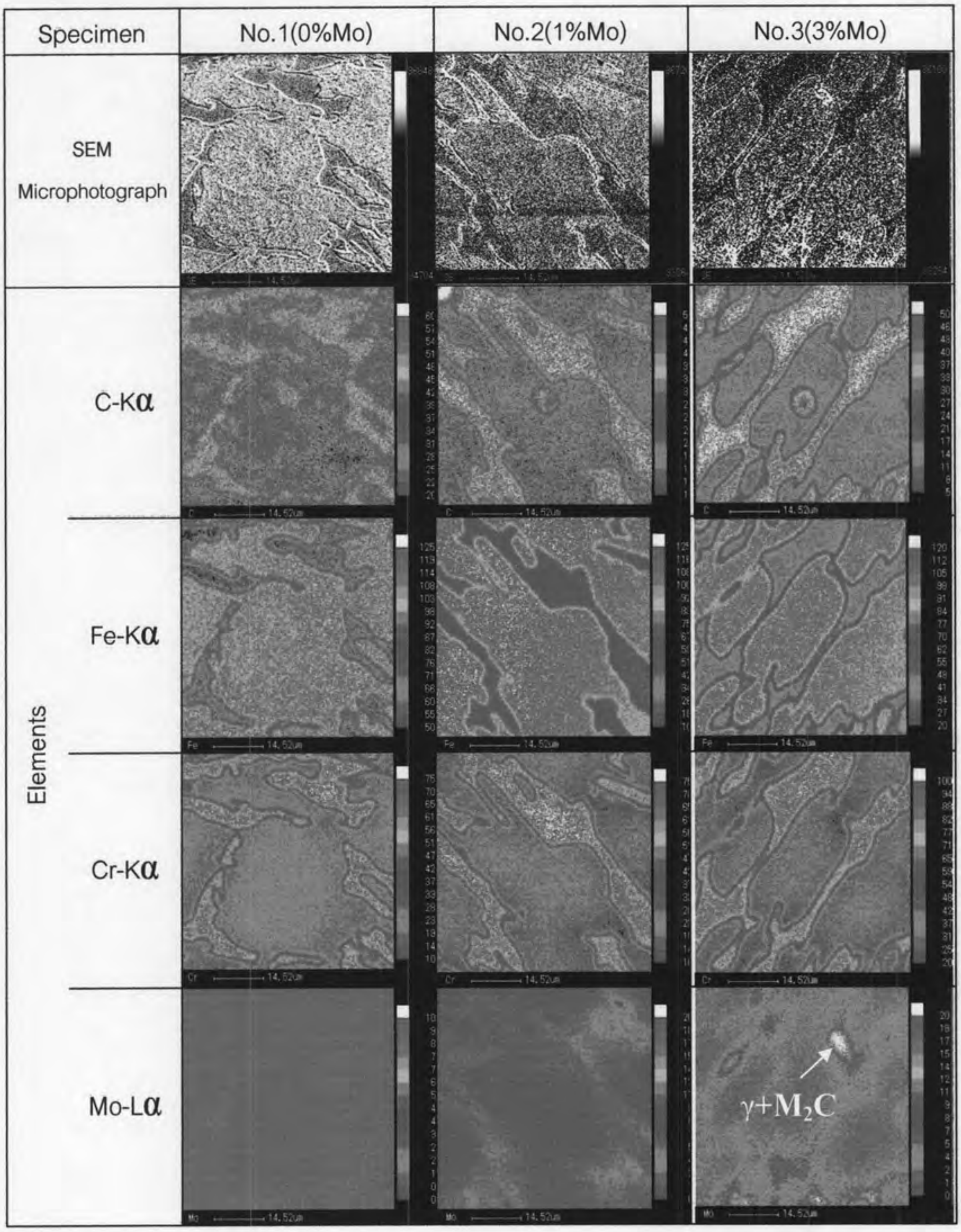


Fig. 4-2 SEM microphotographs and distribution of alloying elements by characteristic X-ray. As-cast state of specimens without and with Mo (By EPMA analysis).

the eutectic carbides. [3] The concentrations of C and Cr near the boundary of eutectic carbide are low. Since C and Cr dissolved in austenite delays the pearlitic transformation, they allows the transformation of austenite into martensite during cooling. The concentrations of C and Cr in the matrix of Mo-free specimen seem to be higher than those in the specimen with Mo. However, the concentrate of C in the eutectic carbides is high and that of Cr is low in the specimen with Mo. With respect to Mo content, it is clear from the mapping of characteristic X-ray images that Mo is greatly concentrated in the carbides precipitating along the grain boundary in the 3%Mo specimen. The carbides show apparently a eutectic configuration, by SEM microstructure and it is perhaps (γ+M_7C_3 or M_2C) eutectic.

