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Output ที่ได้จากโครงการ

1. ได้ศึกษาความต้านทานต่อการสึกหรอแบบขัดสีของเหล็กหล่อโครเมียมสูงที่เติมธาตุผสมโมลิบดินัม (Mo) ซึ่งใช้งานอย่างกว้างขวางในโรงงานอุตสาหกรรมปูนซีเมนต์ อุตสาหกรรมเหมืองแร่ อุตสาหกรรมผลิตเหล็กกล้าและอุตสาหกรรมผลิตกระแสไฟฟ้าในประเทศไทย โดยเป็นงานศึกษาต่อยอดจากงานวิจัยจากทุนวิจัยที่เคยได้รับก่อนหน้านี้ (MRG5180110)

2. ได้สร้างความร่วมมือกับกลุ่มวิจัยและโรงงานอุตสาหกรรมทั้งในและต่างประเทศจึงมั่นใจว่าจะสามารถวิจัยต่อยอดและผลิตผลงานวิจัยเกี่ยวกับการปรับปรุงความต้านทานการสึกหรอของเหล็กหล่อโครเมียมสูงเพื่องานด้านการขัดสีต่อไปได้ในอนาคต

3. ได้ประสบการณ์ในการทำวิจัยมากขึ้นและได้ตีพิมพ์ผลงานวิจัยจำนวน 3 ผลงาน

Appendix

1) สำเนาผลงานที่นำเสนอในงานประชุมวิชาการระดับนานาชาติเรื่อง “Abrasive Wear Resistance of Hypoeutectic 16 wt% and 26 wt% Cr Cast Irons with Molybdenum”, Proceedings of the International Conference ABRASION 2011 (Abrasion Wear Resistant Alloyed White Cast Irons for Rolling and Pulverizing Mills), 4th Edition held at the University of Liege, Belgium, August 21-24, 2011

2) สำเนาผลงานที่นำเสนอในงานประชุมวิชาการระดับชาติเรื่อง “Three-Body-Type Abrasive Wear Behavior of 26% Cr Cast iron with Molybdenum”, The 5 th Thailand Metallurgy Conference, Miracle Grand Conventional, Bangkok, 19-20 January 2012

3) สำเนา Manuscript เรื่อง “Two-body and Three-body Types Abrasive Wear Behavior of Hypoeutectic 26 wt% Cr Cast Irons with Molybdenum” ที่ได้ส่งเพื่อตีพิมพ์วารวสารวิชาการระดับนานาชาติ Materials Transactions ประเทศญี่ปุ่น ซึ่งมีค่า Impact factor ปี 2011 เท่ากับ 0.779

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

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

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 1323 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 $V\gamma$ in the heat-treated specimens varied depending on the Cr and Mo content. 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%V_γ in 16% Cr cast iron and 15%V_γ in 26% Cr cast iron, respectively.

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 form 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 additions 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 900-1100 ^{o}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 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 is 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 ($V\gamma$) and Mo content were clarified. In addition, the wear behaviors were discussed in connection with the microstructure in the cast irons.

Experimental Procedures

Preparation of test specimens

Individual charge calculations were performed 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 1853 K. After holding for 600 s, the melt was poured at 1773-1793 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.

Table 1 Chemical composition of test specimens.

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

Heat treatment procedures

The riser was cut off from the Y-block ingot. The remaining substantial block was annealed at 1173 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 1323 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]

Measurement of hardness and retained austenite

The macrohardness 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 ($V\gamma$) 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 γ_{220}, γ_{311} for austenite. [6, 8-13]

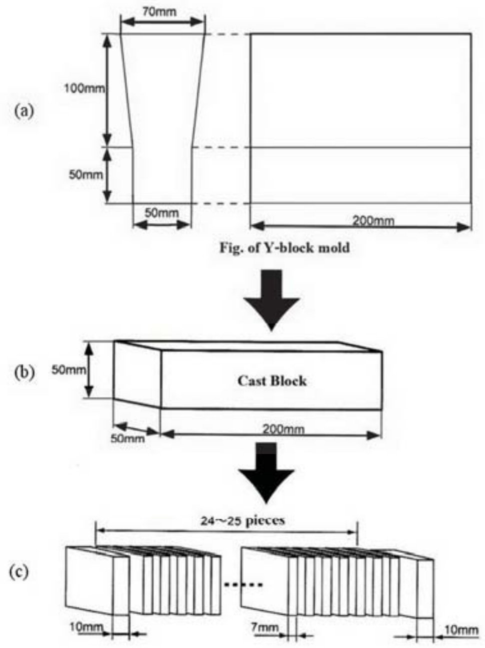


Fig. 1 Schematic drawing of process to make test pieces. a) shape of casting, b) substantial part and c) test pieces.

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.

Abrasion Wear Test

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 one revolution or 360 degrees is 2400 mm and the total area is 12x32x400 mm^2 (9600 mm^2). After a 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.

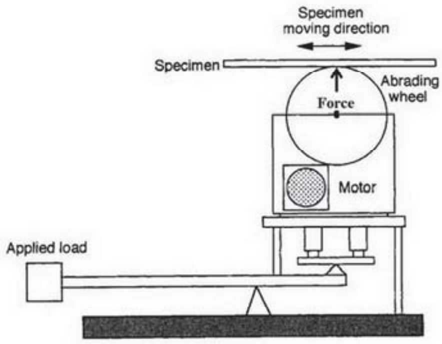


Fig 2. Schematic drawing of Suga abrasion wear tester.

Experimental Results and Discussions

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 3. 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.

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_γ as well as microstructure, were employed for tempering. It is 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 for 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.

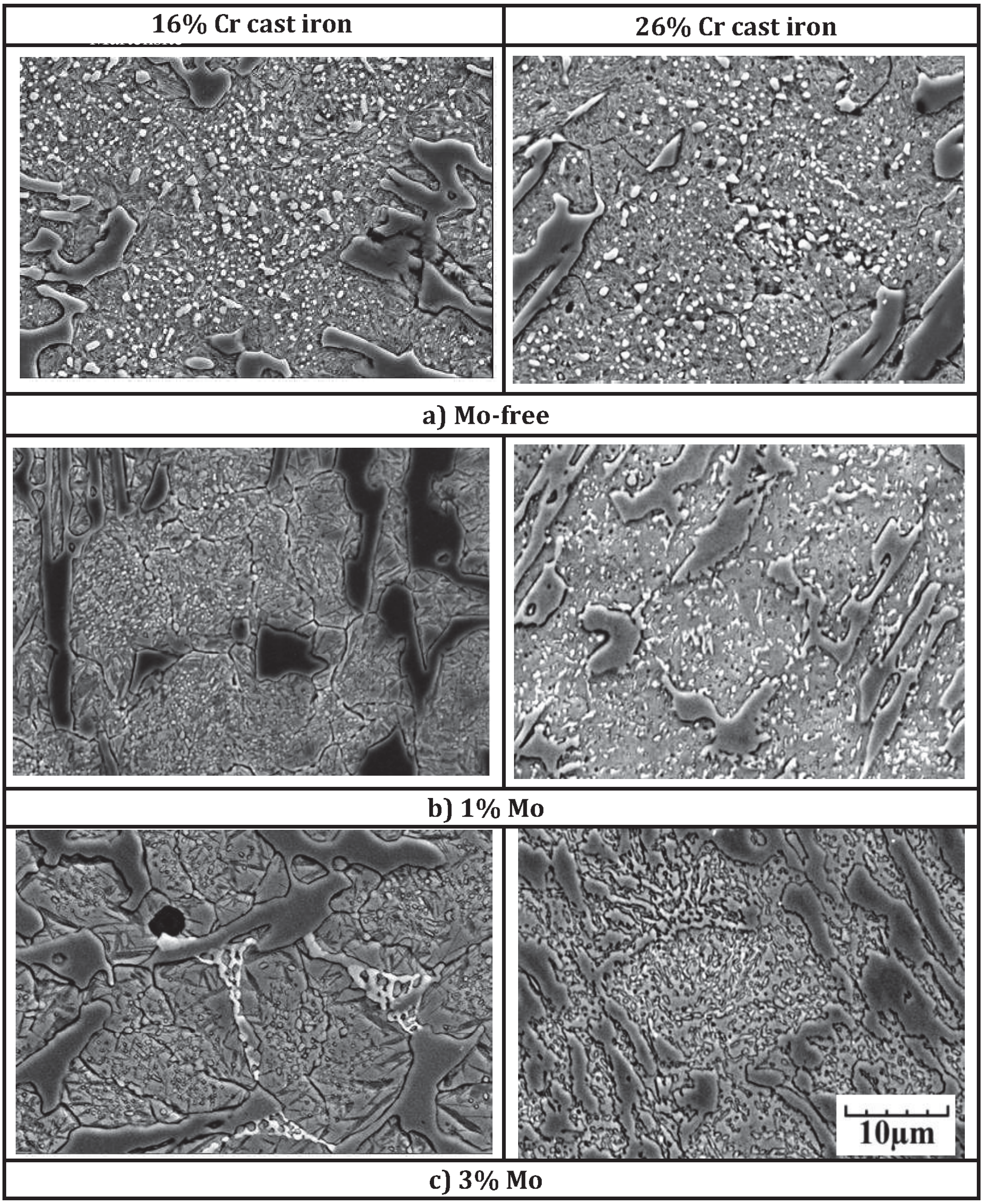


Fig. 3 As-hardened microstructures of hypoeuttectic 16% and 26% Cr cast irons without and with Mo.

Table 3 Hardness and volume fraction of retained austenite (V_γ) of specimens with different heat treatment.

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

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 in all the specimens, it is suitable to adopt an index of wear rate (Rw: 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 4. 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.

