論 文

Effects of Retained Austenite on Mechanical Properties of 2.3%C-26%Cr-1%Ni-0.5%Mo White Cast Iron

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요 약

2.3%C-26%Cr-1%Ni-0.5%Mo 조성의 아공정 백주철을 여러형태로 열처리를 한 후 잔류오스테나이트함량(Vr), 거시 및 미소경도 그리고 내마찰마모성사이의 상호관계를 연구하였다. 주방상태에서의 Vr가 70.2%인 반면 열처리시편들의 경우 0.3-65.4%의 분포를 나타내었다. 초기마모구간 이외에는 마찰마모량과 마모시간과의 사이에 직선적 관계가 얻어졌으며 그 직선의 기울기(Rw)를 내마모성의 비교시 지표로 사용하였다. Rw는 주방상태에서 2.77×10^{-2} mg/s로 가장 낮았으며 1173K에서 18ks동안 균질화 열처리만 한 시편의 경우 4.12×10^{-2} mg/s로 내마모성이 가장 열악하였다. 주방상태에서 내마모성이 가장 좋은 이유는 마찰마모시 오스테나이트가 가공경화를 일으켜 마르텐사이트로 변태되었기 때문으로 여겨진다. 미소경도는 HV 358-HV 756, 거시경도는 이 보다 높은 HV 529-HV 785의 분포를 나타내었는데 이는 거시경도의 측정시 공정탄화물인 M_7C_3가 포함되었기 때문이다. 가장 높은 미소 및 거시경도는 1323K에서 7.2ks동안 오스테나이화열처리한 시편에서 얻어졌으며 주방상태의 시편이 가장 낮은 경도치를 나타내었다. (Received October 9, 1998)

1. Introduction

High chromium white cast irons have been extensively used to resist the various types of abrasive wear encountered in the crushing and grinding of ores, and pulverizing of coal and cement clinker because their microstructures consist of discontinuous but partly interconnected hard eutectic M_7C_3 carbides in a matrix of austenite and/or martensite [1-8].

However, a large amount of austenite is retained in the as-cast condition due to the supersaturation of chromium and carbon. In certain applications, the presence of retained austenite in the matrix is beneficial since it imparts a greater degree of toughness to the casting and gives a work hardening on the wear surface by the formation of strain-induced martensite. Depending upon the type of wear and the kind of abrasive, however, martensitic irons show greater abrasion wear resistance than austenitic irons.

In this research, a hypoeutectic white cast iron of 2.3%C-26%Cr-1%Ni-0.5%Mo was heat-treated by three different methods to obtain the specimens with different levels of retained austenite (Vr) in the matrix. Then, the effect of the Vr value on the abrasion wear resistance, and the macro- and micro-hardnesses of the iron was investigated to derive a mutual relationship among them.

2. Experimental Procedures

2. 1 Preparation of Specimen

Heat was produced using the 15 kg-capacity high frequency induction furnace. Charge calculation of the iron was conducted by materials such as pig iron, steel scrap, pure nickel, ferro-chromium and ferro-molybdenum. The ferroalloys were added to a slag free molten iron in the furnace so as to minimize the oxidation loss and the slag formation. The melt was subsequently heated to 1923 K, and transferred into a pre-heated teapot ladle. After removal of any dross or slag, the melt was poured at 1823 K into Y-block pep-set mold.

2. 2 Heat-Treatment

Three different procedures of heat-treatments employed are as follows :

(1) Heat-Treatment I (HT-I) : Without homogenizing, as-cast specimen was destabilized at 1373 K for 7.2, 18 and 28.8 ks, respectively in vacuum atmosphere, and followed by fan-air hardening to the room temperature.

(2) Heat-Treatment II (HT-II) : As-cast specimen

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was homogenized at 1173 K for 18 ks in vacuum atmosphere, and subsequently cooled in the furnace to the room temperature. Then, the homogenized specimen was austenitized at 1373 K for 7.2, 12.6, 18, 28.8 and 57.6ks, respectively in vacuum atmosphere, and followed by fan-air hardening.