4.1.3 As-hardened state

In order to comprehend the transformed matrix in detail, the microphotographs were taken using OM and SEM. Typical microstructures of as-hardened specimens are shown in Fig. 4-3. The matrix structure consists of a large number of fine precipitated carbides, martensite and retained austenite. It was reported that the secondary carbides which precipitated in the as-hardened state of high chromium cast irons are mostly M_7C_3 carbides co-existing with $M_{23}C_6$ carbides.[3,18,19] In Mo-free specimen, the pearlitic matrix in the as-cast state is replaced by the secondary carbide, martensite and austenite. In the matrix structure of specimens with Mo, the retained austenite which existed more in the as-cast state is destabilized to precipitate fine secondary carbides during holding and transforms into martensite during cooling. When the size of secondary carbides is compared, it can be said that the size is small in the specimens with Mo. As for the precipitation in austenite, it is found that there are little of precipitated carbides in the region near the eutectic carbides. The reason

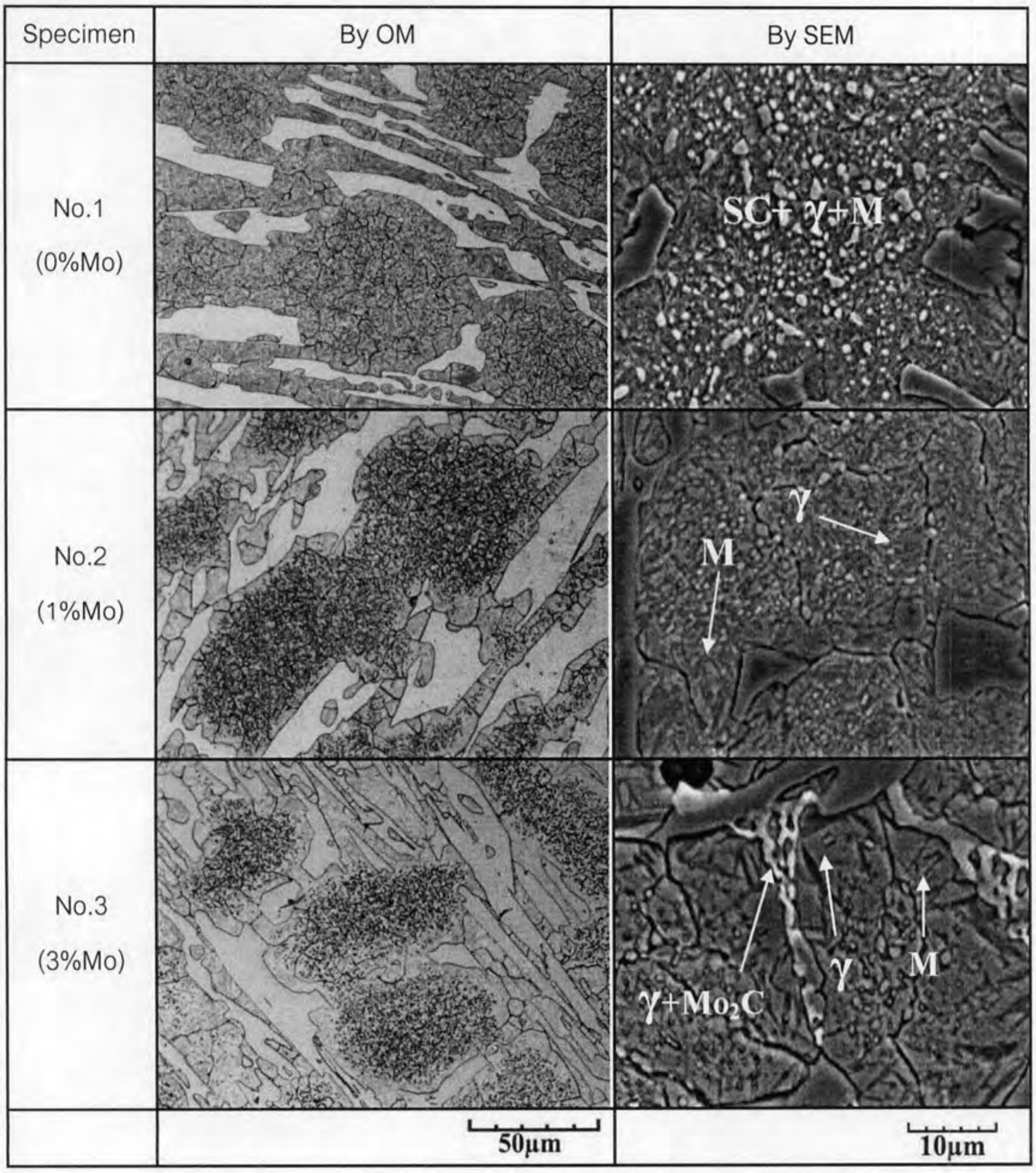


Fig. 4-3 Microphotographs of as-hardened specimens without and with Mo, by OM and SEM.

may be that the precipitated carbides could diffuse to the eutectic carbides.

4.2 Effect of Heat Treatment Condition on Macro-hardness, Micro-hardness and Volume Fraction of Retained Austenite (V_γ)

4.2.1 Characterization of as-cast specimens.

The macro-hardness, micro-hardness or matrix hardness and V_γ of as-cast specimens are listed in Table 4-1. It is well known that the macro-hardness of as-cast specimen is related to the amount and type of eutectic carbides and the matrix structure. The macro-hardness decreases from 523 HV30 to 475 HV30 and the micro-hardness decreases from 409 HV0.1 to 285 HV0.1 as Mo content increases. The V_γ is nil in Mo-free specimens. In the specimens with 1%Mo and 3%Mo, on the other hand, the V_γ value are remarkably high about 90%.