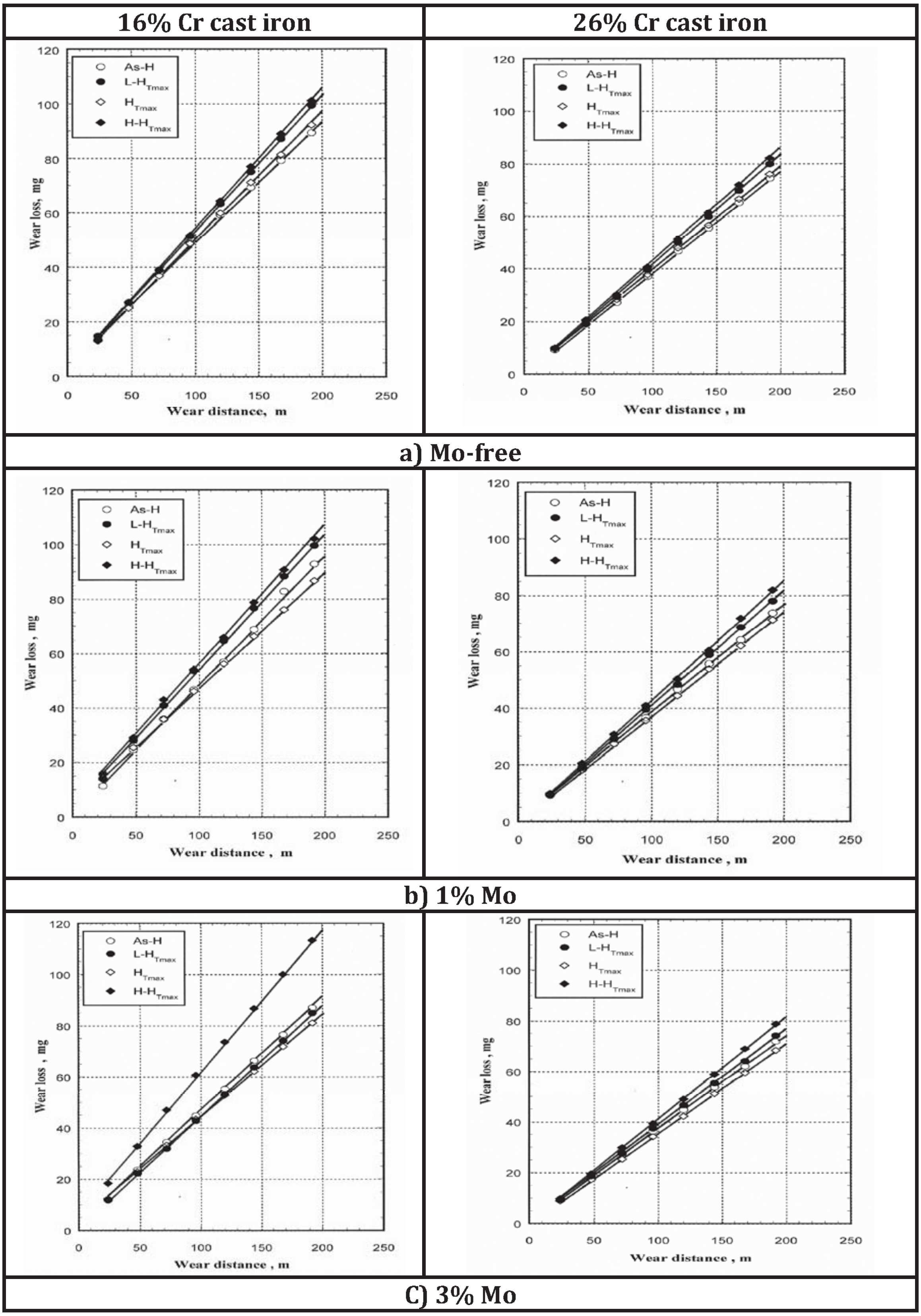
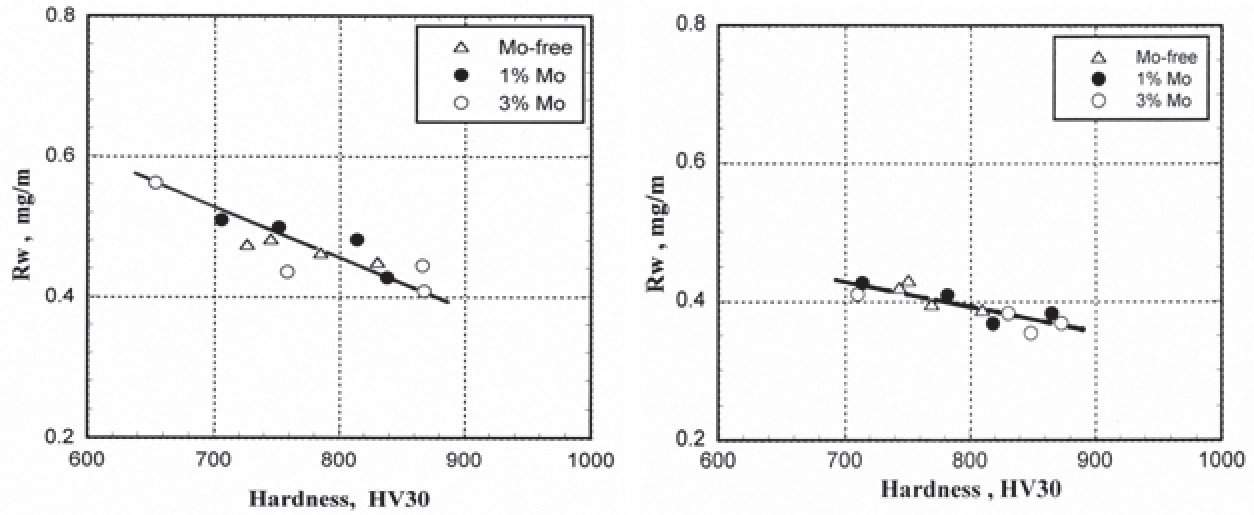


Fig. 4 Relationship between wear loss and wear distance of heat-treated 16% and 26% Cr cast irons with and without Mo.

Table 4 Wear rate (Rw) of test specimens with different heat treatment.

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



a) 16% Cr cast iron b) 26% Cr cast iron

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

Since, it can be considered that both of hardness and Vγ influence on the Rw. The relationship between R_W and hardness is obtained for all specimens in Fig.5. Though the R_W 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 = (-5.3×10^{-4}) x (HV30) + 0.884 (R = 0.85)
26% Cr cast iron: Rw = (-3.8×10^{-4}) x (HV30) + 0.694 (R = 0.86)

It is clear that the higher the hardness, the smaller the R_W 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 R_W 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 relations can be expressed by the following equations,

16% Cr cast iron: $Rw = (1.2\text{x}10^{-4}) \text{ x } (V\gamma)^2 - (6.3\text{x}10^{-3}) \text{ x } (V\gamma) + 0.520$ (R = 0.67)
26% Cr cast iron: $Rw = (2.6\text{x}10^{-4}) \text{ x } (V\gamma)^2 - (6.8\text{x}10^{-3}) \text{ x } (V\gamma) + 0.432$ (R = 0.58)

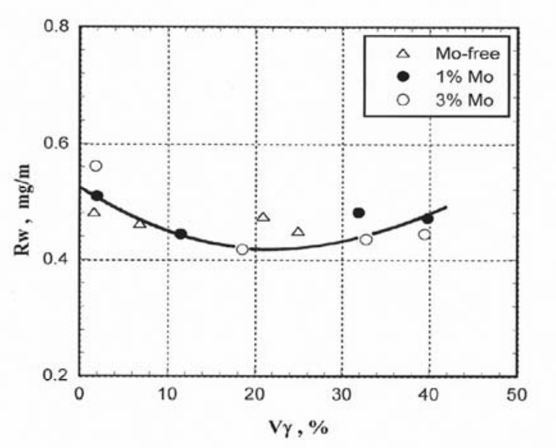
It seems that the minimum value of R_W is obtained at about 20% $V\gamma$ in the 16% Cr cast iron and 10% $V\gamma$ in the 26% Cr cast iron. This suggests that a certain amount of the retained austenite could be available to improve the abrasion wear resistance. The decrease in the R_W to a lowest Rw 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 V_γ value, the R_W 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 R_W 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.

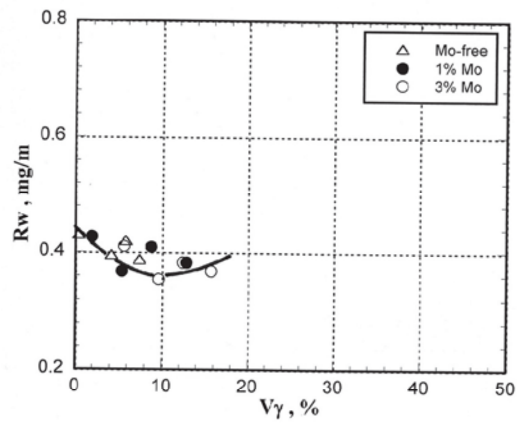
From Fig. 7, the 26% Cr cast iron shows the better wear resistance than the 16% Cr cast iron. The reason can be explained as follows:
In the specimens, the volume fractions of eutectic carbides are almost same, 36.2% in 16% Cr and 36.4% in 26% Cr specimens, respectively. Resultantly, it is considered 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 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 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]



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 specimens.

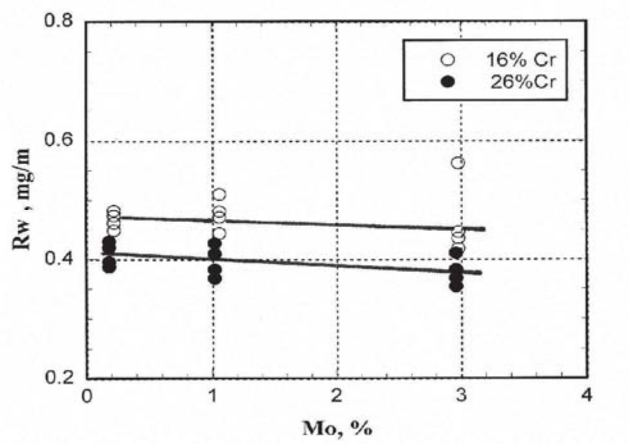
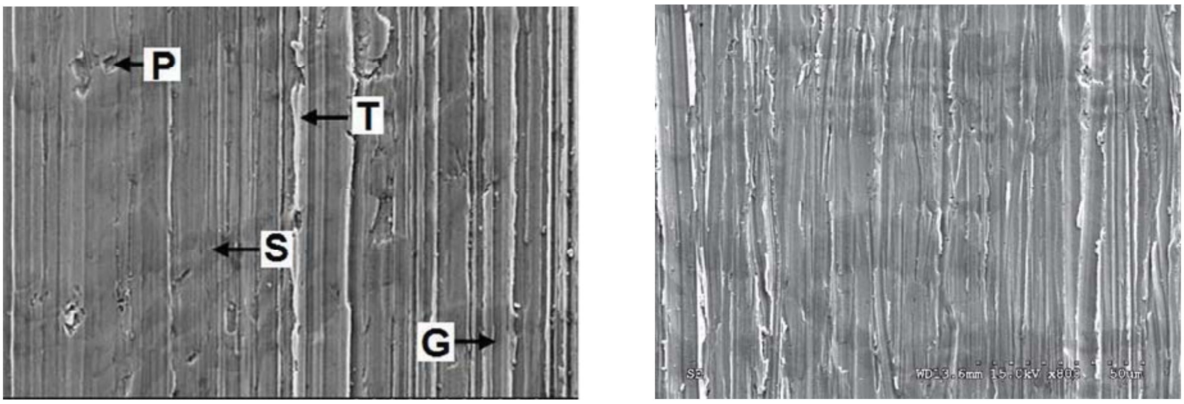


Fig. 7 Effect of Mo content on wear rate (Rw) of 16% and 26% Cr cast irons.

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}.

CONCLUSIONS

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 1323 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 ($V\gamma$) 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 R_W 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 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 R_W appeared in the specimen with a certain amount of retained austenite, 20%V_γ for 16% Cr cast iron and 10%V_γ 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 resultanly, the spalling could take place and the eutectic carbides are removed. The coarser worn surface was formed by such grooving and tearing.

Acknowledgements

The authors gratefully acknowledge to the Thailand Research Fund, the Commission on Higher Education and Mahasarakham University for the research funding.