(3) Heat-Treatment III (HT-III) : Same as the HT-II except that the austenitized condition was at 1323 K for 7.2 ks.

2.3 Measurement for Retained Austenite

The volume fraction of austenite was calculated from the ratio of total area of (200) and (220) peaks for ferrite and martensite, and that of (220) and (311) peaks for austenite. The diffraction patterns were obtained by simultaneously rotating and swinging the sample stage in order to minimize or cancel the effect of textural structure. Details regarding the experimental procedures have been reported elsewhere [9].

2.4 Metallographic Examination

The specimens were polished, etched and examined metallographically by an optical microscope. Villela and Murakami etchants were used to distinguish the phases clearly.

2.5 Abrasion Wear Test

Fundamentals of dry abrasion wear tester is illustrated in Fig. 1(a). Under the load of 1 kgf, the abrading wheel (44 mm diameter and 12 mm thickness) wound the circumference with 120 mesh SiC abrasive paper was revolved intermittently while it moved back and force by 35 mm stroke on the same surface of the test piece in dry condition. The revolving speed of the abrading wheel was 0.345 mm/s and the worn area on the specimen was $420(12\times35)mm^2$, as shown in Fig. 1(b). The abrasion wear loss of the test piece was measured with an electronic balance after each cycle (360° revolution), which test was repeated up to 8 cycles.

2.6 Hardness Measurement

Macro-hardness measurement was carried out on the specimen with Vickers hardness tester employing a load of 30 kgf. On the other hand, micro-hardness of the matrix containing secondary carbides was measured by Micro-Vickers hardness tester with 100 gf load. In both cases, ten impressions were taken and averaged.

3. Experimental Results

3.1 Microstructures

Microstructures of as-cast and homogenized specimens observed by an optical microscope are shown in Fig. 2(a) and 2(b). It is clear that the iron consists of primary austenite dendrite and (austenite+M_7C_3) eutectic. As for the matrix structure, most portion is