Table 4-1 Macro-hardness, micro-hardness and volume fraction of retained austenite (V_γ) in as-cast specimens.

Specimen	Element (wt%)		Hardness		V_γ (%)
	Cr	Mo	HV30	HV0.1	
No. 1	16	nil	523	409	0
N0.3		1	489	302	88
No.4		3	475	285	91

4.2.2 Characterization of test pieces.

The test pieces for abrasion wear tests were heat-treated to give them the scheduled properties according to the conditions of heat treatment shown in Fig.3-2.

The characterized properties of test specimens, that is, macro-hardness, micro-hardness and V_γ of the matrix, are summarized in Table 4-2. These test pieces with different hardness and V_γ were supplied to the abrasion wear tests

When the tempered specimens are compared with the as-hardened specimen, the V_γ in the as-hardened state decreases gradually with an increase in tempering temperature. In each specimen, it is clear that the V_γ in B-H_{Tmax} is relatively large but those in H_{Tmax} and O-H_{Tmax} specimens are very small.

4.3 Effect of Heat Treatment Condition and Mo Content on Wear Rate

The commercial high chromium cast irons used for wear parts in many kinds of industries, have been usually used in heat-treated state Hence, the wear resistance of high chromium cast iron should be evaluated under the different heat treatment and wear conditions. It is found from the previous results that hardness and the amount of retained austenite (V_γ) change significantly depending on the heat treatment condition. In order to prepare the specimens with matrix containing various phases or constituents, therefore, the three different temperatures for tempering, which give the different amount of hardness and V_γ and as well as microstructure, were employed.

It is known that the wear resistance is also influenced by Mo content which affects the matrix transformation and which in turn influences the type and morphology of carbide, austenite and martensite. In this section, the effects of heat treatment condition and Mo content on the wear resistance are described.

Table 4-2 Macro-hardness, micro-hardness and volume fraction of retained austenite (V_γ) in heat-treated specimens for abrasion wear tests.

Specimen	Mo (wt%)	Tempering Condition	Macro-hardness (HV30)	Micro-hardness (HV0.1)	V_γ , %
No.1	-	As-hardened (As-H)	822	696	25
		Before H_{Tmax} (B-H_{Tmax})	755	731	21
		H_{Tmax}	786	764	6
		Over H_{Tmax} (O-H_{Tmax})	748	727	2
No.2	1	As-hardened (As-H)	811	722	34
		Before H_{Tmax} (B-H_{Tmax})	744	728	32
		H_{Tmax}	831	780	5
		Over H_{Tmax} (O-H_{Tmax})	718	697	2
No.3	3	As-hardened (As-H)	824	808	40
		Before H_{Tmax} (B-H_{Tmax})	762	724	37
		H_{Tmax}	816	764	5
		Over H_{Tmax} (O-H_{Tmax})	654	545	2

4.3.1 Suga Abrasion Wear Test

The relationships between wear loss and wear distance by Suga abrasion wear test are shown in Fig. 4-4 for specimens No.1, Fig.4-5 for specimens No.2 and Fig.4-6 for specimens No.3, respectively. The equations for the relationship in specimens with different heat treatment are shown at the upper part of each figure. In all figures, the wear loss increases in proportion to the wear distance regardless of heat treatment condition.

Total wear losses of specimens with different heat treatment condition at about 192 m wear test are summarized in Table 4-3. In each diagram, the slope of the straight line, in other word, the difference in the wear loss among the specimens,

increases as the wear distance increases. This means that the wear rate (R_W) of the specimen varies by the difference of heat treatment conditions. The R_W were calculated from the relation of wear loss vs. wear distance and they are summarized in Table 4-4.

Table 4-3 Total wear loss at 192 m of Suga abrasion wear test with a load of 1kg, for specimens with and without Mo.

Heat Treatment Condition	Total wear loss by Suga wear test at 192 m, mg.		
	No.1 (0%Mo)	No.2 (1%Mo)	No.3 (3%Mo)
As-hardened (As-H)	89.0	93.0	87.0
Before H_{Tmax} (B-H_{Tmax})	99.0	99.5	84.9
H_{Tmax}	97.1	89.0	84.7
Over H_{Tmax} (O-H_{Tmax})	101.0	98.5	113.3

As-H	—○—	$W_\ell = 0.449 \times W_d + 4.25$ (R=0.999)
B-H_{Tmax}	—●—	$W_\ell = 0.502 \times W_d + 2.99$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.510 \times W_d - 1.42$ (R=1.000)
O-H_{Tmax}	- - ◆ - -	$W_\ell = 0.522 \times W_d + 1.35$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

