Abrasive Wear Resistance of Hypoeutectic 16 wt% and 26 wt% Cr Cast Irons with Molybdenum

Sudsakorn INTHIDECH[1,*] and Yasuhiro MATSUBARA[2]

[1,*] Faculty of Engineering, Mahasarakham University, Kham Riang, Kantarawichai, Maha Sarakham 44150, Thailand
[2] National Institutes of Technology- Kurume College, Fukuoka, Japan, 811-1313

sudsakorn.i@msu.ac.th

Abstract. *Hypoeutectic 16 wt% and 26 wt% Cr cast irons with nil, 1 and 3 wt% Mo were prepared in order to investigate their abrasion wear resistance. The annealed test pieces were hardened from 1,323 K and then tempered at three levels of temperatures between 673 and 823 K for 7.2ks, the temperature giving the maximum hardness (H_{Tmax}), lower temperature than that at H_{Tmax} (L-H_{Tmax}) and higher temperature than that at H_{Tmax} (H-H_{Tmax}). The abrasive wear behavior was evaluated using the two-body type abrasion wear test or Suga abrasion wear test. It was found that hardness and Vγ in the heat-treated specimens varied depending on the Cr and Mo contents. A linear relation was obtained between wear loss and wear distance. The lowest wear rate (R_W) was obtained in the H_{Tmax} specimen. The highest R_W was obtained in the H-H_{Tmax} specimen. Under the same heat treatment condition, the R_W in 16% Cr cast iron was much larger than that in 26% Cr cast iron. The R_W decreased with increasing the hardness in the both series of the cast irons. The lowest R_W obtained in the specimen with a certain amount of retained austenite, 25%Vγ in 16% Cr cast iron and 15%Vγ in 26% Cr cast iron, respectively.*

Keywords:

High chromium cast irons, abrasive wear resistance, heat treatment, hardness, volume fraction of retained austenite

1. Introduction

Alloyed white cast irons containing 15-30 wt% Cr (hereafter shown by %) have been employed as abrasion wear resistant materials for more than 50 years. The microstructure of these alloys consists of hard eutectic carbides and strong matrix providing the excellent wear resistance and suitable toughness. It is well known that 15% to 20% Cr cast irons have been commonly used for rolling mill rolls in the steel plants, while cast irons with 25% to 28% Cr have been applied to rollers and tables of pulverizing mills in the mining and cement industries. High Cr cast irons with hypoeutectic composition are preferable because they are free from precipitation of primary carbides that reduce the toughness [1]-[3]. As-cast microstructure of hypoeutectic composition consists of austenite dendrite and eutectic M_7C_3 carbides. The austenite is stable at high temperature and in an equilibrium state, it transforms to ferrite and carbides on the way of cooling. However, under non equilibrium state, the austenite may remain stable or partially transform to pearlite or martensite depending on the chemical composition and the cooling rate [1],[2]. Austenite is favored by high cooling rate, high Cr/C ratio and addition of Ni, Cu and Mo [1]-[3]. The supersaturation of Cr and C in the austenite depresses the martensite start temperature (Ms). Resultantly, the austenite exists even at the room temperature.

Austenite has low hardness and so toughness is high but it can be work-hardened during service to increase the surface hardness. However, it should be limited for the spalling problem. Improvement of performance for wear resistance and mechanical properties can be obtained by heat treatment and addition of alloying elements which give the martensitic matrix with higher wear resistance. In the most cases, a suitable martensitic matrix is preferred to increase the abrasion wear resistance. To obtain the martensitic matrix, the cast iron is held in austenite region at 900-1,100 °C to enable secondary carbide precipitation that is called as destabilization of austenite, and followed by fan air cooling to room temperature. The precipitation of secondary carbides in the matrix during heat treatment must be also related to the wear resistance and somewhat to the mechanical properties [4],[5]. The retained austenite should be normally less than 10% by single or multiple tempering to avoid the spalling during service [3]. In practical, applications of high chromium cast iron, adequate heat treatment should be given to the cast iron to get an optimal combination of the hardness and the toughness which is mainly controlled by quantity of retained austenite. Since quantitative measurement of retained austenite for the high chromium cast iron has been performed successfully by X-ray diffraction method [6]-[14]. It is possible to clarify the relationship between properties such as wear resistance, hardness and the amount of retained austenite.

The purpose of alloy addition is to avoid the formation of pearlite in the as-cast condition and to improve the hardenability during heat treatment. Since Cr is present in both the eutectic and secondary carbides, the rest of Cr retains in the matrix and increase the hardenability, by suppressing the pearlite transformation. Therefore, the addition of the third alloying elements such as Mo, Ni, Cu

are needed to harden the matrix fully [1]. The researches of alloying elements to high chromium cast iron have been extensively carried out [5]-[16]. It was reported that the highest hardness after heat treatment of 16% and 26% Cr cast iron was obtained by Mo addition [8]. This is because of the fact that Mo can form its special carbide of Mo_2C or M_2C with extremely high hardness as eutectic and secondary precipitates [4]. These carbides result in an increase of abrasion wear resistance.

The commercial high chromium cast irons used for wear parts in many kinds of industries, have been usually heat-treated. Hence, the wear resistance should be evaluated relating to heat treatment conditions. Many laboratory tests have been carried out to evaluate the abrasion wear resistance. However, the test data was not often valid to simulate correctly the wear behavior occurred in the industrial applications. Therefore, it is considered that the systematic and detailed studies on the abrasive wear behavior must be requested. Particularly, the systematic investigation of Mo addition on the abrasion wear and heat treatment behavior is much more important. There are many researches on the wear resistance of high Cr cast irons [3],[5],[13]-[16], and recently authors reported the effect of Mo content on the heat treatment behavior of hypoeutectic high Cr cast irons [8]. However, the systematic researches on the effect of Mo content on abrasion wear behavior of heat-treated high chromium cast irons have not been carried out.