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แบบตอบรับบทความวิชาการ ในการประชุมวิชาการทางโลหวิทยาแห่งประเทศไทย ครั้งที่ 5

26 ธันวาคม 2554

ที่ TMETC.SP110/2554

เรื่อง ตอบรับบทความวิชาการ

เรียน **ผู้ช่วยศาสตราจารย์ ดร.สุดสาคร อินธิเดช**

ตามที่ท่านได้ส่งบทความวิชาการ เรื่อง "**Three-Body-Type Abrasive Wear Behavior of 26% Cr Cast iron with Molybdenum**" เข้าร่วมการประชุมวิชาการทางโลหวิทยาแห่งประเทศไทย ครั้งที่ 5 (๕TMETC) ระหว่างวันที่ 19-20 มกราคม 2555 ณ โรงแรมมิราเคิลแกรนด์

ในการนี้ คณะกรรมการดำเนินการ การประชุมวิชาการทางโลหวิทยาแห่งประเทศไทย ครั้งที่ 5 มีความยินดีที่จะเรียนให้ท่านทราบว่า บทความเรื่องดังกล่าวได้ **ผ่านการพิจารณา** โดยผู้ทรงคุณวุฒิให้นำเสนอในการประชุมวิชาการทางโลหวิทยาแห่งประเทศไทย ครั้งที่ 5 แล้ว

จึงเรียนมาเพื่อโปรดทราบ

ขอแสดงความนับถือ

(ผศ.ดร.สมฤกษ์ จันทรอัมพร)

ประธานคณะกรรมการดำเนินการ

การประชุมวิชาการทางโลหวิทยาแห่งประเทศไทย ครั้งที่ 5

ภาควิชาวิศวกรรมวัสดุและเทคโนโลยีการผลิต คณะวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าพระนครเหนือ เลขที่ 1518 ถนนพิบูลสงคราม บางซื่อ กทม. 10800 โทรศัพท์ 0-2587-4335 โทรสาร 0-2587-4335 ต่อ 116 เว็บไซต์ : www.tmetc5.kmutnb.ac.th อีเมล์: tmetc5@kmutnb.ac.th

Three-Body-Type Abrasive Wear Behavior of 26% Cr Cast iron with Molybdenum

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Abstract

Hypoeutectic 26 wt% Cr cast irons without and with Mo were prepared in order to investigate their abrasion wear resistance. The annealed specimens were hardened from 1323 K (As-H) 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 resistance was evaluated using Rubber Wheel abrasion test (three-body-type). It was found that hardness and volume fraction of retained austenite ($V\gamma$) in the heat-treated specimens varied with the Mo content and heat treatment condition. A linear relation was obtained between wear loss and wear distance in all specimens. The lowest wear rate (Rw) was obtained in both the As-H or H_{Tmax} specimens. The highest Rw was obtained in both the L- H_{Tmax} or H- H_{Tmax} specimens. Rw decreased with increasing hardness. The lowest Rw obtained in the specimen with 10% $V\gamma$ and Rw was independent on Mo content.

Keywords: *High chromium cast iron, Three-body-type 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 microstructures of these alloys consist of hard eutectic carbides and strong matrix structure 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 than those with hypereutectic composition because they are free from precipitation of massive primary carbides that reduce the toughness. [1]

In the hypoeutectic cast iron, as-cast microstructure consists of primary matrix and eutectic M_7C_3 carbide. Austenite which is stable at high temperature under an equilibrium condition will transform to ferrite and carbides or pearlite on the way of cooling. Under non-equilibrium condition, however, the austenite may remain stable or partially transforms to pearlite or martensite depending on the chemical composition and the cooling rate. [1,2] Austenite has high toughness and it can be work-hardened to increase the surface hardness during service. However, it is limited to the spalling wear resistance. Improved service performance could be obtained by heat treatment and addition of some alloying elements to provide martensitic matrix with higher wear resistance.

The three-body-type abrasive wear environment consists of two counter materials and abrasive particles. It occurs in the application where moving particles come freely into wearing surfaces. Typical applications involving this type of wear are for ball and rod mills, pulverizers, like vertical mill and roll crushers. [1,3] The suitable wear testing machine for three-body-type abrasion wear is a Rubber Wheel wear tester where SiO_2 particles are used as the abrasives.[1]

Many laboratory tests have been carried out to evaluate the abrasion wear resistance of high Cr cast irons. [4-9] However, the test data did not often validly to simulate correctly the wear behavior occurred in the industrial applications. [1] Therefore, it is considered that the systematic and detailed studies on the abrasive wear behavior are necessary. In this study, hypoeutectic 26% Cr cast irons varying Mo content were prepared and they were heat-treated. Then, Rubber Wheel abrasion wear test was conducted. The relationships between abrasive wear, hardness, volume fraction of retained austenite ($V\gamma$) and molybdenum content are discussed.

2 EXPERIMENTAL

Hypoeutectic 26% Cr cast irons with and without molybdenum were produced using a 30 kg capacity high frequency induction furnace with alumina lining. Raw materials such as mild steel, pig iron, ferro-alloys and pure metals were used as charge materials. The charge materials were melted down and superheated up to 1853 K. After holding at the temperature, each melt was poured from 1793 to 1773 K into preheated CO_2 Y-block mold with a cavity size of 50x50x200 mm, and the surface of the top riser was immediately covered with dry exothermic powder to prevent the riser from fast cooling. The Y-block castings were sectioned to obtain the dimension of 50x50x7 mm. The chemical compositions of each specimen are shown in Table 1.

After annealing at 1273 K for 18 ks, the test pieces were austenitized at 1323 K for 5.4 ks and hardened by fan air cooling. The hardened test pieces (As-H) were tempered in a furnace at 3 levels of temperatures between 673 and 823 K, a temperature just at H_{Tmax}, a temperature lower than that at H_{Tmax} (L-H_{Tmax}) and an higher temperature than that at H_{Tmax} (H-H_{Tmax}) for 7.2 ks. The specimens were cooled to room temperature by fan air cooling.

The microstructure was observed by Optical microscope (OM) and Scanning Electron Microscope (SEM). The measurement of macro-hardness was performed by Vickers hardness tester with a load of 30 kgf, and micro-hardness of matrix was measured by Micro-Vickers hardness tester with a load of 100 g. More than five indentations were taken at random and the measured values were averaged. The volume fraction of retained austenite ($V\gamma$) was obtained by X-ray diffraction method using a special goniometer with automatic rotating and swinging sample stage. [10] Mo-Kα characteristic line with a wavelength of 0.007 nm (0.711 A°) filtered by Zr was used as a source of X-ray beam. The diffraction peaks used for $V\gamma$ calculation were (200) and (220) planes for ferrite (α) or martensite (M) and (220) and (311) planes for austenite (γ).

The schematic drawing of Rubber Wheel abrasion wear tester is shown in Figure 1. The silica sand of AFS 60 grade was used as the abrasives. The sands were fed to the contacting face between the rotating rubber wheel with 250 mm in diameter and test piece. The test was conducted at a rotating speed of 120 rpm. The rate to feed the abrasives was approximate 250-300 g/min. The load applied was 8.7 kgf. After the rubber wheel rotates for 1,000 revolutions or at wear distance 785.5 m, the specimen was cleaned in an ultrasonic acetone and then dried. The weight of the test piece was measured using a high precision digital weight balance with 0.1 mg accuracy. The test was repeated four times or up to the wear distance 3142 m per one test piece.

Table 1: Chemical composition of test specimens

Specimens	Alloy (wt%)				
	C	Cr	Si	Mn	Mo
Mo-free	2.66	26.08	0.47	0.55	0.18
1% Mo	2.64	26.12	0.50	0.56	1.02
2% Mo	2.63	25.92	0.44	0.45	1.97
3% Mo	2.71	25.98	0.47	0.53	2.96

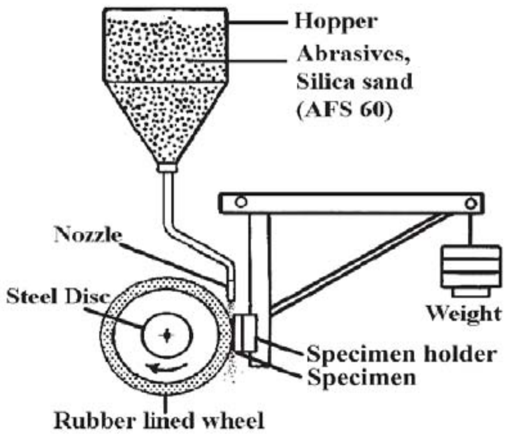


Figure 1: Schematic drawing of Rubber Wheel abrasion wear tester. [1]

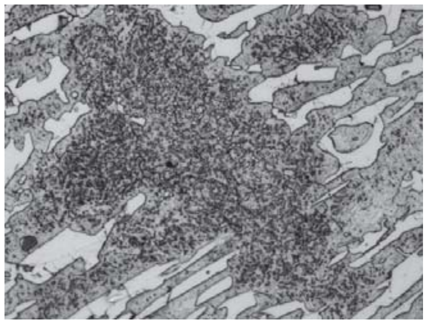
3 Results and Discussion

3.1 *Microstructure of test specimen*

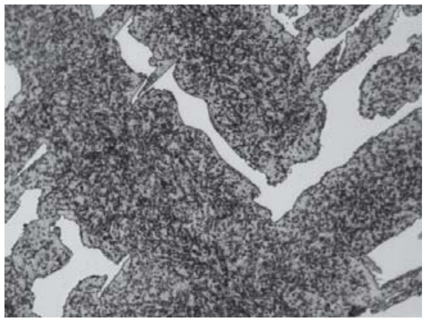
As-hardened microstructures of test specimens are example in Figure 2 by OM. The eutectic carbides appear unchanged from as-cast condition. On the other hand, it is found that the matrix transformed to precipitate a large number of fine carbides. The matrices among the carbides should consist of some martensite and retained austenite, but they cannot be seen in these photomicrographs. It has been reported that the secondary carbides which precipitated in the as-hardened state of high Cr cast iron are mostly $M_{23}C_6$ carbides co-existing with a certain amount of M_7C_3 carbides. [1,3,4,6] The retained austenite which existed in the as-cast state is destabilized to precipitate fine secondary carbides during holding and transforms into martensite during cooling.

3.2 *Abrasive wear test*

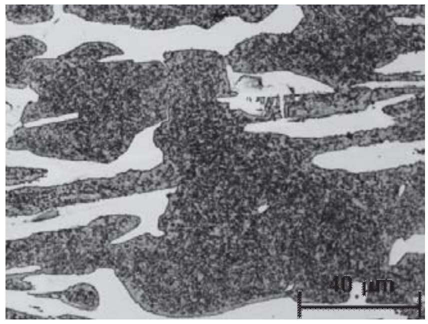
The results of Rubber Wheel wear tester are displayed in Figure 3 as an example for Mo-free and 3% Mo specimens. It is found that the wear loss increased in portion to the wear distance in all the specimens. Since, the linear relations were obtained between wear loss and wear distance in all the specimens, the parameter of wear rate (Rw) which is expressed by the slope of each straight line is introduced. The Rw values are correspondingly summarized in Table 2. It is found that that the smallest Rw is obtained in the as-hardened and H_{Tmax} specimens. The largest Rw value is obtained in the H-H_{Tmax} specimen.



a) Mo-free



b) 1% Mo



c) 3% Mo

Figure 2: Microstructures of as-hardened specimens with different Mo content taken by OM.

Table 2: Wear rate (Rw) of heat-treated specimens with different Mo content.

Specimen	Wear rate (Rw) , mg/m			
	As-H	L-H_{Tmax}	H_{Tmax}	H-H_{Tmax}
Mo-free	0.046	0.067	0.054	0.057
1% Mo	0.056	0.068	0.054	0.078
2% Mo	0.051	0.055	0.047	0.052
3% Mo	0.053	0.066	0.059	0.096

Relationship between Rw and macro-hardness is shown in Figure 4. The Rw values decrease in proportion to the macro-hardness. The relations are expressed by next equations,

$$Rw = -1.6 \times 10^{-4} \times (HV30) + 0.19 \quad (R = 0.73)$$

It is clear from above relations that the higher macro-hardness provides better wear resistance. It can be said that the hardness has strong effect on the Rw. This could be due to the microstructure. The hardness of heat-treated specimen rises due to an increase in the amount of martensite and precipitated carbides in the matrix. It was reported that the martensite wore by cutting mechanism, and the wear resistance was improved by marginal with increasing the hardness. [1,6,9] Under wear condition, the martensite offers high abrasion wear resistance due to the high strength enough to support eutectic carbides and thus, diminishes carbide fracture. In addition, the secondary carbides increase the matrix strength through a dispersion hardening effect, and this also lead to the improvement of the wear resistance.