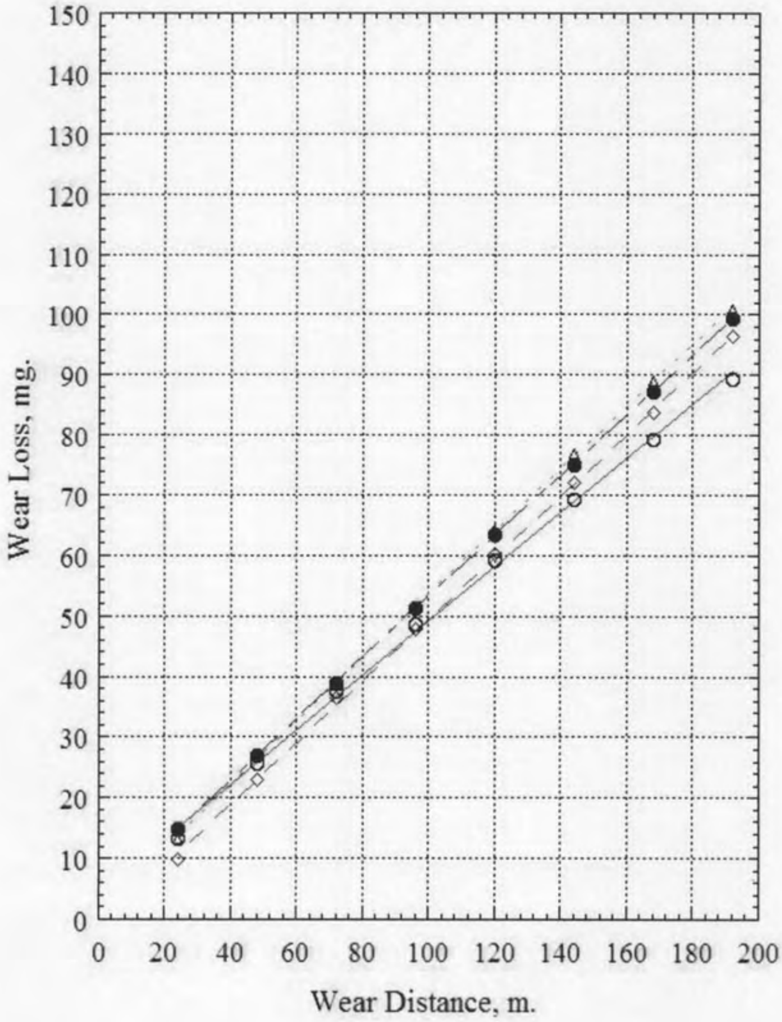


Fig.4-4 Relationship between wear loss and wear distance by Suga abrasion wear test with 1 Kg load. Specimen No.1 (0% Mo).

As-H	—○—	$W_\ell = 0.481 \times W_d + 0.48$ (R=0.999)
$B\text{-}H_{Tmax}$	—●—	$W_\ell = 0.499 \times W_d + 4.52$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.454 \times W_d + 2.53$ (R=1.000)
$O\text{-}H_{Tmax}$	- - ◆ - -	$W_\ell = 0.510 \times W_d + 2.08$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

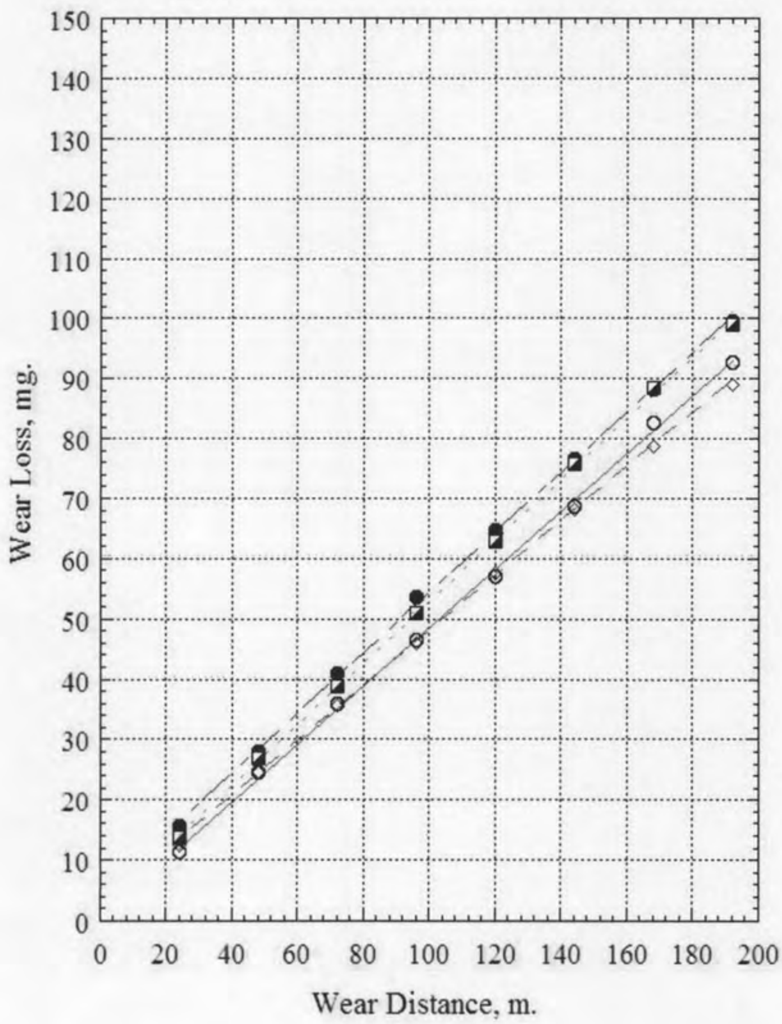


Fig.4-5 Relationship between wear loss and wear distance by Suga abrasion wear test with 1 Kg load. Specimen No.2 (1% Mo).