In this study, hypoeutectic 16% Cr and 26% Cr cast irons with 0 to 3 % Mo were prepared in the heat-treated state, and the abrasion wear resistance was evaluated using a two-body-type abrasion wear tester or Suga type wear tester. The relationships between abrasion wear resistance and hardness, volume fraction of retained austenite (V_γ) and Mo content were clarified. In addition, the wear behaviors were discussed in connection with the microstructure in the cast irons.

2.　Experimental Procedures

2.1　Preparation of Test Specimens

Individual charge calculations were performed in order to obtain the target chemical compositions in the test specimens. Total heat of 30 kg was melted in a high frequency induction furnace with an alumina (Al_2O_3) lining and superheated at 1,853 K. After holding for 600 s, the melt was poured at 1,773-1,793 K into a preheated CO_2 bonded sand mold in Y-block shape which consists of a cavity for the specimen with 50x50x200 mm and sufficient volume of the riser. After pouring, the melt was immediately covered with dry exothermic powder to hold the temperature of riser. The chemical compositions of the test specimens are shown in Table 1. The schematic drawings of Y-block casting and the process to make the test pieces is shown in Fig. 1.

Specimen	Element (wt%)				
	C	Cr	Si	Mn	Mo
No.1	2.96	15.93	0.51	0.55	0.22
No.2	2.95	16.00	0.50	0.55	1.06
No.3	2.91	15.91	0.47	0.55	2.98
No.4	2.66	26.08	0.47	0.55	0.18
No.5	2.64	26.12	0.50	0.56	1.02
No.6	2.71	25.98	0.47	0.53	2.96

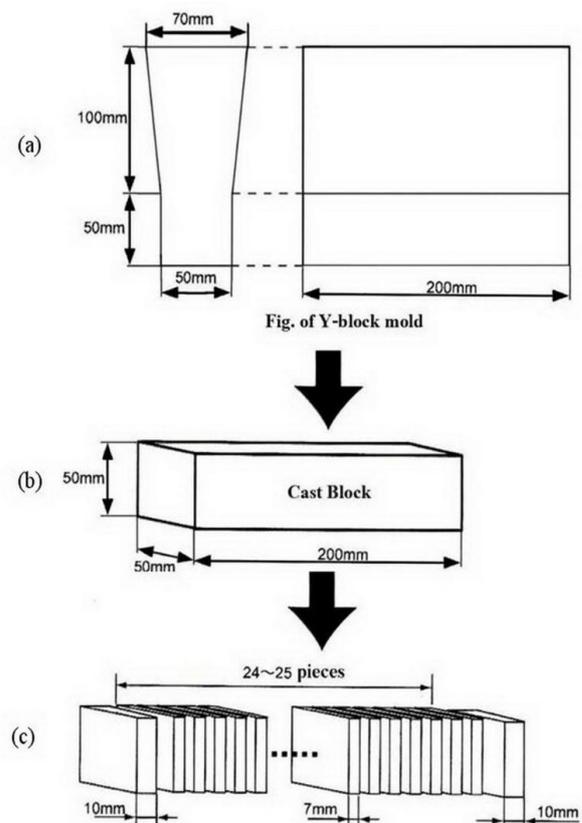**Table 1** Chemical composition of test specimens

Fig. 1　Schematic drawings of processes to make test pieces: (a) shape of casting, (b) substantial part and (c) test pieces

2.2　Heat treatment procedures

The riser was cut off from the Y-block ingot. The remaining substantial block was annealed at 1,173 K for 18 ks and sliced into test pieces with 7 mm in thickness using a wire-cutting machine. The sliced test pieces were austenitized at 1,323 K for 5.4 ks and air cooled by a fan. The as-hardened (As-H) test piece was tempered at three temperatures from 673 to 873 K for 7.2 ks, the temperature giving the maximum hardness (H_{Tmax}) and the lower and higher temperatures than that at H_{Tmax} (L-H_{Tmax}, H-H_{Tmax}). These three temperatures were determined referring to the tempered hardness curves shown in the previous work [8].

2.3 Measurement of Hardness and Retained Austenite

The macro-hardness of test specimens were measured with a Vickers hardness tester employing a load of 294 N (30 kgf). More than five indents were taken on each specimen and the measured values were averaged. The volume fraction of retained austenite (V_γ) was obtained by X-ray diffraction method using a simultaneously rotating and swinging sample stage. The diffraction peaks adopted for calculation are α_{200}, α_{220} for ferrite or martensite and α_{220}, α_{311} for austenite [6],[8]-[13].

2.4 Observation of Microstructure

To observe the microstructures, specimens were polished using emery papers in the order of No.180, 320, 400, 600 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 microstructure observation was performed by an optical microscope (OM) and a scanning electron microscope (SEM). As for the SEM investigation, the secondary electron image was taken using an accelerating voltage of 20 kV and a working distance of 15 mm.