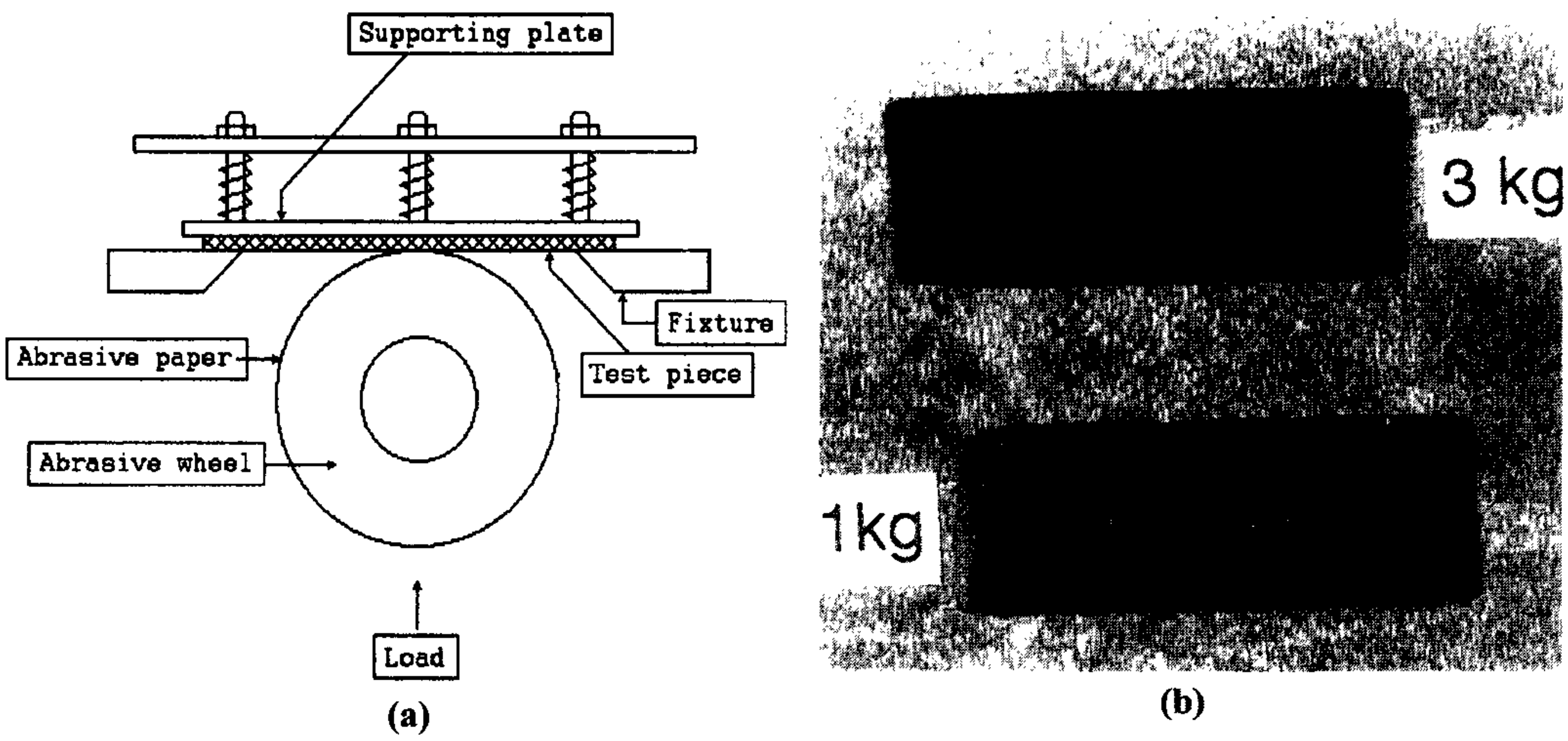

Fig. 1. (a) A schematic drawing of abrasion wear tester. (b) The shape of worn area on the specimen after 8 cycles. (top: load 3 kgf, bottom: load 1 kgf).