As-H	—○—	$W_\ell = 0.444 \times W_d + 2.01$ (R=0.999)
B-H_{Tmax}	—●—	$W_\ell = 0.435 \times W_d + 1.07$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.427 \times W_d + 3.15$ (R=1.000)
O-H_{Tmax}	- - ◆ - -	$W_\ell = 0.562 \times W_d + 5.82$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

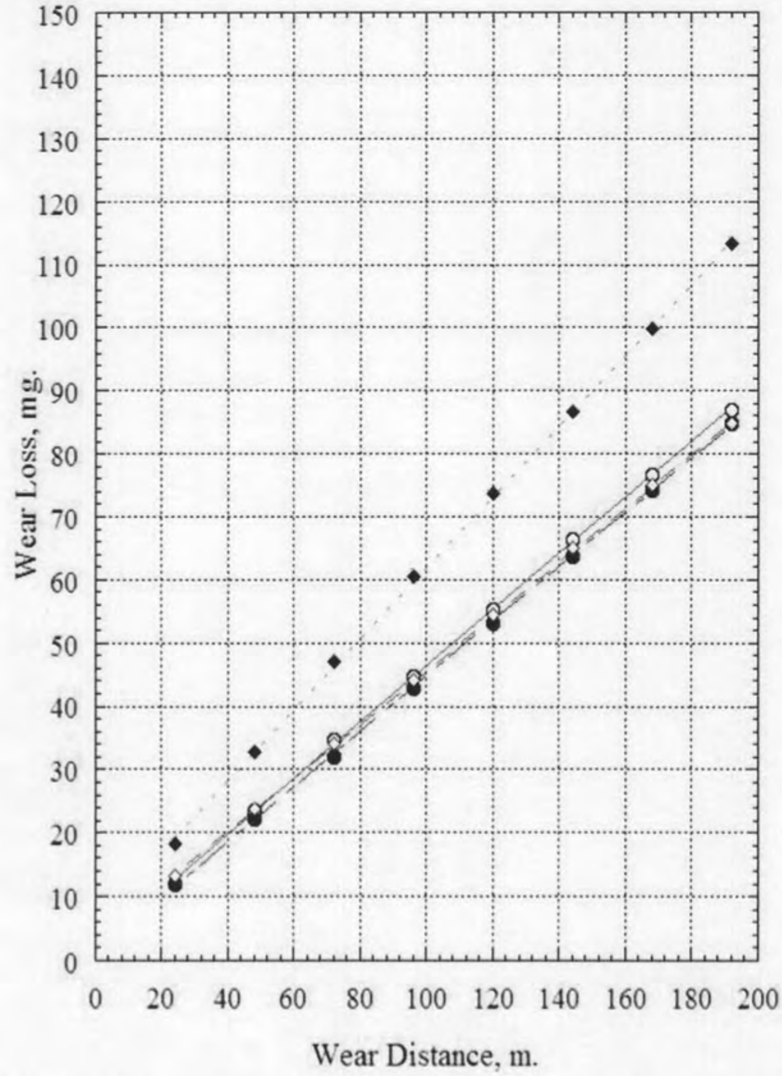


Fig.4-6 Relationship between wear loss and wear distance by Suga abrasion wear test with 1 Kg load. Specimen No.3 (3% Mo).

Table 4-4 Wear rate (R_W) of Suga abrasion wear test with a load of 1kg for specimens with and without Mo.

Heat Treatment Condition	Wear rate (Rw), mg/m		
	No.1 (0%Mo)	No.2 (1%Mo)	No.3 (3%Mo)
As-H	0.449	0.481	0.444
B-H_{Tmax}	0.502	0.499	0.435
H_{Tmax}	0.510	0.454	0.427
O-H_{Tmax}	0.522	0.510	0.562

In the results of Mo-free specimen No.1 shown in Fig.4-4, the total wear loss increases in the order of 89 mg in as-hardened, 97 mg in H_{Tmax}, 99 mg in before H_{Tmax}, and 101 mg in over-tempered specimens, the smallest R_W value (0.449 mg/m) or highest wear resistance is obtained in As-H specimen and followed by B-H_{Tmax} specimen (0.510 mg/m). The largest R_W value (0.522 mg/m) or lowest wear resistance is obtained in O-H_{Tmax} specimen.

In the results of 1% Mo specimen No.2 shown in Fig 4-5, the relationship between wear loss and wear distance is similar to that of Mo-free specimen, that is, the wear loss increases proportionally with an increase in the wear distance in the specimens with each heat treatment condition. The order of an increase in the total wear loss is H_{Tmax} specimen (89 mg), As-H specimen (93 mg), O-H_{Tmax} specimen (98.5 mg) and B-H_{Tmax} specimen (99.5 mg). From Table 4-4, the R_W values are smallest of 0.454 mg/m in H_{Tmax} specimen, 0.481 mg/m in As-H specimen, 0.499 mg/m in B-H_{Tmax} specimen and 0.510 mg/m in O-H_{Tmax} specimen. Form these results, the highest wear resistance are obtained in the specimen with H_{Tmax} whereas the lowest wear resistance is obtained in O-H_{Tmax} specimen.