2.5 Abrasion Wear Tests

Surface roughness of test piece was kept less than 3μm Ra-max using a grinding machine. A schematic drawing of Suga type abrasion wear tester is illustrated in Fig. 2. The force of 9.8 N (1 kgf) is applied from the abrading wheel contacted to the test piece. A 180 mesh SiC abrasive paper is fixed on the circumference of an abrading wheel. The wheel moves forth and back for 30 mm stoke on the same area of the test piece. Simultaneously, the wheel is rotated intermittently 0.9 degree per stroke, that is, the speed of rotation of the wheel was 0.345 mm/s. Since the worn area is 12x30 mm^2 (360 mm^2), the total of distance of
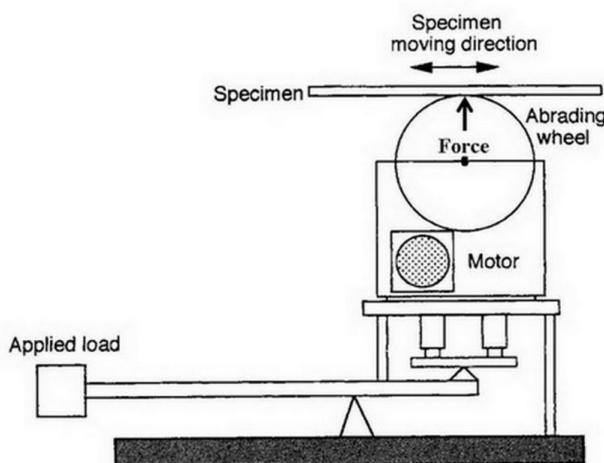

Fig. 2　Schematic drawing of Suga abrasion wear tester

one revolution or 360 degrees is 2,400 mm and the total area is 12x32x400 mm^2 (9,600 mm^2). After each test, the specimen was cleaned with acetone in an ultrasonic bath and then dried. The weight loss of the test piece was measured using a high precision digital balance with 0.1 mg accuracy. The test was repeated for eight times on one test piece.

3. Experimental Results and Discussions

3.1 Characterization of As-Hardened Test Specimens

The SEM photomicrographs of as-hardened 16% and 26% Cr cast irons with and without Mo are displayed in Fig. 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 [1],[3]. 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. In the specimen of 16 % Cr with 3% Mo, it is clear that the M_2C eutectic carbides crystallized in the residual liquid after precipitation of primary austenite are observed.

Hardness and V_γ of test specimens are summarized in Table 2. These test pieces with different hardness and V_γ were supplied to the abrasion wear test. It is found that hardness and the V_γ change significantly depending on the heat treatment condition and Mo content. The V_γ in the as-hardened state is higher than that the tempered state. It is clear that the V_γ value of L-H$_{Tmax}$ specimen is greater than those of H$_{Tmax}$ and H-H$_{Tmax}$ specimens.

Specimen		Heat treatment condition	Hardness (HV30)	Vγ, %
16% Cr	No.1 (Mo-free)	As-H　　(1323 K)	822	25
		L-H$_{Tmax}$　(673 K)	755	21
		H$_{Tmax}$　　(748 K)	786	6
		H- H$_{Tmax}$ (773 K)	748	2
	No.2 (1%Mo)	As-H　　(1323 K)	811	38
		L-H$_{Tmax}$　(673 K)	744	32
		H$_{Tmax}$　　(798 K)	831	12
		H- H$_{Tmax}$ (823 K)	718	2
	No.3 (3%Mo)	As-H　　(1323 K)	824	40
		L-H$_{Tmax}$　(673 K)	762	33
		H$_{Tmax}$　　(823 K)	816	18
		H- H$_{Tmax}$ (873 K)	654	2
26% Cr	No. 4 (Mo-free)	As-H　　(1323 K)	810	7
		L-H$_{Tmax}$　(673 K)	743	6
		H$_{Tmax}$　　(723 K)	769	4
		H-H$_{Tmax}$　(773 K)	751	1
	No. 5 (1% Mo)	As-H　　(1323 K)	865	13
		L-H$_{Tmax}$　(673 K)	782	9
		H$_{Tmax}$　　(748 K)	818	5
		H-H$_{Tmax}$　(800 K)	714	2
	No.6 (3% Mo)	As-H　　(1323 K)	873	15
		L-H$_{Tmax}$　(673 K)	831	12
		H$_{Tmax}$　　(748 K)	849	10
		H-H$_{Tmax}$ (823 K)	710	6

Table 2 Hardness and volume fraction of retained austenite (V_γ) of specimens with different heat treatment