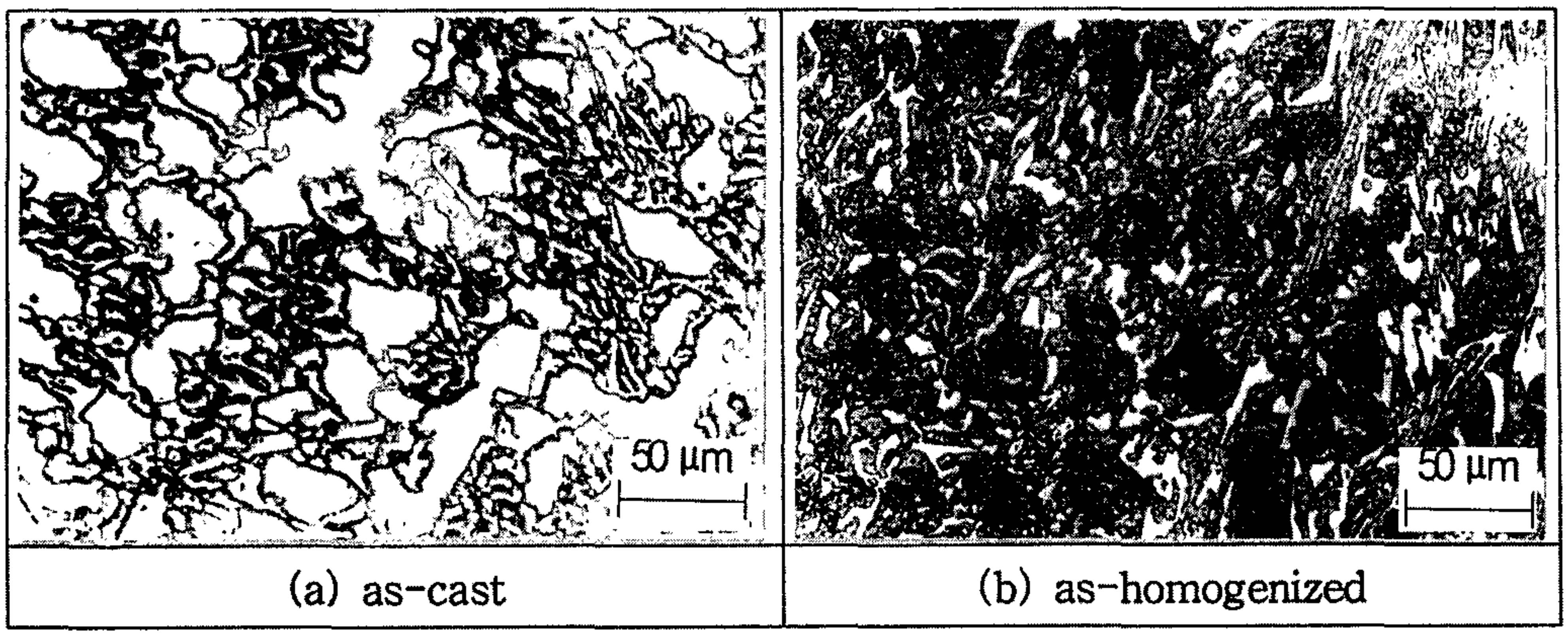

Fig. 2. Microstructures of as-cast and as-homogenized specimens [Etched by Villela's reagent].

austenitic in as-cast specimen, and ferritic with precipitated secondary carbides in homogenized specimen.

The microstructures of heat-treated specimens are shown in Fig. 3(a) and 3(b). Each specimen is characterized by secondary carbides, eutectic carbides and retained austenite. The secondary carbides are precipitated little in the eutectic matrix but mainly in the