As for the results of 3% Mo specimen shown in Fig. 4-6, the wear losses are comparably small except for the O-H_{Tmax} specimen. The total wear loss values at 192m are 87, 84.9, 84.7 and 113.3mg in As-H specimen, B-H_{Tmax} specimen, H_{Tmax} specimen, and O-H_{Tmax} specimen, respectively. As shown in Table 4-4, the smallest R_W value is 0.427mg/m in H_{Tmax} specimen but the R_W values of As-H specimen and B-H_{Tmax} specimen do not make much difference from the smallest value of 0.444mg/m in As-H specimen and 0.435mg/m in B-H_{Tmax} specimen. The largest R_W of 0.562mg/m is obtained in the O-H_{Tmax} specimen.

From above results, it can be concluded that the largest wear resistance or the smallest R_W is obtained in the H_{Tmax} specimen which matrix contains large portion of tempered martensite and some retained austenite except for 0%Mo specimen. The lowest wear resistance or highest R_W is obtained in O-H_{Tmax} specimen where a large portion of martensite is tempered and the retained austenite is almost nil. The smallest R_W value or largest wear resistance is obtained in 3% Mo specimen.

4.3.2 Rubber wheel abrasion wear test

The relationships between wear loss and wear distance by Rubber wheel abrasion wear test are shown in Fig.4-7 for specimen No.1, Fig.4-8 for specimen No.2 and Fig.4-9 for specimen No.3, respectively. The linear relationship is obtained between wear loss and wear distance in all of the specimens. The equations of relationship between wear loss and wear distance for specimens with different heat treatment are shown at the upper part of each figure. In the same manner as Suga abrasion wear test, the slope of the straight line or RW is different in the specimens with different heat treatment.

Total wear losses of each specimen with different heat treatment conditions at the wear test of 3143m are summarized in Table 4-5 and, in the same

As-H	—○—	$W_\ell = 0.053 \times W_d + 17.06$ (R=0.999)
B-H_{Tmax}	—●—	$W_\ell = 0.066 \times W_d + 12.58$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.057 \times W_d + 5.58$ (R=1.000)
O-H_{Tmax}	- - ◆ - -	$W_\ell = 0.074 \times W_d + 10.66$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

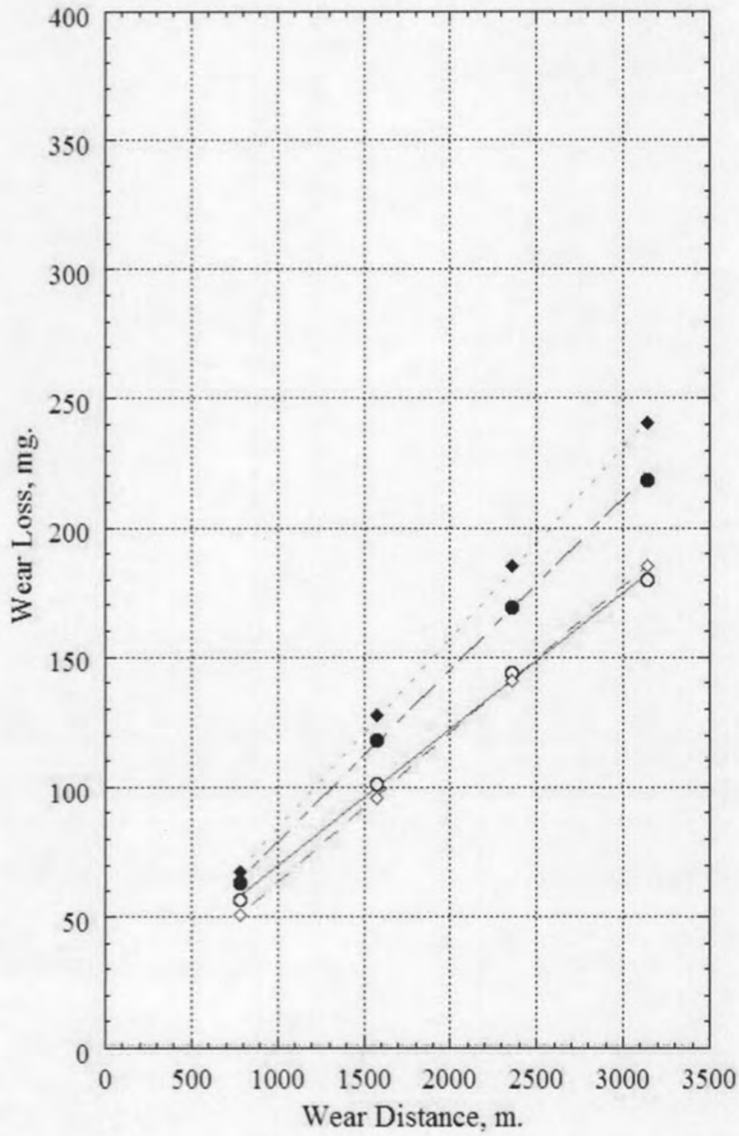


Fig.4-7 Relationship between wear loss and wear distance by Rubber wheel abrasion wear test with 8.7 kg load. Specimen No.1 (0% Mo).