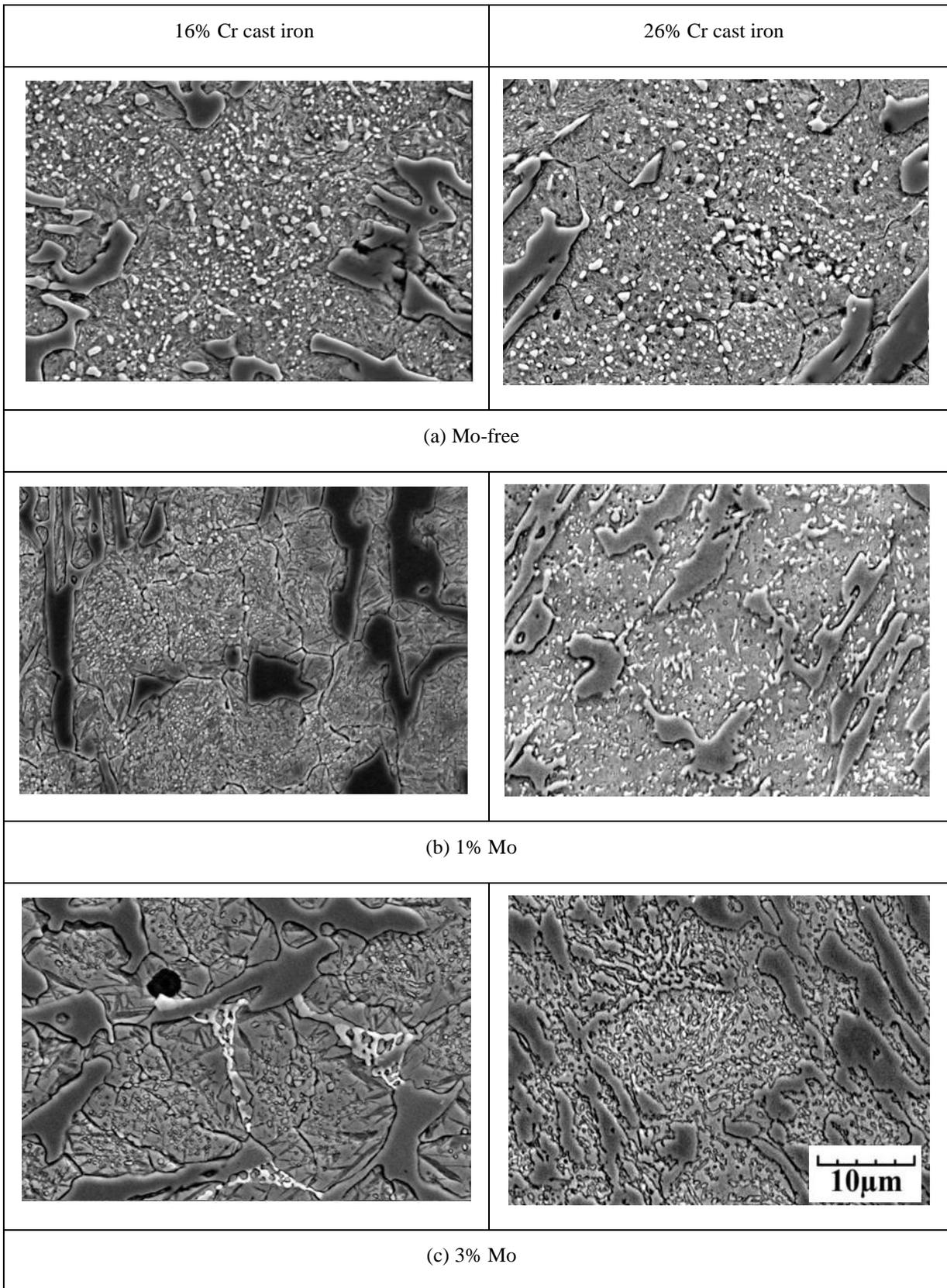| 16% Cr cast iron	26% Cr cast iron
(a) Mo-free	
(b) 1% Mo	
(c) 3% Mo	

Fig. 3   As-hardened microstructures of hypoeutectic 16% and 26% Cr cast irons without and with Mo

3.2 Abrasion Wear Behaviour

In order to prepare the specimens with matrix structure consisting of various phases or constituents, the three different temperatures which give the different amount of hardness and $V\gamma$ as well as microstructure, were employed for tempering. It is normally known that the wear resistance is also influenced by Mo content which affects the matrix transformation and which in turn influenced the type, morphology and amount of carbide, the amount of austenite and martensite. Here, the effects of heat treatment condition and Mo content on the wear resistance are described.

The relationships between wear loss and wear distance are shown in Fig. 4. The figure shows the results of the test specimens under different heat treatment conditions of As-H, L-H_{Tmax}, H_{Tmax} and H-H_{Tmax}, and for the cases of 16% and 26% Cr cast irons. In all diagrams, the wear loss increases in proportion to the wear distance regardless of the kind of specimen and heat treatment condition. In each diagram, the slope of the straight line which means the wear rate (Rw) of the specimen, varies according to the difference of heat treatment conditions.

In the 16% Cr cast iron, the difference in wear loss of the Mo-free specimen is influenced a little by the difference of heat treatment. In the Mo-bearing specimens, the difference in wear losses according to the condition of heat treatment are revealed clearly compared with that in Mo-free specimen, and it can be seen that the wear losses are smallest in the specimen with 3% Mo. The similar relations are obtained in the 26% Cr cast irons. At the same Mo content, however, the total wear losses of 26% Cr cast iron are smaller than those in the 16% Cr cast iron.

Since the linear relationships were obtained between wear loss and wear distance for all the test specimens, it is suitable to adopt an index of wear rate (R_w: mg/m) as a description of the wear resistance, which is expressed by the slope of each straight line. The R_W values of all the specimens are summarized in Table 3.

It is found that the smallest R_W or the largest wear resistance is obtained in the specimens with H_{Tmax} in which matrix contains large portion of tempered martensite and some retained austenite except for the Mo-free specimen which shows the smallest R_W in the As-H specimen. The largest R_W or the smallest wear resistance is obtained in all the specimens with H-H_{Tmax} where a large portion of martensite is tempered to ferrite and carbides and the retained austenite is mostly decomposed. It is clear that the smallest R_W or the largest wear resistance is obtained in the specimen with 3% Mo in the 16% Cr and 26% Cr cast irons.