The amount of retained austenite also affects the wear resistance of high Cr cast iron. The relationship between Rw and $V\gamma$ is shown in Figure 5. Though, the data are scattering a little, the Rw decreases gradually to the minimum point and then increases again as $V\gamma$ increases. The smallest Rw is obtained at about 10% $V\gamma$. This suggests that a certain amount of $V\gamma$ improves the abrasion wear resistance. This result agrees with the results from the other researches using different wear test methods, pin-on-disc test, which is about 20% $V\gamma$. [8] The decrease in the Rw with raising the $V\gamma$ is considered due to the work hardening effect of retained austenite. In the case of very low $V\gamma$ value, some pearlite possibly appears there which reduces the wear resistance. In the case of high $V\gamma$ value, excessive retained austenite reduces not only the hardness but also work hardening effect. Resultantly, the Rw increases gradually as the $V\gamma$ rises.

The effect of Mo content on Rw is shown in Figure 6. Molybdenum does not show significant effect on Rw. The Rw values are little scattered and it seems independent on the Mo content. Although, Mo raises the macro-hardness, the Rw values are almost same. It is known that the stress

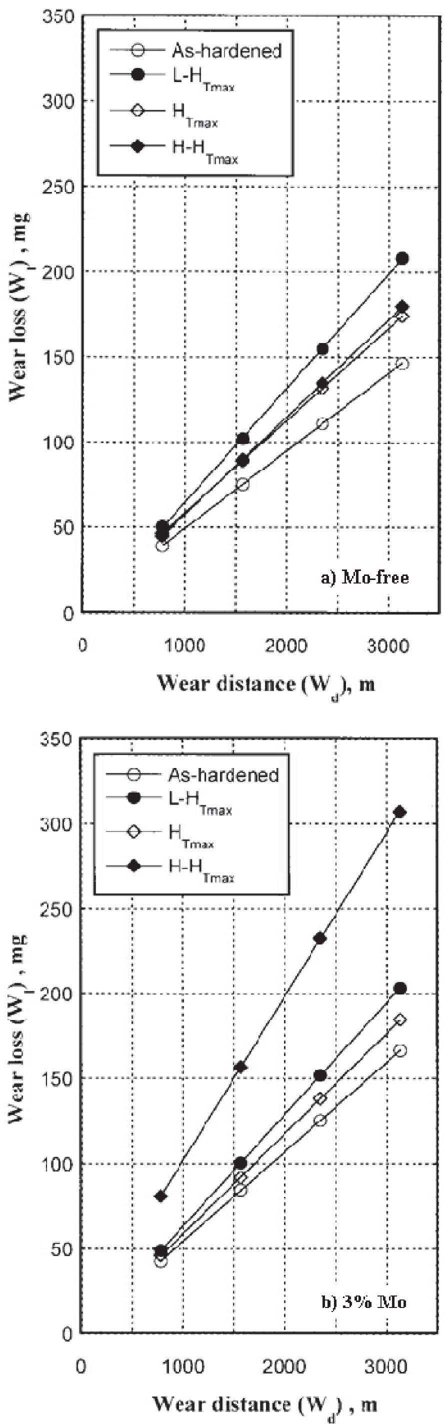


Figure 3: Relationship between wear loss and wear distance of heat-treated Mo-free and 3% Mo specimens.

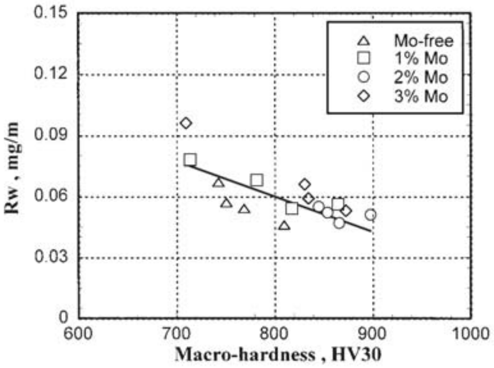


Figure 4: Relationship between wear rate (Rw) and macro-hardness of heat-treated specimens with different Mo content.

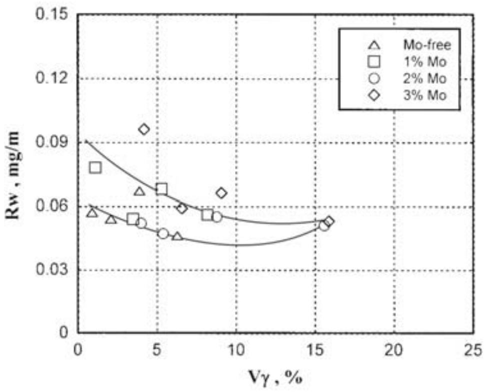


Figure 5: Relationship between wear rate (Rw) and volume fraction of retained austenite (Vγ) of heat-treated specimens with different Mo content.

concentration on the worn surface in this test is quite low. The hardness of abrasive particle about 1200 HV is smaller than that of eutectic M_7C_3 carbide which is about 1500-1800 HV. [1] Therefore, the matrix regions with lower hardness wore preferentially. From this viewpoint, the matrix hardness could be the major effect on the Rw. The average values of matrix hardness are 737 HV0.1 for Mo-free, 722 HV0.1 for 1% Mo, 780 HV0.1 for 2% Mo and 733 HV0.1 for 3% Mo specimens, respectively. It is found that the matrix hardness is almost the same except for 2% Mo specimen. Therefore, it is not a surprise that the Rw do not change so much by Mo addition.

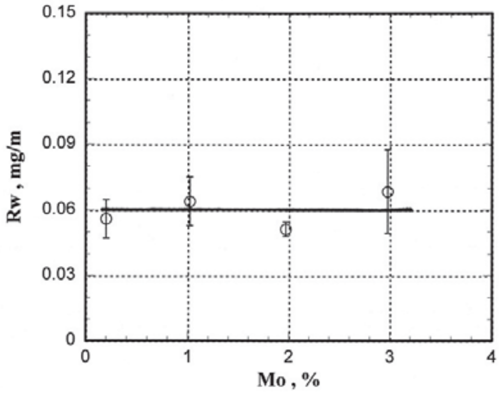


Figure 6: Effect of Mo content on wear rate (Rw).

4 Conclusions

Abrasion wear behaviour of heat-treated hypoeutectic 26% Cr cast irons without and with Mo was investigated. After annealing, the specimens were hardened from 1323 K (As-H) and tempered at three levels of temperatures, a temperature giving the maximum hardness (H_{Tmax}), and lower and higher temperatures than the H_{Tmax} temperature (L-H_{Tmax}, H-H_{Tmax}). The effects of hardness, volume fraction of retained austenite (Vγ), heat treatment condition and Mo content on the wear behaviour were clarified. The following conclusions have been drawn from the experimental results and discussions.

1. In heat-treated state, the hardness and Vγ varied with heat treatment condition and Mo content.
2. A linear relationship was obtained between wear loss and wear distance regardless of heat treatment condition and Mo content.
3. The largest wear resistance was obtained in both the as-hardened specimen (As-H) for Mo-free and 3% Mo cast irons and the H_{Tmax} specimen for 1% and 2% Mo cast irons. The smallest wear resistance was obtained in both the L-H_{Tmax} specimen for Mo-free and 2% Mo cast irons and the H-H_{Tmax} specimen for 1% and 3% Mo cast irons.
4. The Rw decreased as the macro-hardness increased and the smallest Rw appeared in the specimen with 10% Vγ.
5. The Rw was independent on Mo content.

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Two-body and Three-body Types Abrasive Wear Behavior of Hypoeutectic 26 wt% Cr Cast Irons with Molybdenum

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Abstract

Hypoeutectic 26 wt% Cr cast irons with 0-3 wt% Mo were prepared in order to investigate their abrasive wear behavior. The annealed test pieces were hardened from 1323 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 resistance was evaluated using Suga wear test (two-body-type) and Rubber wheel wear test (three-body-type). It was found that hardness and $V\gamma$ 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 both the as-hardened and H_{Tmax} specimens. The highest R_W was mostly obtained in the H-H_{Tmax} specimens. Under the same heat treatment condition, the R_W in Suga wear test was much greater than that in Rubber wheel wear test. The R_W decreased with increasing the hardness. The lowest R_W obtained in the specimen with a certain amount of retained austenite, 10-15%V_γ. The Rw decreased with increasing Mo content in Suga abrasive test and it decreased little by Mo addition in Rubber wheel wear test.

Keywords: High chromium cast iron, 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 abrasive wear resistant materials for more than 50 years. The microstructure of these alloys consists of eutectic chromium carbides with high hardness 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 chromium cast irons with hypoeutectic composition are preferable because they are free form primary carbides that reduce the toughness.[1-3] As-cast microstructure of hypoeutectic composition consists of austenite dendrite and eutectic M_7C_3 carbides. Under non equilibrium state, the austenite may remain stably due to the supersaturation of chromium and carbon during solidification.

Austenite has low hardness 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, both of which give the martensitic matrix with higher wear resistance. In the most cases, a suitable martensitic matrix is preferred to increase the abrasive wear resistance. To obtain the martensitic matrix, the cast iron is held at 900-1100 ^{o}C to enable the secondary carbides to precipitate in the austenite matrix that is called as destabilization of austenite, and followed by fan air cooling to room temperature. The precipitation of secondary carbides 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 in the cast iron 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 the amount of retained austenite and properties such as wear resistance and hardness.

Abrasive wear is divided into two-body type and three-body type.[3)] In the process of two-body type abrasive wear, the wear takes place when the hard abrasive particles contact one side of the wear surface, e.g., hammer and liner of impact crusher. The local stress between abrasive particles and surface of material must be high enough to crush the particles, leading up to the heavy plastic deformation on the wear surface. In order to evaluate the resistance to the two-body type abrasive wear, an abrasive paper, which is made by high hardness abrasive particles such as SiC or Al_2O_3 fixed on the paper by glue, are generally used. Suga wear tester is suitable to evaluate the behavior of two-body type abrasive wear. In the three-body type abrasive wear, the wear environment consists of two counter materials and abrasive particles between them. The stress in this case is lower than that in the case of two-body type abrasive wear. This type wear occurs in ball mill, rod mill for pulverizing and roll crushers. [3)] The suitable wear testing machine for three-body type abrasive wear is a Rubber wheel wear tester where SiO_2 particles are used as the abrasives.

Many laboratory tests have been carried out to evaluate the abrasive wear resistance of high chromium cast iron. [3,5,13-17)] 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 abrasive wear and heat treatment behavior is much more important.

In this study, hypoeutectic 26% Cr cast irons with 0 to 3 % Mo were prepared in the heat-treated state, and the abrasive wear resistance is evaluated using Suga wear test for two-two-body type and Rubber wheel wear test for three-body type. The relationships between abrasive wear resistance and hardness, volume fraction of retained austenite ($V\gamma$) and Mo content were investigated.

2. Experimental Procedures

2.1 Preparation of test specimens

Individual charge calculations for each test specimen were performed to obtain the target chemical compositions. Total heat of 30 kg was melted in a high frequency induction furnace with an alumina (Al_2O_3) lining and superheated at 1853 K. After holding for 600 s, the melt was poured at 1773-1793 K into a preheated CO_2 mold in Y-block shape which consists of the 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 prevent the riser from cooling fast. The chemical compositions of test specimens are shown in Table 1. The schematic drawings of Y-block and the process to make the test pieces are displayed in Fig. 1.