As-H	—○—	$W_\ell = 0.047 \times W_d + 8.53$ (R=1.000)
B-H_{Tmax}	—●—	$W_\ell = 0.058 \times W_d + 6.19$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.058 \times W_d + 4.96$ (R=1.000)
O-H_{Tmax}	- -◆- -	$W_\ell = 0.078 \times W_d + 7.11$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

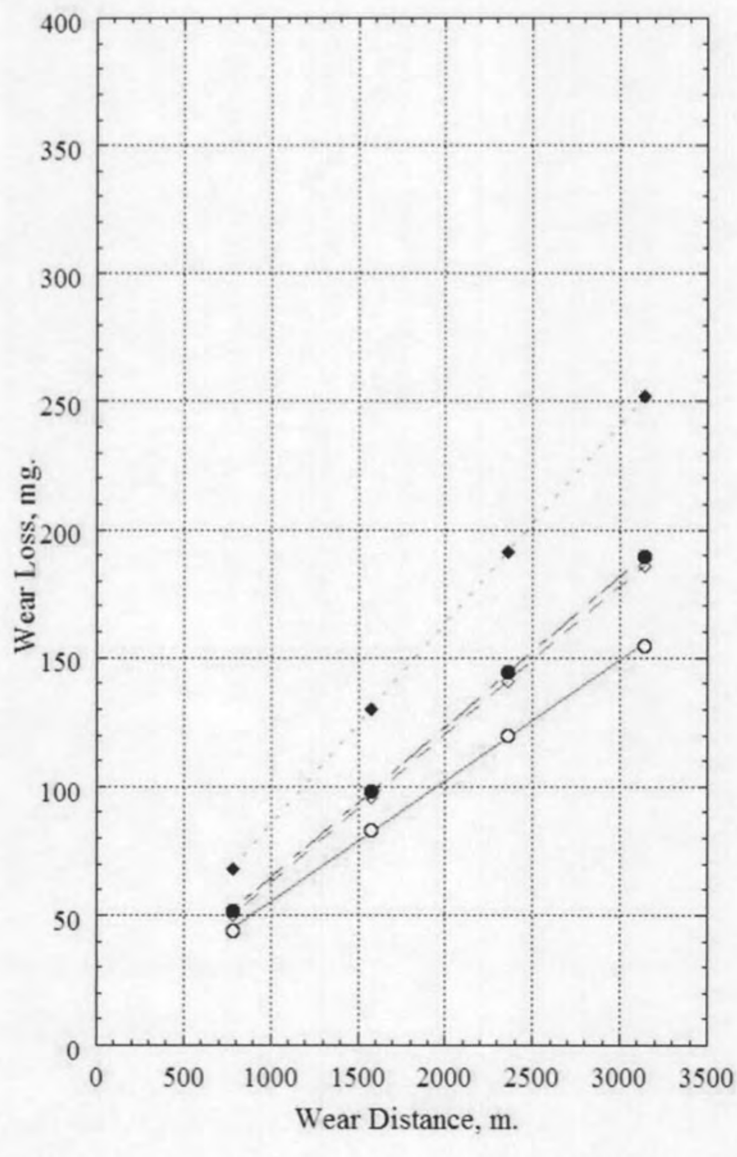


Fig.4-8 Relationship between wear loss and wear distance by Rubber wheel abrasion wear test with 8.7 kg load. Specimen No.2 (1% Mo).

As-H	—○—	$W_\ell = 0.058 \times W_d + 8.53$ (R=1.000)
B-H_{Tmax}	—●—	$W_\ell = 0.071 \times W_d + 6.19$ (R=1.000)
H_{Tmax}	– ◇ –	$W_\ell = 0.069 \times W_d + 4.96$ (R=1.000)
O-H_{Tmax}	- - ◆ - -	$W_\ell = 0.113 \times W_d + 7.11$ (R=1.000)