Specimen	Heat treatment condition	Wear rate (Rw), mg/m	
		16% Cr	26%Cr
Mo-free	As-H	0.45	0.39
	L-H_{Tmax}	0.47	0.42
	H_{Tmax}	0.46	0.40
	H-H_{Tmax}	0.48	0.43
1% Mo	As-H	0.47	0.38
	L-H_{Tmax}	0.48	0.41
	H_{Tmax}	0.44	0.37
	H-H_{Tmax}	0.51	0.43
3% Mo	As-H	0.45	0.37
	L-H_{Tmax}	0.44	0.38
	H_{Tmax}	0.42	0.35
	H-H_{Tmax}	0.56	0.41

Table 3 Wear rate of test specimens with different heat treatment conditions

Since, it can be considered that both of hardness and $V\gamma$ influence on the Rw. The relationship between R_W and hardness is obtained for all specimens in Fig. 5. Though the RW values are a little scattered, they decrease in proportion to the hardness regardless of heat treatment condition and Mo content. The relations are expressed as follows:

16% Cr cast iron: Rw (mg/m) = (-5.3×10^{-4}) x (HV30) +0.884   (R = 0.85)

26% Cr cast iron: Rw (mg/m) = (-3.8×10^{-4}) x (HV30) +0.694   (R = 0.86)

It is clear that the higher the hardness, the smaller the RW or the larger the wear resistance. In the tempered state, therefore, the specimen with H_{Tmax} has the largest wear resistance in both the 16% and 26% Cr cast irons. To clarify the sensitivity of the RW effect to an increase in hardness between 16% and 26% Cr cast irons, the slopes of the lines, α_1 for Fig.5 (a) and α_2 for (b), respectively, are calculated. The ratio of α_1 to α_2 (α_1/α_2) is 1.39 and this means that the hardness effected the R_W of 16% Cr cast iron around 40% more than that of 26% Cr cast iron.

The relationships between R_W and $V\gamma$ are shown in Fig. 6 (a) for 16% Cr and (b) for 26% Cr cast irons. The relationship between these two parameters can be expressed by the following equations,

16% Cr cast iron: Rw = (1.2×10^{-4})x$(V_\gamma)^2$ - (6.3×10^{-3})x(V_γ) + 0.520   (R = 0.67)

26% Cr cast iron: Rw = (2.6×10^{-4})x$(V_\gamma)^2$ - (6.8×10^{-3})x(V_γ) + 0.432   (R = 0.58)

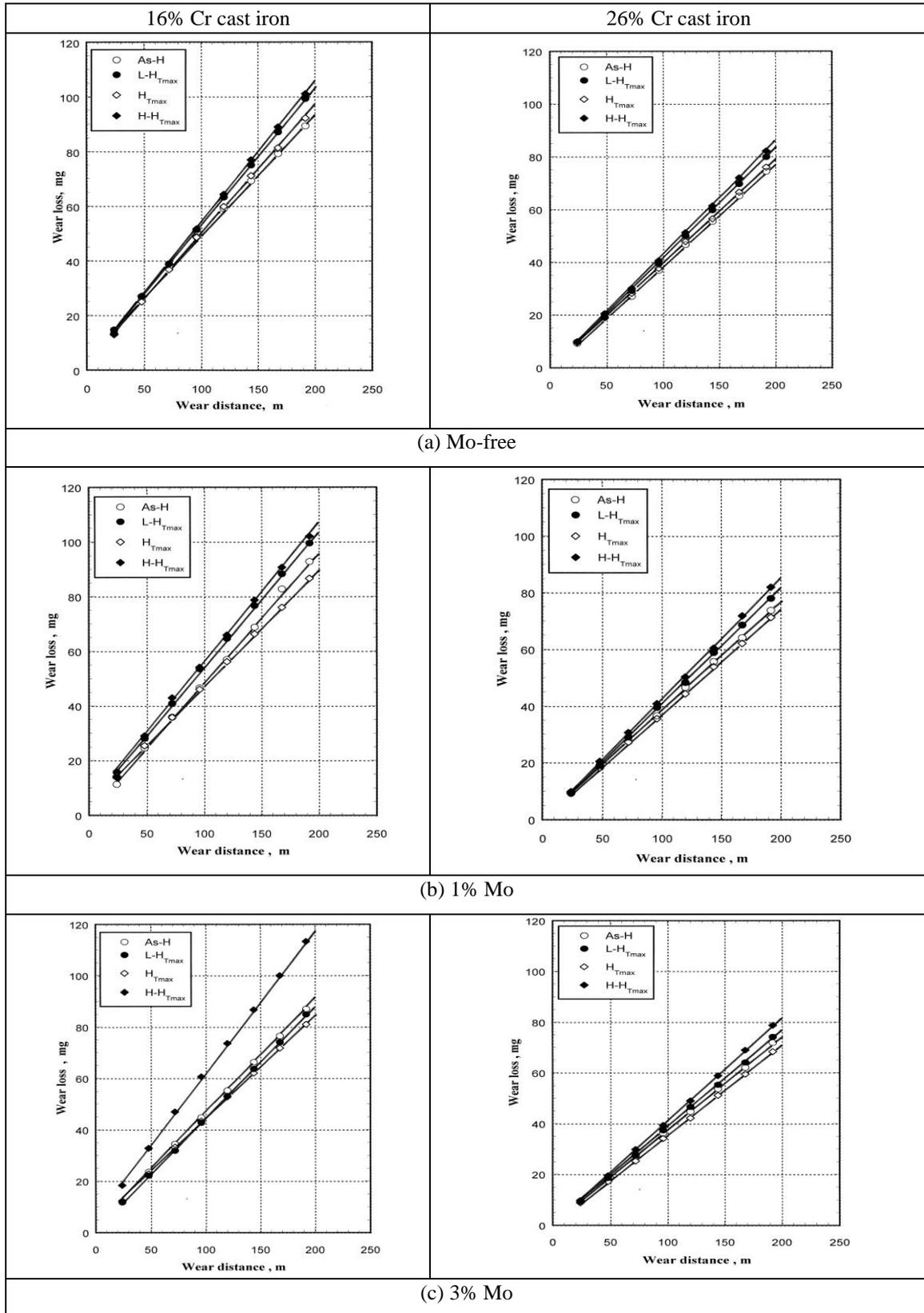| 16% Cr cast iron	26% Cr cast iron
(a) Mo-free	
(b) 1% Mo	
(c) 3% Mo	