2.2 Heat treatment procedures

The riser was cut off from the Y-block ingot. The remaining substantial block was annealed at 1173 K for 18 ks and sliced into test piece with 7 mm in thickness using a wire-cutting machine. The sliced test pieces were austenitized at 1323 K for 5.4 ks and cooled by fan air. The as-hardened test piece was tempered at three temperatures from 673 to 823 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} and H-H_{Tmax}, respectively. These three temperatures were determined referring to the tempered hardness curves clarified in the previous work. [8)]

2.3 Measurement of hardness and retained austenite

The macro-hardness of test specimens and micro-hardness of the matrix were measured with Vickers hardness testers employing loads of 294 N (30 kgf) and 0.98 N (0.1kgf), respectively. More than five indents were taken on each specimen and the measured values were averaged. The volume fraction of retained austenite ($V\gamma$) was calculated from the diffraction peaks of α_{200}, α_{220} for ferrite or martensite and γ_{220}, γ_{311} for austenite, which were obtained by X-ray diffraction method using a simultaneously rotating and swinging sample stage. [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 on a buff cloth by water mixed with extremely fine alumina powder, 0.3 μm in diameter. The microstructures were revealed using Vilella's reagent and the microstructure observation was performed by an optical microscope (OM) and a scanning electron microscope (SEM).

2.5 Abrasive wear test

Surface roughness of test piece is kept less than 3μm (Ra-max) using a grinding machine. Schematic drawings of abrasive wear testers are illustrated in Fig.2 a) for Suga wear test and Fig. 2 b) for Rubber wheel wear test. In Suga wear test, 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 the abrading wheel. The wheel moves forth and back for 30 mm stoke on the same area of the test piece. Simultaneously, the wheel revolves on its axis intermittently for 0.9 degree per stroke, that is, the speed of revolution is 0.345 mm/s. After 400 strokes, the specimen is cleaned with acetone in an ultrasonic bath and then dried. The weight loss of test piece is measured using a high precision digital weight balance with 0.1 mg accuracy. The test is repeated for eight times at the same area on one test piece.

For Rubber wheel wear test in Fig. 2 b), the silica sand of AFS 60 grade is used as the abrasives. The sands are fed to the contacting face between the rotating rubber wheel with 250 mm in diameter and test piece. The test is conducted at a revolution speed of 120 rpm. The rate of feeding the abrasives is approximate 250-300 g/min. The load applied is 8.7 kgf. After the test continues to 1,000 revolutions, the specimen is detached from the tester and cleaned in an ultrasonic acetone and then dried. The weight of the test piece is measured using a high precision digital balance. The test is repeated four times per one test piece.

3. Experimental Results and Discussions

3.1 Characterization of test specimens

The as-hardened microstructures of 26% Cr cast irons with and without Mo are shown 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 at the austenitizung temperature, and then transforms into martensite during cooling.

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 abrasive wear test. It is found that hardness and the V_γ change depending on the heat treatment condition and Mo content.The V_γ in the as-hardened state is higher than that in the tempered state, and 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.

3.2 Abrasive wear behaviour

The relationships between wear loss and wear distance are shown in Fig. 4 for Suga wear test and Fig. 5 for Rubber wheel wear test, respectively. In all the diagrams, the wear loss increases in proportion to the wear distance regardless of the kind of specimen and heat treatment condition. In Suga wear test, the difference in wear losses due to the condition of heat treatment in each specimen is a little. In the Rubber wheel wear test, however, the differences appear clearly. In each diagram, the slope of the straight line varies according to the difference in the heat treatment condition. The total wear loss of each specimen is summarized in Table 3. It is found that the lowest wear loss is obtained in the as-hardened and H_{Tmax} specimens and the highest wear loss is obtained in H-H_{Tmax} specimen in both the Suga and Rubber wheel wear tests.

Since the linear relationships were obtained between wear loss and wear distance in all the specimens, it is suitable to adopt the slope as an index of wear rate (Rw: $mg.m^{-1}$) or the wear resistance. The R_W values of all the specimens are summarized in Table 4. It can be also said that the lowest R_W i.e. the highest wear resistance is obtained in both the as-hardened and H_{Tmax} specimens in which matrices contain large portion of tempered martensite and a certain quantity of retained austenite. The highest R_W i.e. the lowest wear resistance is obtained in all of the H-H_{Tmax} specimens where a large portion of martensite is tempered to ferrite and carbides and the retained austenite is mostly decomposed as well as very little austenite is left.

Here, it can be considered that both of the hardness and $V\gamma$ influence on the Rw. The relationship between hardness and R_W was obtained for all the specimens and shown in Fig.6 a) for Suga wear test and b) for Rubber wheel wear test, respectively. Though the R_W values are a little scattered, they decrease in proportion to the hardness regardless of heat treatment condition and Mo content. The equations of Rw vs. macro-hardness are obtained for two types of abrasive wear using a software of Kaleida Graph analysis, and they are as follows,

Suga wear test: $Rw = -4.2 \times 10^{-4} \times HV30 + 0.72$ (R = 0.88)

Rubber wheel wear test: $Rw = -1.6 \times 10^{-4} \times HV30 + 0.19$ (R = 0.73)

It is clear that the higher the hardness, the lower the R_W. In the tempered state, therefore, the specimen with H_{Tmax} has the highest wear resistance. Comparing the slopes of the line in Fig.6 a) with Fig 6 b), it is found that the hardness affects more the R_W in Suga wear test than that in Rubber wheel wear test.

The relationships between R_W and $V\gamma$ are shown in Fig. 7 a) for Suga wear test and b) for Rubber wheel wear test. The relations can be expressed by the following equations,

Suga wear test: $Rw = (4.5 \times 10^{-4}) \times (V\gamma)^2 - (1.2 \times 10^{-3}) \times (V\gamma) + 0.44$ (R = 0.78)

Rubber wheel wear test: $Rw = (2.8 \times 10^{-4}) \times (V\gamma)^2 - (5.7 \times 10^{-3}) \times (V\gamma) + 0.08$ (R = 0.58)

It is found that the minimum value of R_W is obtained at about 10-15% $V\gamma$. This result agrees with other works using the different type of abrasive wear test that a certain amount of the retained austenite could be available to improve the abrasive wear resistance.[3,7,13-15] It is considered that a decrease in the R_W is due to the work hardening of austenite as well as the precipitation of secondary carbides in the matrix and an increase of the matrix strength. At very low V_γ value, the R_W is relatively high because the matrix contained pearlite, coarse secondary carbides and little V_γ.

The effect of the Mo content in the cast iron on the R_W is shown in Fig. 8 a) for Suga wear test and b) for Rubber wheel wear test. In Suga wear test, the R_W decreases totally as the Mo content increases. It could be explained by the fact that Mo increases the hardness of not only matrix but also eutectic carbide. Under the high stress abrasive wear, the abrasive particles with extremely high hardness (2500-2600 HV) [3)] cut through both of the eutectic carbide and matrix. So, an increase in hardness by Mo addition could check the crack propagation, and resultantly, the Rw decreased.

As for Rubber wheel wear test in Fig. 8 b), on the other side, the Rw values are little scattered and they decrease slightly as Mo content increases. This is because the stress concentration on the worn surface is quite low in this test and the hardness of silica sand abrasive particles with about 1200 HV is smaller than that of eutectic M_7C_3 carbide with 1500-1800 HV.[3)] Therefore, the matrix region with lower hardness was preferentially worn by silica sands. It was reported that the removal rate of matrix controls greatly the fracture of carbide and then, the work hardening of austenite is hard to appear effectively because of the low stress concentration.[1,15,17)] In this case, the harder matrix provides the better resistance to the abrasive wear. From this viewpoint, it is considered that the matrix could have a major effect on the Rw. In order to explain this result, the micro-hardness of matrices in the test pieces with H_{Tmax} in Table 2 was compared. Looking over the micro-hardness, 741 HV0.1 for Mo-free, 752 HV0.1 for 1%Mo, 780 HV0.1 for 2%Mo and 768 HV0.1 for 3%Mo specimens, it is found that the matrix hardness changes little to an increase in the Mo content.This can support that the Rw varied little by Mo addition, compared with the reasonable change of the Rw in Suga wear test.

3.3 Mechanism of abrasive wear

In order to comprehend the abrasive wear behavior, the worn surface of 1%Mo specimen with H_{Tmax} was observed by SEM. The representative examples of worn surface appearance are shown in Fig. 9. In Suga wear test, the abraded regions showing fine lines caused by scratching correspond to the matrix region. On the microphotographs, it is found that the eutectic carbides are worn very little by scratching and more by spalling or pitting, and that much rougher worn surfaces are formed in the portion of matrix by grooving and tearing. The matrix is preferably shaved or worn and removed more than the eutectic carbides. The crack forms probably in the eutectic carbides because the load concentrates on the carbides. Once the cracks are produced, the spalling of carbides begins to take place. The tearing and grooving were observed because the ductile matrix with austenite can be deformed easily without cracking by the stress of abrasive particles.[3)] Therefore, the grooving is limited in the matrix region and the tearing could originates at the grooves in the matrix.

In Rubber wheel wear test, the lines displaying the wear direction are not observed. This is because the abrasive particles move freely on the surface of test piece. The worn surface consists of the pitting in the matrix region and the scratching in the eutectic area. The matrix removes first followed by the fracture of carbides.

In the cross-sectional microstructures, the worn surface by Suga wear test is smooth and flat. This means that the abrasive particles passed through both of matrix and carbides simultaneously. However, it is also found that the wear of matrix is more violent than that of eutectic carbide, particularly in the primary matrix region. For the specimen of Rubber wheel wear test, the matrix has a concave surface and seems to be worn preferentially compared with the eutectic area, i.e. the matrix removes first followed by the fracture of carbides. It can be said that the removal rate of matrix is related to not only the total wear rate but also the fracture rate of carbide.

4. Conclusions

The abrasive wear behavior of heat-treated hypoeutectic 26% Cr cast irons without and with Mo was investigated. After annealing, the specimens were hardened from 1323 K 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 ($V\gamma$) and the heat treatment conditions on the abrasive 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 in both of the two-body type Suga wear test and the three-body type Rubber wheel wear test. The highest wear resistance was obtained in the as-hardened or H_{Tmax} specimens.The lowest wear resistance was obtained in H-H_{Tmax} specimen.

2) The Rw decreased with an increase in the hardness. The hardness had more effect on Rw in Suga wear test than that in Rubber wheel wear test.

3) The smallest R_W was obtained in the tempered specimen containing a certain quantity of retained austenite, 10-15%V_γ.

4) The Rw decreased gradually with increasing Mo content in Suga wear test. On the other hand, the Rw varies little by Mo addition in Rubber wheel wear test.

5) The macro-hardness showed a strong effect on the Rw in Suga wear test. By contrast, matrix hardness or micro-hardness gave a major effect on the Rw in Rubber wheel wear test.

6) The matrix was preferably shaved off or worn off, and removed faster and more than the eutectic area. When this process continues, the cracks causes in the eutectic carbides, and resultanly, the spalling occurs and the eutectic carbides are removed.

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Table 1 Chemical composition of test specimens.

Specimen	Element (wt%)				
	C	Cr	Si	Mn	Mo
No.1	2.66	26.08	0.47	0.55	0.18
No.2	2.64	26.12	0.50	0.56	1.02
No.3	2.63	25.92	0.44	0.45	1.97
No.4	2.71	25.98	0.47	0.53	2.96

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

Specimen		Macro-hardness (HV30)	Micro-hardness (HV0.1)	V_γ , %
Mo content	Heat treatment condition			
Mo-free	As-hardened	810	755	6
	L-H_{Tmax} (673 K)	743	724	4
	H_{Tmax} (723 K)	769	741	2
	H-H_{Tmax}(773 K)	751	726	1
1% Mo	As-hardened	865	762	8
	L-H_{Tmax} (673 K)	782	737	5
	H_{Tmax} (748 K)	818	752	4
	H-H_{Tmax}(800 K)	714	636	1
2% Mo	As-hardened	898	816	16
	L-H_{Tmax} (673 K)	845	757	9
	H_{Tmax} (748 K)	866	780	5
	H-H_{Tmax}(800 K)	854	768	4
3% Mo	As-hardened	873	780	16
	L-H_{Tmax} (673 K)	831	766	9
	H_{Tmax} (748 K)	835	768	7
	H-H_{Tmax}(823 K)	710	616	4

Table 3 Total wear loss of each test specimen with different heat treatment.