W_ℓ : Wear loss, W_d : Wear distance

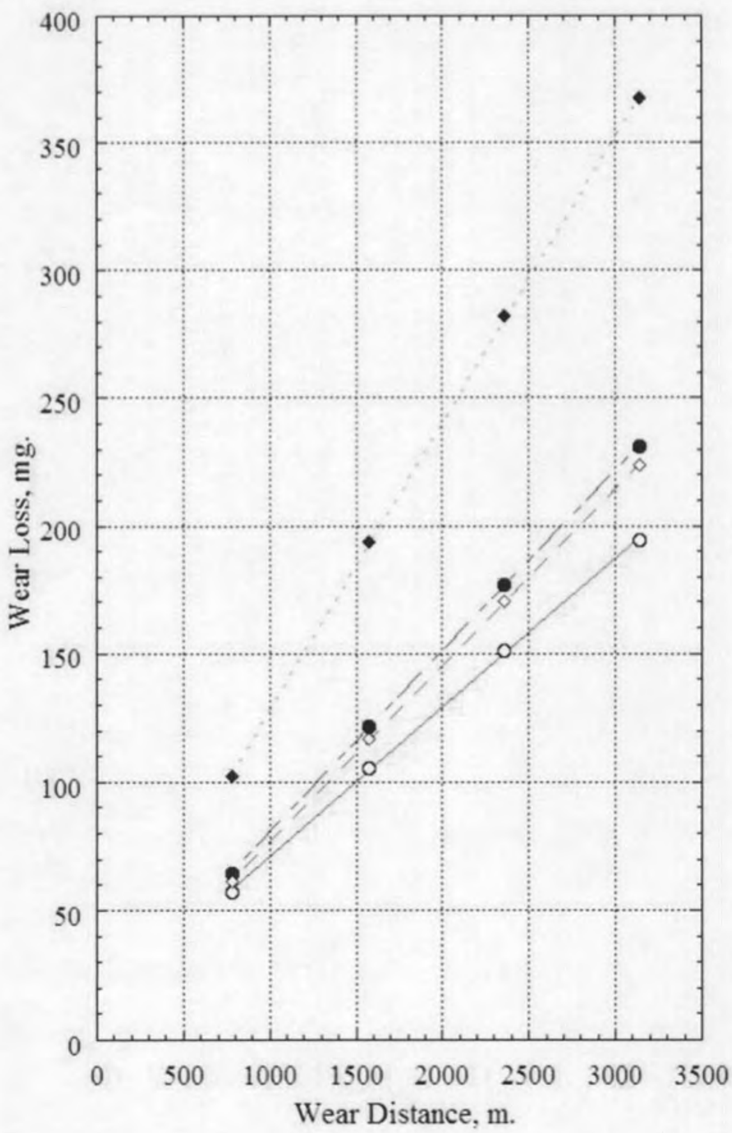


Fig.4-9 Relationship between wear loss and wear distance by Rubber wheel abrasion wear test with 8.7 kg load. Specimen No.3 (3% Mo).

reason, the values of total wear loss vary depending on the heat treatment condition. And The RW values of all the specimens are also listed up in Table 4-6.

Table 4-5 Total wear loss at 3143m of Rubber wheel abrasion wear test with a load of 8.7kg, for cast irons with and without Mo.

Heat Treatment Condition	Total wear loss in Rubber wheel wear test at 3143 m. (mg.)		
	No.1 (0%Mo)	No.2 (1%Mo)	No.3 (3%Mo)
As-H	180	155	194
B-H_{Tmax}	219	190	231
H_{Tmax}	186	186	224
O-H_{Tmax}	241	252	367

Table 4-6 Wear rate of Rubber wheel abrasion wear test with a load of 8.7kg, for cast irons with and without Mo.

Heat Treatment Condition	Wear rate (Rw), mg/m		
	No.1 (0%Mo)	No.2 (1%Mo)	No.3 (3%Mo)
As-H	0.053	0.047	0.058
B-H_{Tmax}	0.066	0.058	0.071
H_{Tmax}	0.057	0.058	0.069
O-H_{Tmax}	0.074	0.078	0.113

The results of Mo-free specimen No.1 is shown in Fig.4-7. They are 180 mg in As-H specimen, 219mg in specimen B-H_{Tmax}, 186mg in H_{Tmax} specimen and 241mg in the O-H_{Tmax} specimen. The smallest R_W value of 0.053mg/m is obtained in As-H specimen followed by the R_W of 0.057mg/m in H_{Tmax} specimen. The largest R_W value of 0.074 mg/m is obtained in O-H_{Tmax} specimen.

Fig. 4-8 shows the results of 1% Mo specimen. The linear relation is also obtained in the same manner as Mo-free specimen. The total wear losses at 3143m are 155mg in As-H specimen, 190mg in B-H_{Tmax} specimen, 186mg in H_{Tmax} specimen and 252mg in O-H_{Tmax} specimen, respectively. The smallest R_W value (0.047mg/m) or highest wear resistance is obtained in As-H specimen and followed by B-H_{Tmax} and H_{Tmax} specimens of 0.058mg/m. The largest R_W value or lowest wear resistance is 0.078mg/m in O-H_{Tmax} specimen.

In 3% Mo specimen as shown in Fig. 4-9, the total wear losses increase in the order of 194mg in As-H specimen, 224mg in H_{Tmax} specimen, 231mg in B-H_{Tmax} specimen and 367mg in O-H_{Tmax} specimen. The R_W values are 0.058mg/m in As-H specimen, 0.069mg/m in H_{Tmax} specimen, 0.071mg/m in B-H_{Tmax} specimen and 0.113mg/m in O-H_{Tmax} specimen, respectively.

Here, it can be concluded from the above results that the smallest R_W is obtained in As-H specimen that contains a large amount retained austenite, and the largest R_W value is obtained in the specimen tempered over H_{Tmax} of which matrix consists mostly of pearlite, secondary carbides and little austenite. When the effect of Mo content is considered, it is found that the smallest R_W is obtained in the specimen with 1% Mo.

From the results mentioned above, it is clear that the heat treatment condition and Mo content of specimen greatly affected on the wear rate (R_W) in both Suga abrasion wear test and Rubber wheel abrasion wear test. This is because the heat treatment controls the matrix structure and the hardness which are the main factors to determine the wear resistance. Therefore, the effects of hardness, retained austenite, and Mo content on wear rate are discussed under the each abrasion wear test in the chapter 5.