Fig. 4   Relationship between wear loss and wear distance of heat-treated 16% and 26% Cr cast irons with and without Mo
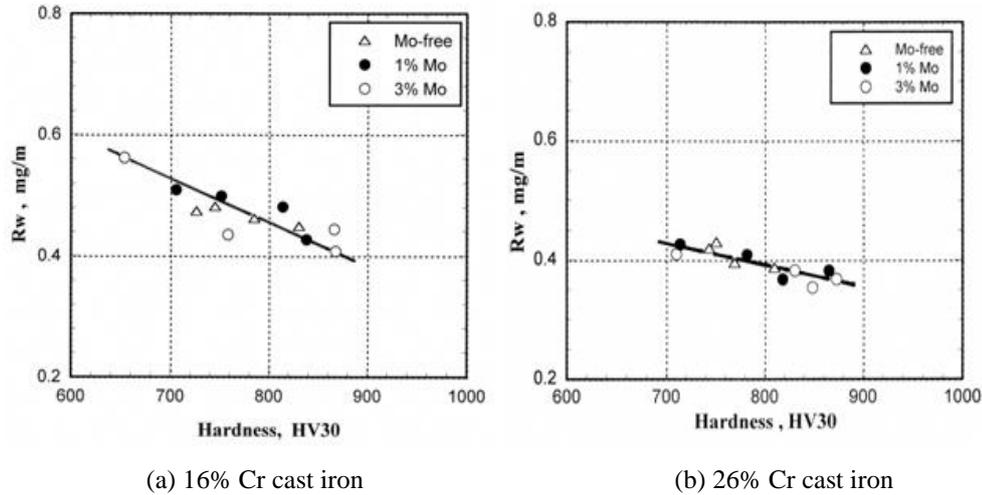
(a) 16% Cr cast iron   (b) 26% Cr cast iron

Fig. 5   Relationship between wear rate (Rw) and hardness of the specimens

(a) 16% Cr cast iron   (b) 26% Cr cast iron
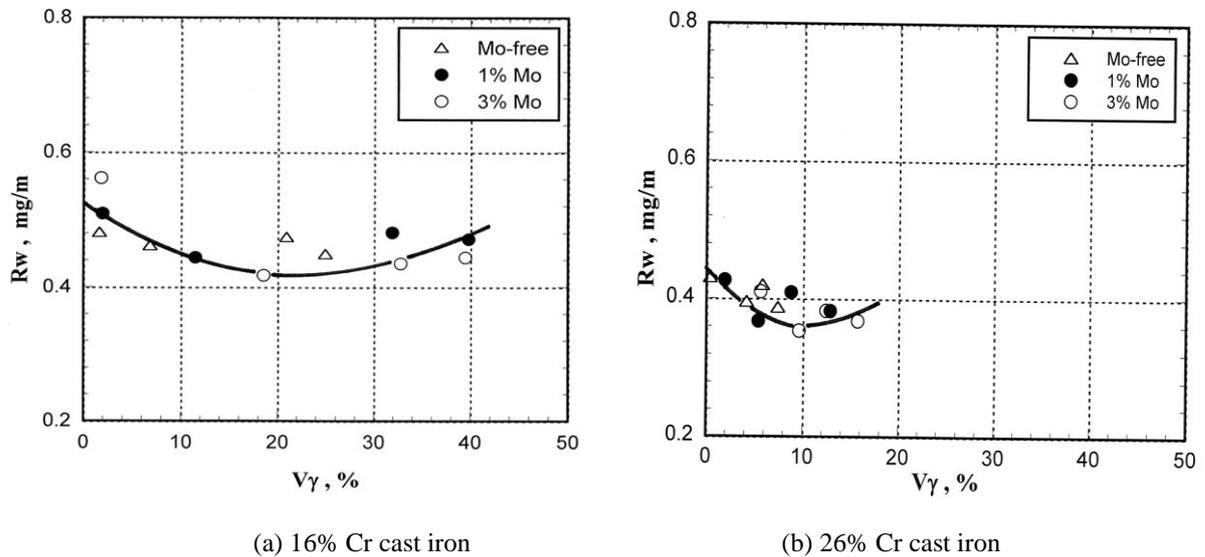
Fig. 6   Relationship between wear rate (Rw) and volume fraction of retained austenite (Vγ) of the specimens

It seems that the minimum value of RW is obtained at about 20% Vγ in the 16% Cr cast iron and 10% Vγ in the 26% Cr cast iron. This suggests that a certain amount of the retained austenite could be available to improve the abrasion wear resistance. The decrease in the RW to a lowest Rw value is due to an increase in the hard martensite and the precipitation of secondary carbides in the matrix and that in the strength of matrix. At very low Vγ value, the RW is relatively high in both the 16% and 26%Cr cast irons because the matrix is contained of pearlite and coarse secondary carbides.