Specimen	Heat treatment condition	Total wear loss, mg	
		Suga abrasive test	Rubber wheel abrasive test
Mo-free	As-hardened	74	146
	L-H_{Tmax} (673 K)	80	208
	H_{Tmax} (723 K)	76	174
	H-H_{Tmax}(773 K)	82	180
1% Mo	As-hardened	74	179
	L-H_{Tmax} (673 K)	78	213
	H_{Tmax} (748 K)	71	171
	H-H_{Tmax}(800 K)	82	247
2% Mo	As-hardened	66	165
	L-H_{Tmax} (673 K)	68	177
	H_{Tmax} (748 K)	70	149
	H-H_{Tmax}(800 K)	75	168
3% Mo	As-hardened	72	166
	L-H_{Tmax} (673 K)	74	203
	H_{Tmax} (748 K)	68	184
	H-H_{Tmax}(823 K)	79	307

Table 4 Wear rate (Rw) of test specimens heat-treated by different conditions.

Specimen	Heat treatment condition	Wear rate (Rw), mg/m	
		Suga abrasive test	Rubber wheel abrasive test
Mo-free	As-hardened	0.39	0.046
	L-H_{Tmax} (673 K)	0.42	0.067
	H_{Tmax} (723 K)	0.40	0.054
	H-H_{Tmax}(773 K)	0.43	0.057
1% Mo	As-hardened	0.38	0.056
	L-H_{Tmax} (673 K)	0.41	0.068
	H_{Tmax} (748 K)	0.37	0.054
	H-H_{Tmax}(800 K)	0.43	0.078
2% Mo	As-hardened	0.34	0.051
	L-H_{Tmax} (673 K)	0.35	0.055
	H_{Tmax} (748 K)	0.36	0.047
	H-H_{Tmax}(800 K)	0.38	0.052
3% Mo	As-hardened	0.37	0.053
	L-H_{Tmax} (673 K)	0.38	0.066
	H_{Tmax} (748 K)	0.35	0.059
	H-H_{Tmax}(823 K)	0.41	0.096

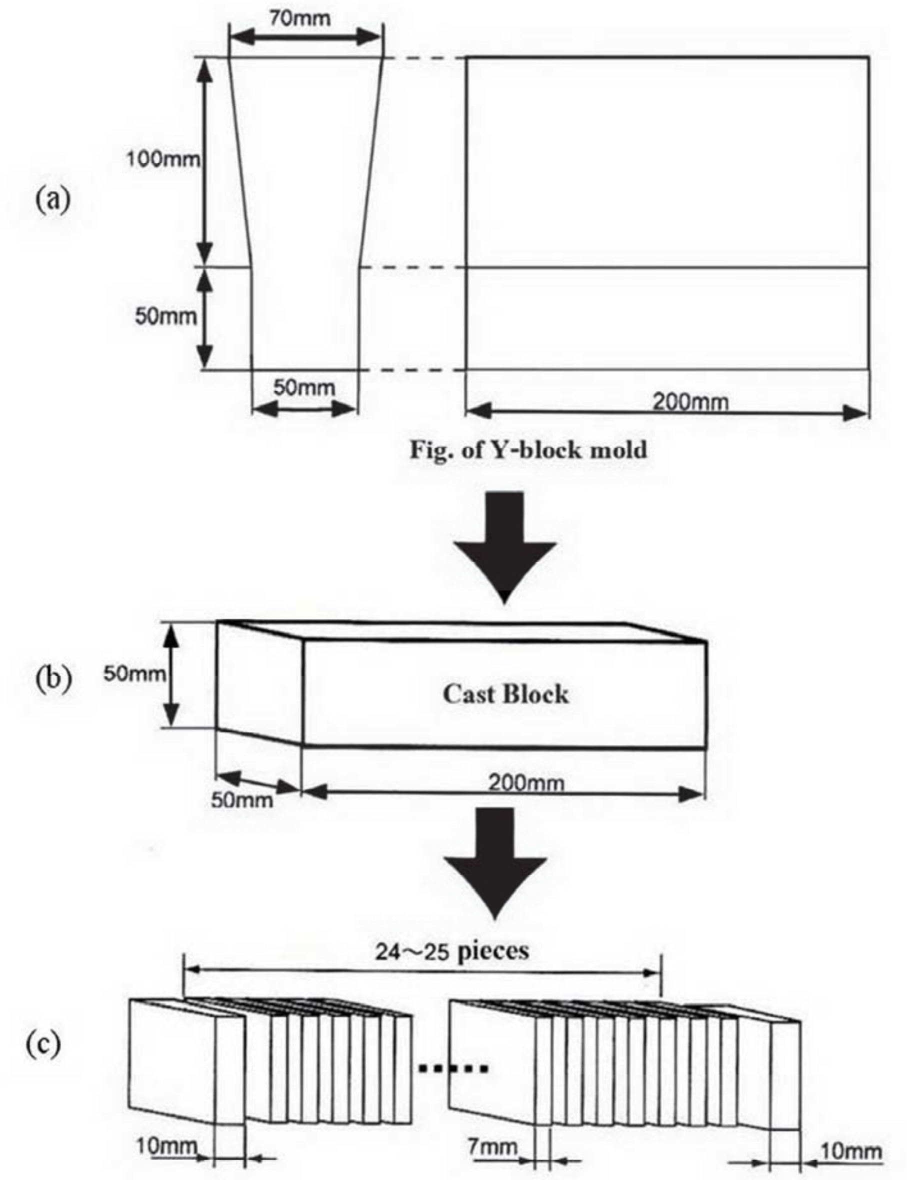

Fig. 1 Schematic drawings of process to make test pieces.

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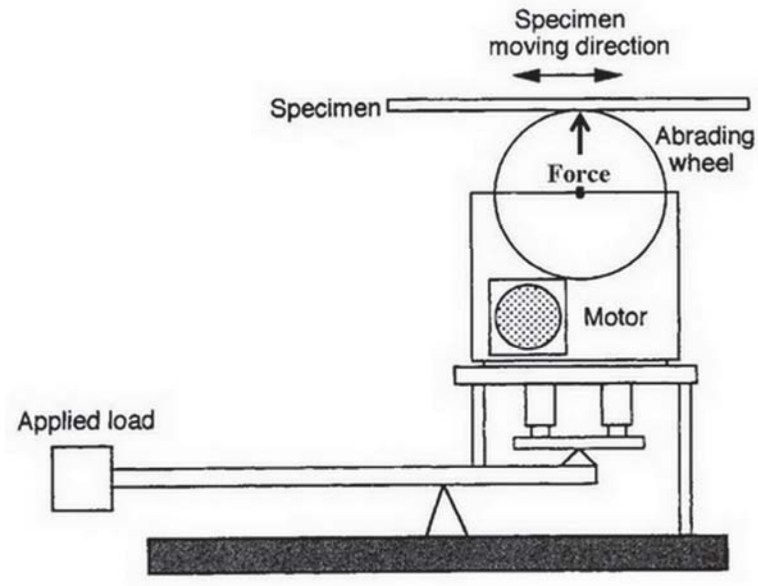
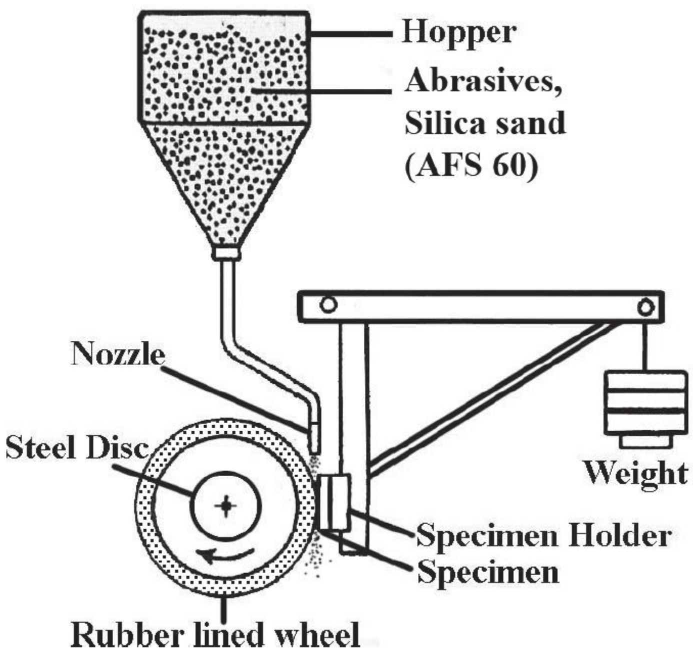


(a) Suga wear tester (two-body type)



(b) Rubber wheel wear tester (three-body type)

Fig. 2 Schematic drawings of abrasive wear testers.

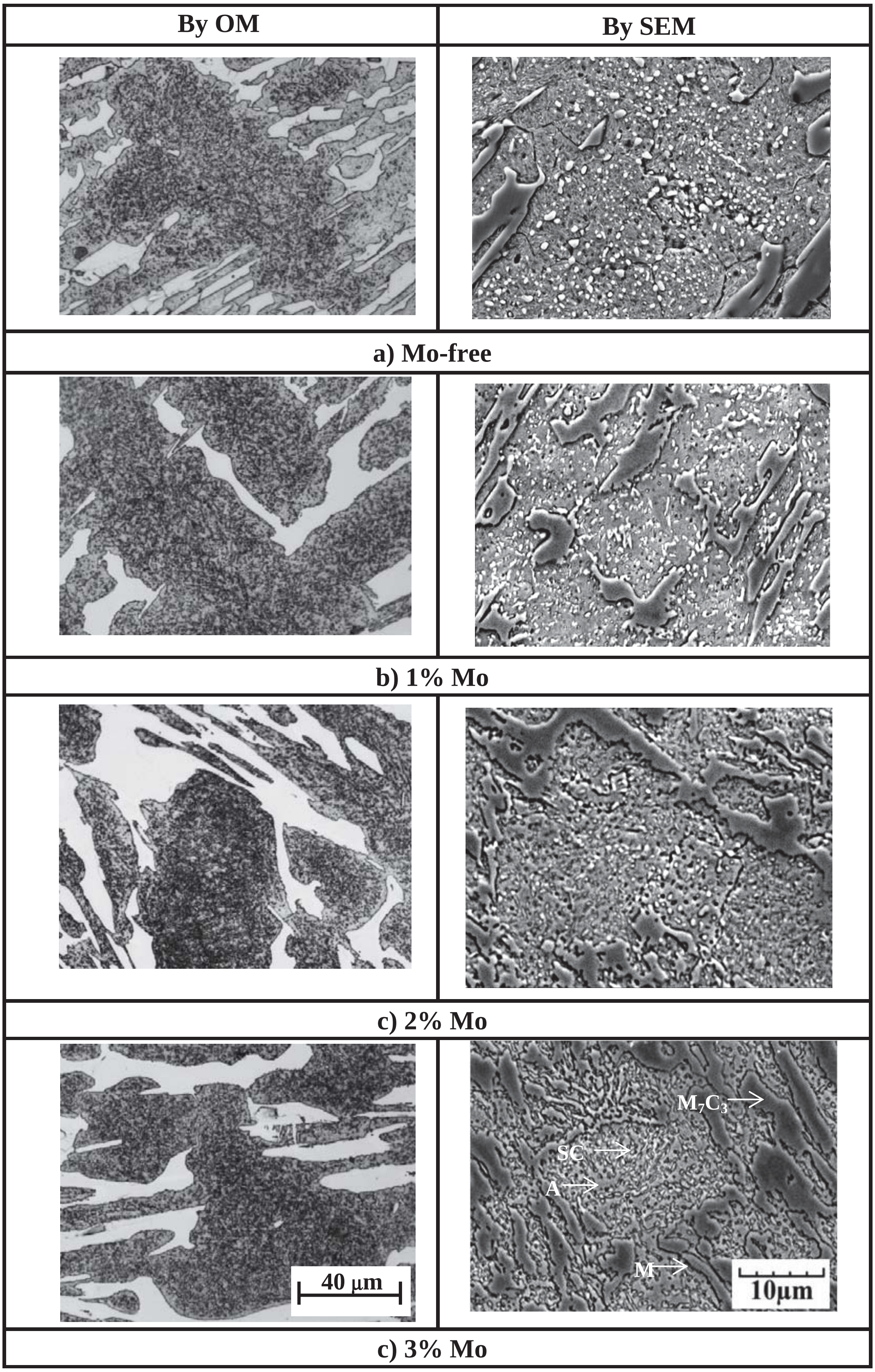
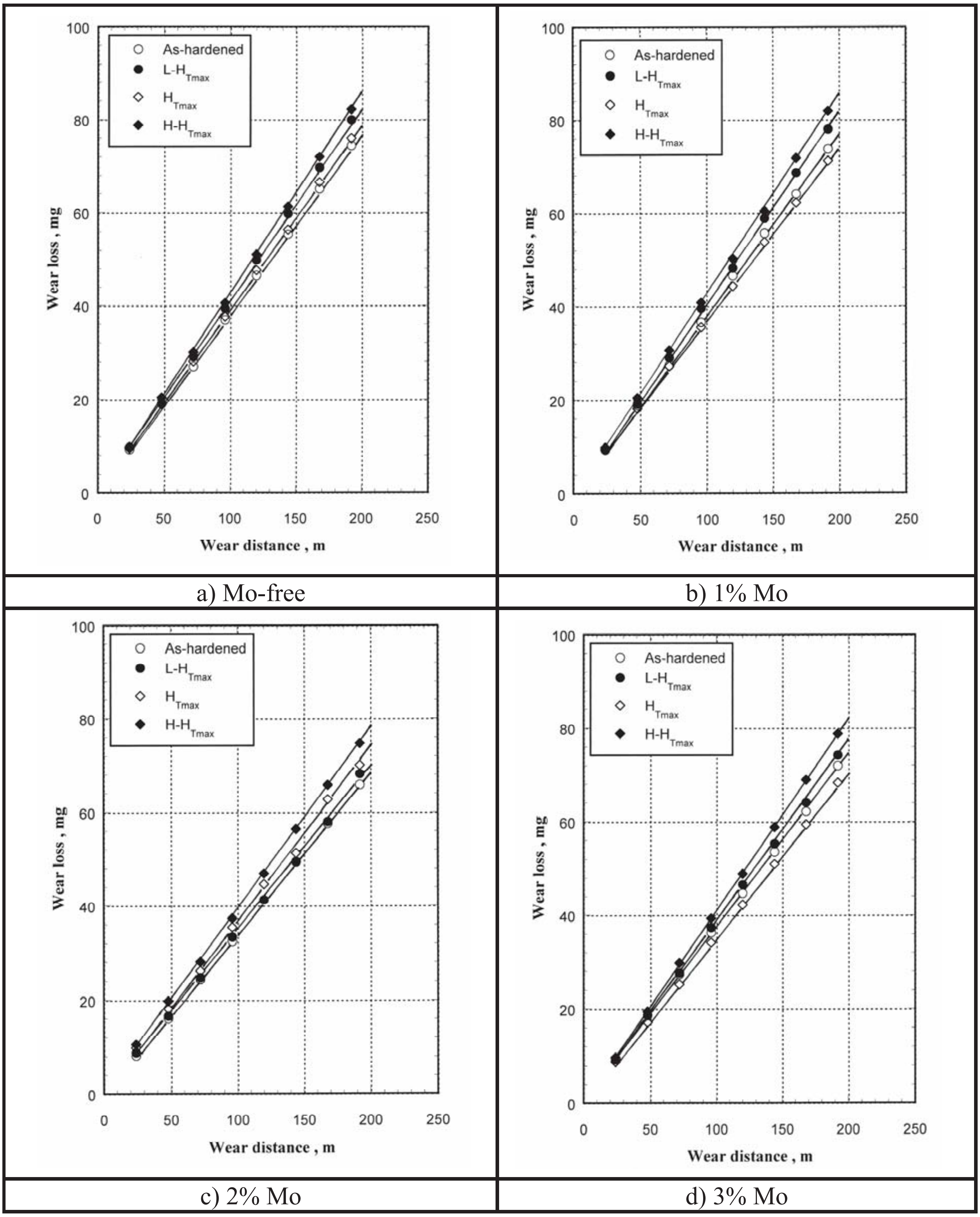


Fig. 3 As-hardened microstructures of hypoeutectic 26% Cr cast irons without and with Mo.

(A: Austenite, M: Martensite, SC : Secondary carbide)



a) Mo-free

b) 1% Mo

c) 2% Mo

d) 3% Mo

Fig. 4 Relationship between wear loss and wear distance of heat-treated 26%Cr cast irons by Suga wear test (two-body type) with load 9.8 N (1 kgf).

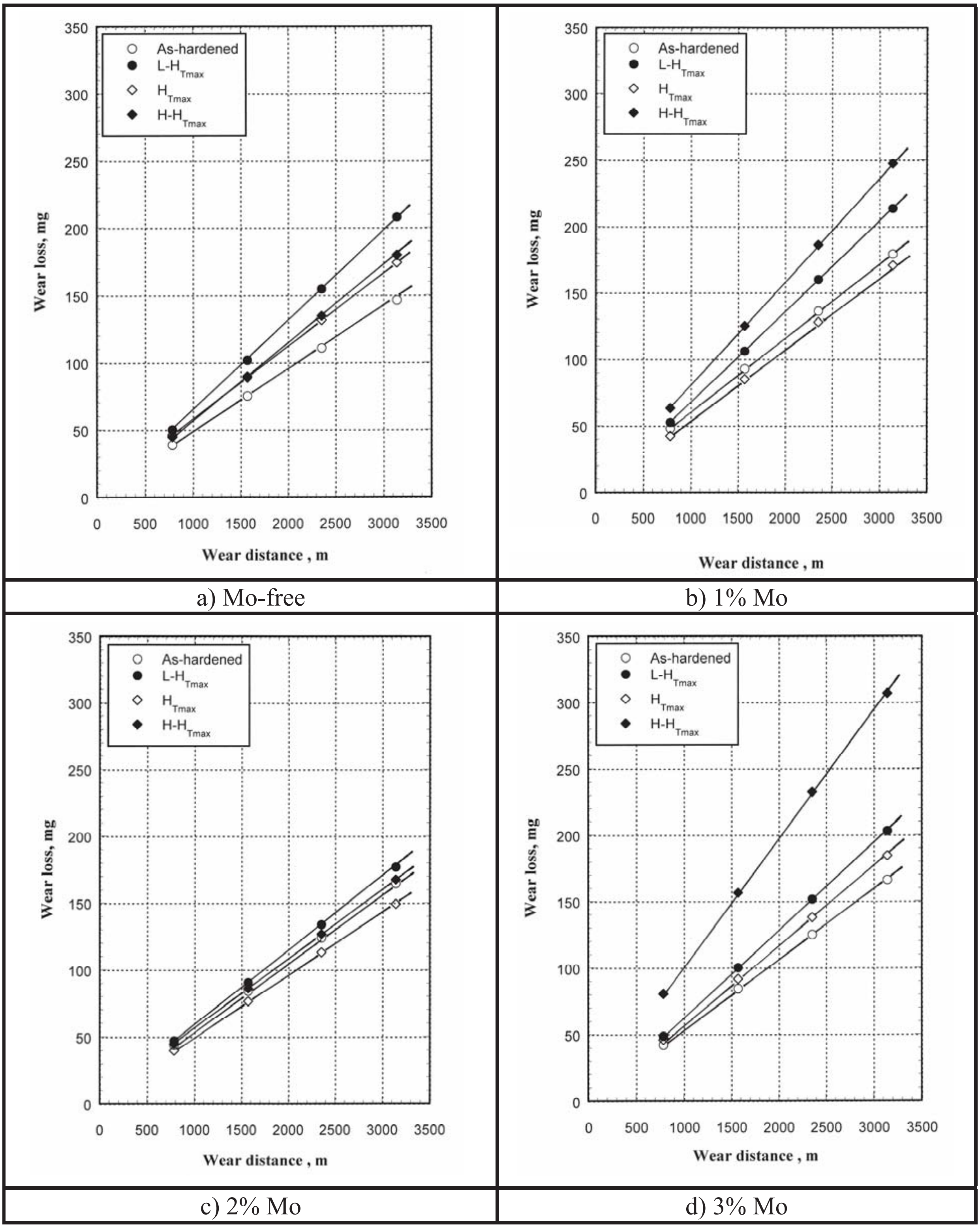
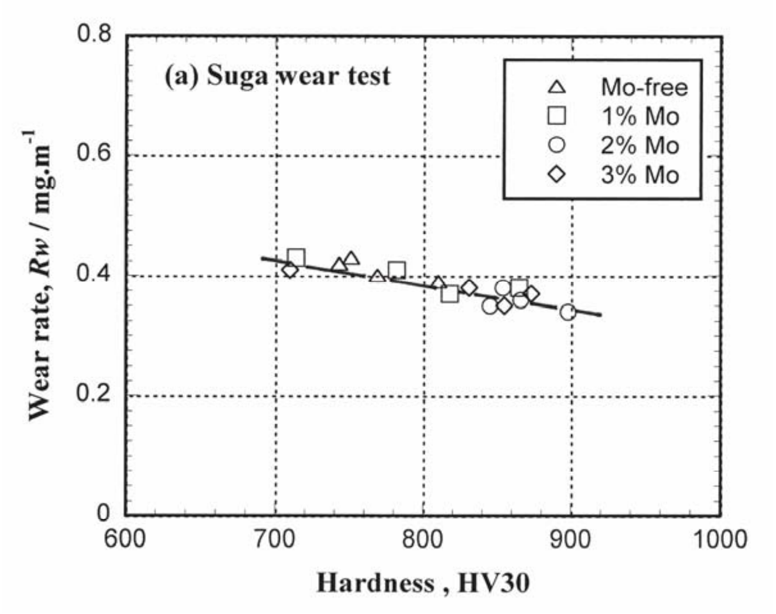


Fig. 5 Relationship between wear loss and wear distance of heat-treated 26%Cr cast irons by Rubber wheel wear test (three-body type) with load 85.3 N (8.7 kgf).