The effect of the Mo content of the cast iron on the RW is shown in Fig. 7. The R_W decreases totally a little as the Mo content increases and the decreasing rate is similar between 16% and 26% Cr cast irons. From the results, it can be concluded that an increase in Mo content to 3%

improves the wear resistance of hypoeutectic 16% and 26% Cr cast irons. At the same Mo content, the Rw value of 16% Cr cast iron is larger than that of 26% Cr cast iron.

From Fig. 7, the 26% Cr cast iron shows the better wear resistance than the 16% Cr cast iron. The reason can be explained as follows:

In the specimens, the volume fractions of eutectic carbides are almost same, 36.2% in 16% Cr and 36.4% in 26% Cr specimens, respectively. Resultantly, it is considered that the effect of the amount of eutectic carbide on the Rw is less between the 16% and 26% Cr specimens. When the hardness of H_{Tmax} are compared between the specimens with 1% Mo, they are almost the same, 831 HV30 and 818 HV30 for 16% Cr and 26% Cr, respectively. It can be considered from these results that the difference in the wear resistance between 16% and 26% Cr specimens
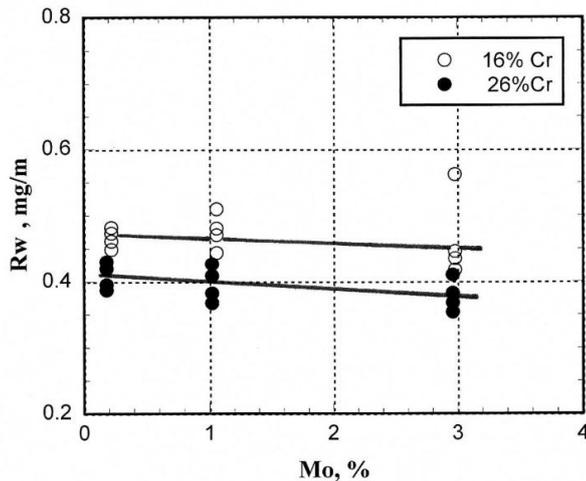
Fig. 7 Effect of Mo content on wear rate (Rw) of 16% and 26% Cr cast irons

arises from the difference in the morphology and the hardness of eutectic carbides. That is, the morphology of eutectic carbide in 16% Cr cast iron is thicker and more interconnected in comparison with that of 26% Cr cast iron which is fine and less interconnected. It is well known that the hardness of eutectic carbides in the 26% Cr cast iron is higher than that in the 16% Cr cast iron due to more dissolution of Cr [1]-[3]. Under a high stress abrasion occurred by the abrasives with very high hardness, the harder and tougher carbides provide the better resistance. As mentioned before, Mo distributed in the austenite during solidification influences the transformation of matrix. The partition coefficient of Mo to the austenite is given as the ratio of Mo content in austenite to that in the quenched liquid, 0.36 for 15 % Cr and 0.45 for 30 % Cr cast irons, respectively [17]. More Mo concentration in the matrix of 26 % Cr cast iron promotes more precipitation of hard secondary carbides with Mo. It is possible by tempering that some special molybdenum carbides could precipitate as a result of carbide reaction in the martensite.

Here, it can be said that the Mo gives a positive effect on the wear resistance of 16% and 26% Cr cast irons. This is because the Mo represses the formation of pearlite in the as-cast condition and improves the hardenability. From wear test results of heat-treated specimens, the wear resistance increases with an increase in the hardness as well as that in the Mo content. As the Mo contents increase, the Mo distributed to the austenite promotes not only to precipitate the molybdenum carbides with extremely high hardness but also the Mo in M_7C_3 eutectic carbide increases the hardness of the carbide. The presence of a certain amount of M_2C carbides is beneficial for the wear resistance because it could prevent the propagation of cracking in the matrix [4].

3.3 Mechanism of Abrasion Wear

In order to comprehend the abrasion wear behavior, the SEM microphotographs of 1% Mo specimen with H_{Tmax} are taken and representative examples of worn surface are shown in Fig. 8 (a) for 16% Cr and (b) for 26% Cr cast irons, respectively. In the both specimens, the abraded regions showing fine lines caused by scratching correspond to the matrix areas. On the microphotographs, it is found that the eutectic carbides are worn a little by scratching and more by spalling or pitting, and much rougher worn surfaces are formed by grooving and tearing. The matrix is preferably cut off or worn and removed more than the eutectic carbides. The cracks occur probably in the eutectic carbides because the load concentrates on the carbides. As a result, spalling of carbides could take place. The tearing and grooving are observed because the austenitic matrix with more ductility can be deformed easily without cracking by the stress of abrasive particles [3]. The tearing could form in the matrix area of the grooving. In addition, this plastic deformation could absorb the mechanical energy applied by the abrasive particle [3]. As a result, the grooving is narrow in the austenitic region. It is clear from the photographs in Fig. 8 that the worn surface of 16% Cr cast iron is heavily deformed more than that of 26% Cr cast iron. These results agree well with the data of abrasion wear test.
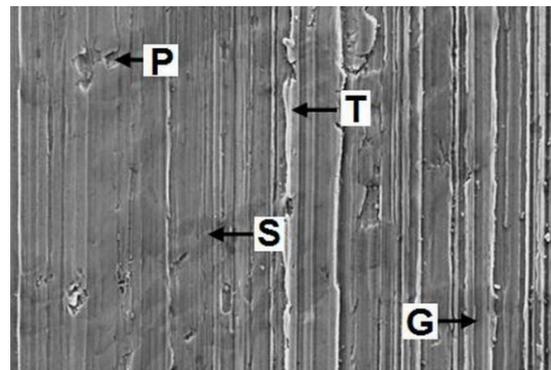
(a) 16% Cr cast iron
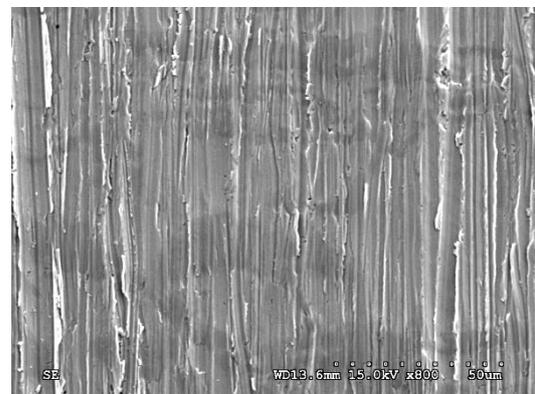
(b) 26% Cr cast iron