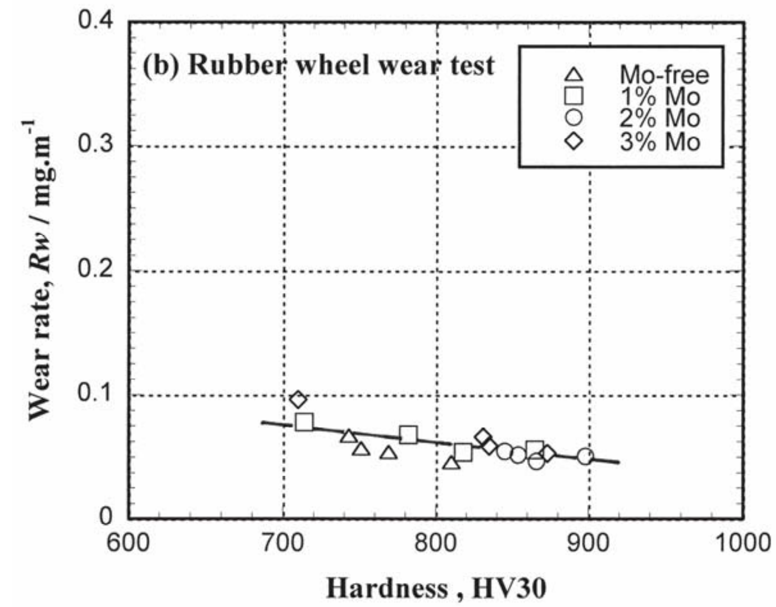
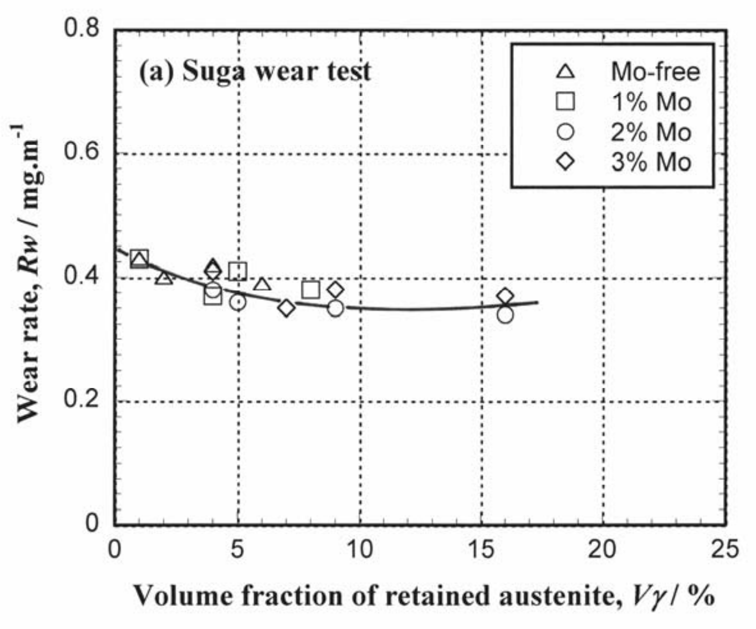


Fig. 6 Relationship between wear rate (Rw) and hardness of all the specimens.



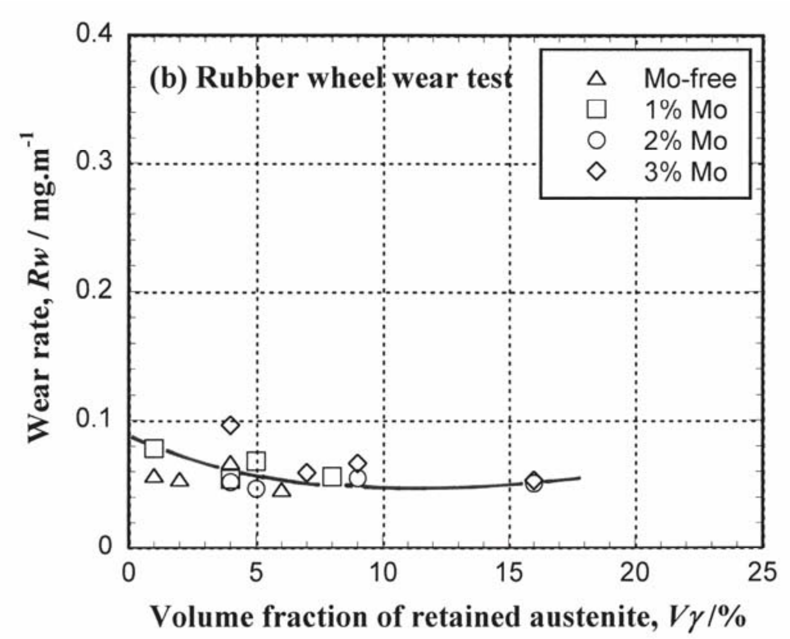


Fig. 7 Relationship between wear rate (Rw) and volume fraction of retained austenite (Vγ) of all the specimens.

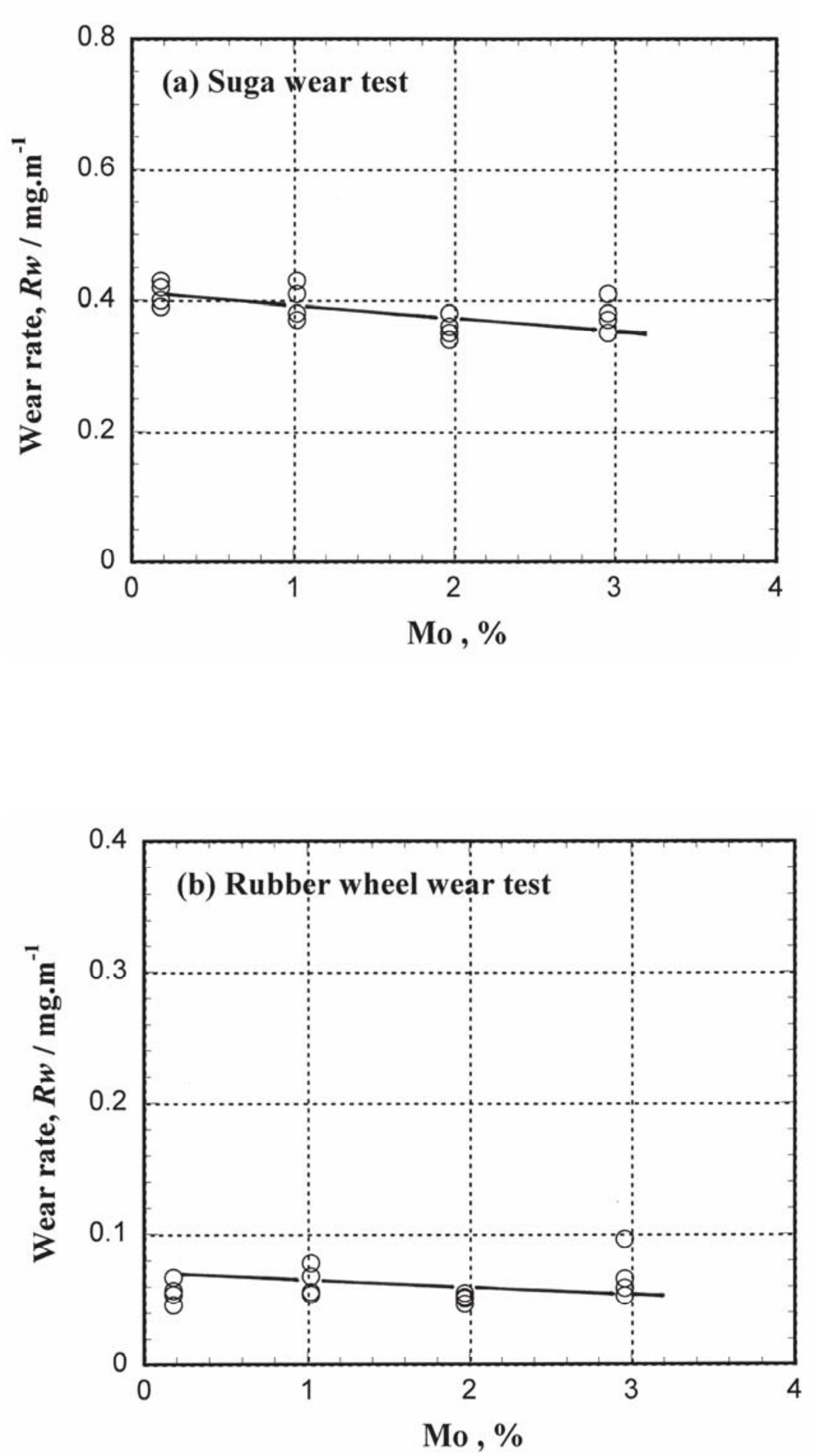


Fig. 8 Effect of Mo content on wear rate (Rw) of all the specimens.

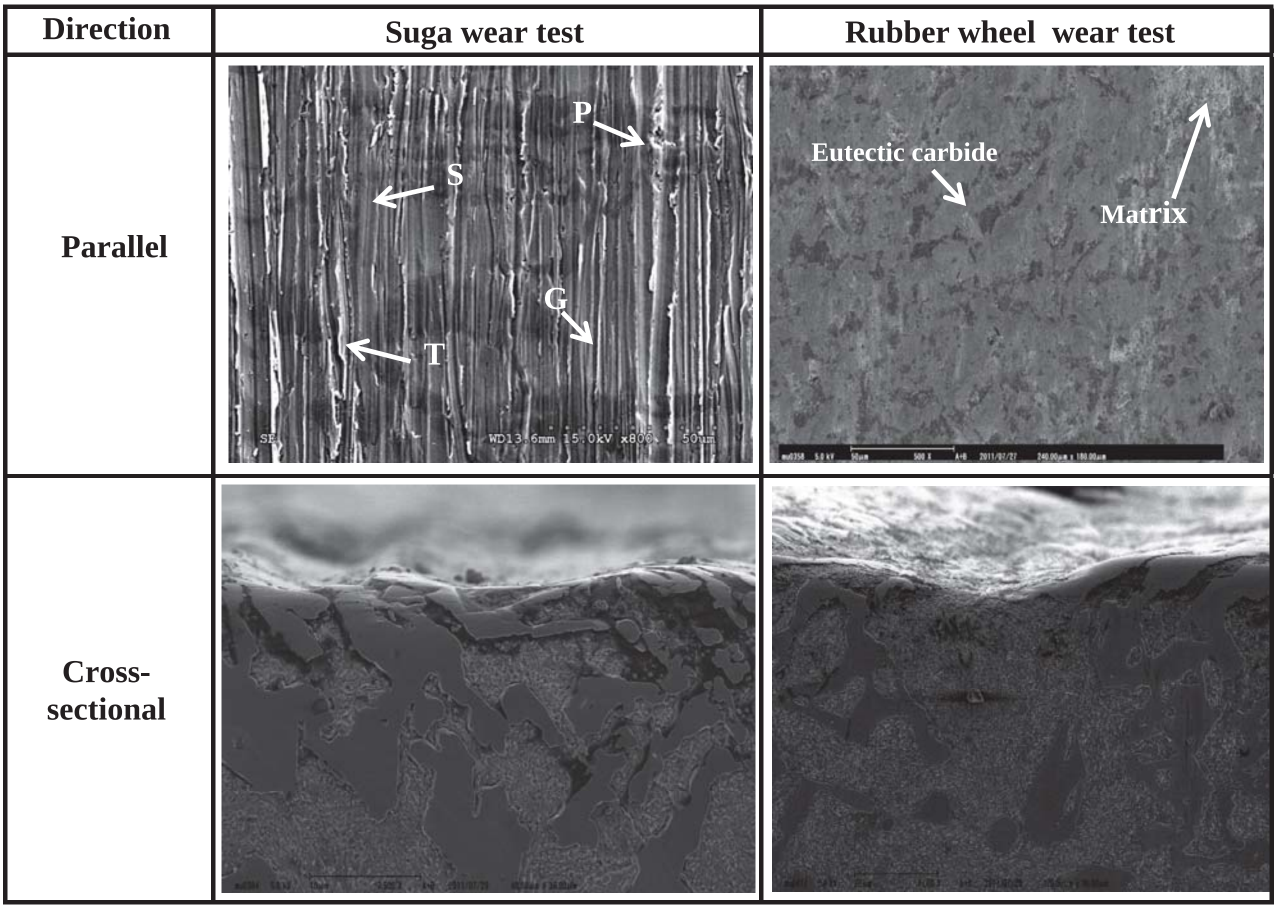


Fig. 9 Parallel and cross-sectional microstructures of worn surfaces of 1%Mo specimen with H_{Tmax}.

(S: Scratching, G: Grooving, P: Pitting and T: Tearing.)