Fig. 8 SEM microphotographs of worn surfaces of 1%Mo specimens with H_{Tmax}

4.   Conclusion

The abrasive wear behavior of heat-treated hypoeutectic 16% and 26% Cr cast irons without and with Mo was investigated. After annealing, the specimens were hardened from 1,323 K (As-H) and tempered at three levels of temperatures, the temperature giving the maximum hardness (H_{Tmax}), and the lower and higher temperature than the H_{Tmax} temperature, (L-H_{Tmax}, H-H_{Tmax}). The effects of hardness, volume fraction of retained austenite (Vγ) and the heat treatment conditions on the abrasion wear behavior were clarified. The following conclusions have been drawn from the experimental results and discussions.

1) The linear relationship was obtained between wear loss and wear distance. The largest wear resistance or the smallest RW value was obtained in the specimen with H_{Tmax} except for the Mo-free specimen. The smallest wear resistance or the greatest R_W value was obtained in the H-H_{Tmax} specimen. The R_W value in the 16% Cr cat iron was much larger than that in the 26% Cr cast iron.

2) The R_W decreased with an increase in the hardness. The hardness had more effect on 16% Cr cast iron than 26% Cr cast iron.

3) The smallest RW appeared in the specimen with a certain amount of retained austenite, 20%Vγ for 16% Cr cast iron and 10%Vγ for 26% Cr cast iron, respectively.

4) The R_W was decreased with increasing the Mo content of the specimen. At the same Mo content, the Rw in the 16% Cr cast iron is higher than that in the 26% Cr cast iron. The smallest Rw was obtained in the specimens with 3% Mo in both the 16% and 26% Cr cast irons.

5) The matrix was preferably cut off or worn and removed faster and much more than the eutectic area. When this process continued, the cracks were caused in the eutectic carbides, and resultantly, the spalling could take place and the eutectic carbides are removed. The coarser worn surface was formed by such grooving and tearing.

Acknowledgements

References

[1] G.L.F Powell, Metals Forum, Vol. 3 (1980), p. 37-46.

[2] Y. Matsubara, K. Ogi and K Matsuda, AFS Trans. Vol. 89 (1981), p.183-196.

[3] G. Laird, R. Gungdlach and K. Rohring, Abrasion-Resistance Cast Iron Handbook (American Foundry Society, USA, 2000)

[4] M. Ikeda, ISIJ International. Vol. 32 (1992), p.1157-1162.

[5] S.K. Yu, N. Sasaguri and Y. Matsubara, Int. J. Cast Metals Res., Vol. 11 (1999), p. 561-566.

[6] C. Kim. J. Heat treating ASM. Vol. 1 (1979) p. 43-51.

[7] I.R. Sare and B.K. Arnold , Metal Trans A. Vol. 26A (1995), p. 359-370.

[8] S. Inthidech, P. Sricharoenchai and Y. Matsubara: Mat. Trans. Vol. 47 (2006), p. 72-81.

[9] S. Inthidech, P. Sricharoenchai, N. Sasaguri, Y. Matsubara: AFS Trans. Vol. 112 (2004), p. 899-910.

[10] P. Sricharoenchai, S. Inthidech, N. Sasaguri, Y. Matsubara: AFS Trans. Vol. 112 (2004), p. 911-923.

[11] S. Inthidech, P. Sricharoenchai and Y. Matsubara: Mat. Trans., Vol. 49 (2008), p. 2322-2330.

[12] S. Inthidech, K. Boonmak, P. Sricharoenchai, N. Sasakuri and Y. Matsubara, Mat. Trans., Vol. 51 No. 7 (2010), p. 1264-1271.

[13] S. Inthidech, P. Aungsupaitoon, P. Sricharoenchai and Y. Matsubara, Int. J. Cast Metals Res. Vol. 23 No.3 (2010), p. 164-172.

[14] G. Laird II, AFS Transactions. Vol. 99 (1991), p. 339-357.

[15] C.P. Tabrett, I.R. Sare and M.R. Ghomashchi, Int. Mater. Rev., Vol. 41 (1996) p. 59-82.

[16] G. laird and G.L.F. Powell, Mat. Trans., Vol. 24A (1993), p. 981-988.

[17] Y. Ono, N. Murai and K. Ogi: ISIJ., Vol 32 (1992), p. 1150-1156.