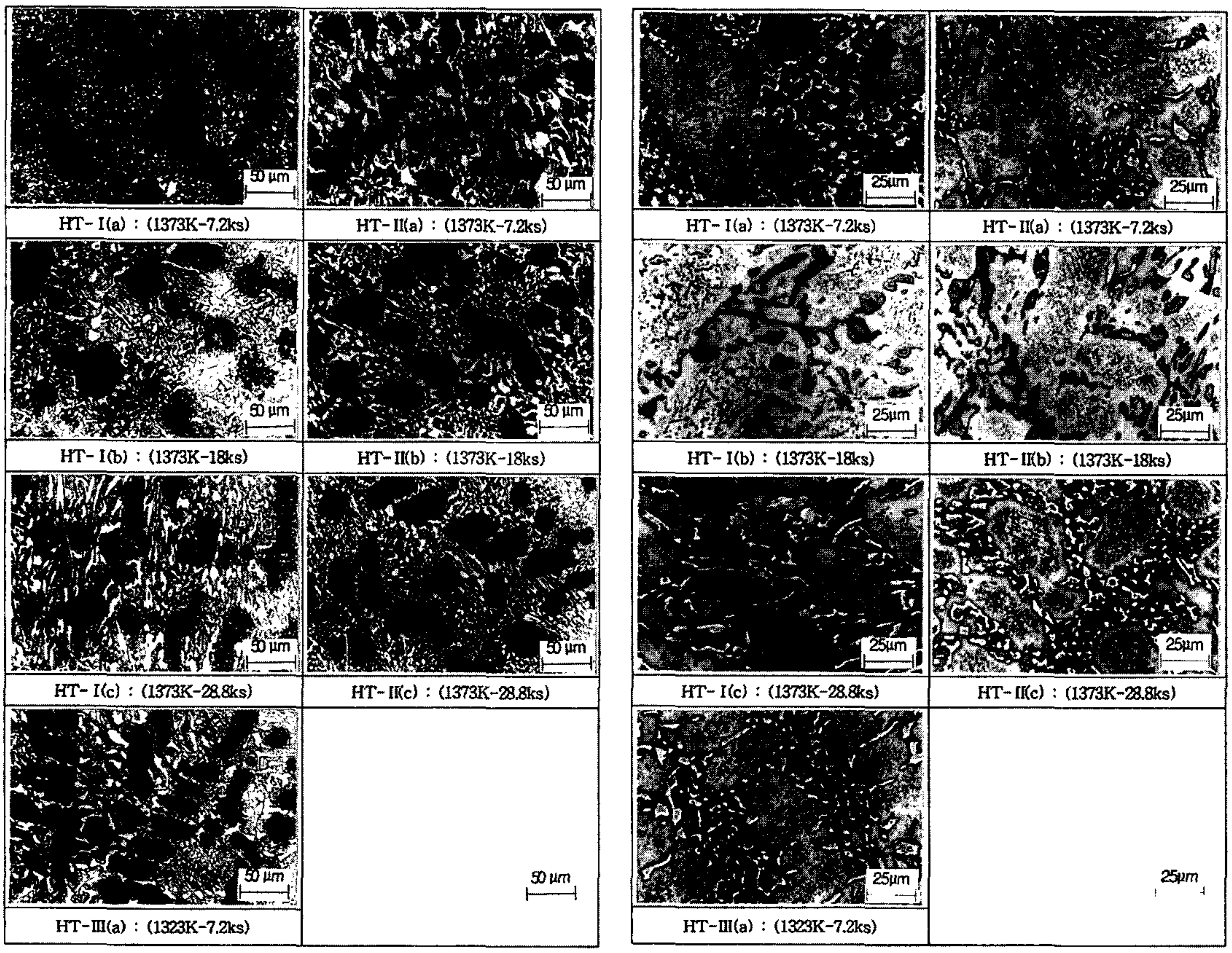

Fig. 3. Variation of microstructures associated with different heat-treatment conditions. (a) Etched by Villela's reagent, (b) Etched by Murakami's reagent.

Table 1. Measured values of retained austenite in all the specimens

Specimen	Vr (%)	Specimen Type	V_γ (%)
As-Cast	67.7 (min) 70.2 (ave) 72.7 (max)	HT-II(a) (1373K-7.2ks)	59.3 (min) 65.5 (ave) 71.6 (max)
Homogenized	0.8	HT-II(b) (1373K-12.6ks)	64.2 (min) 67.0 (ave) 69.8 (max)
HT-I(a) (1373K-7.2ks)	54.7 (min) 56.6 (ave) 58.4 (max)	HT-II(c) (1373K-18ks)	52.8 (min) 54.1 (ave) 55.3 (max)
HT-I(b) (1373K-18ks)	46.0 (min) 52.8 (ave) 59.6 (max)	HT-II(d) (1373K-28.8ks)	55.4 (min) 55.5 (ave) 55.6 (max)
HT-I(c) (1373K-28.8ks)	49.7 (min) 50.8 (ave) 51.8 (max)	HT-II(e) (1373K-57.6ks)	52.6 (min) 55.5 (ave) 58.3 (max)

primary austenite dendrite. The amount of retained austenite in each specimen is listed in Table 1.

While the volume fraction of retained austenite (Vr) is 70.2% in as-cast specimen, those of heat-treated specimens range from 0.3% to 65.4% depending upon the heat-treatment conditions.

3.2 Abrasion Wear Test

A relationship between wear loss and testing time is shown in Fig. 4. In all the specimens, the wear losses increase linearly after the primary stage of unsteady wear. In this case, it is convenient to adopt as a wear index, the abrasion wear rate (Rw:mg/s), which is expressed by the slope of each straight line. The Rw values range from 2.77×10^{-2} to 4.12×10^{-2}, the lowest Rw being obtained in as-cast specimen and the highest value in homogenized specimen.

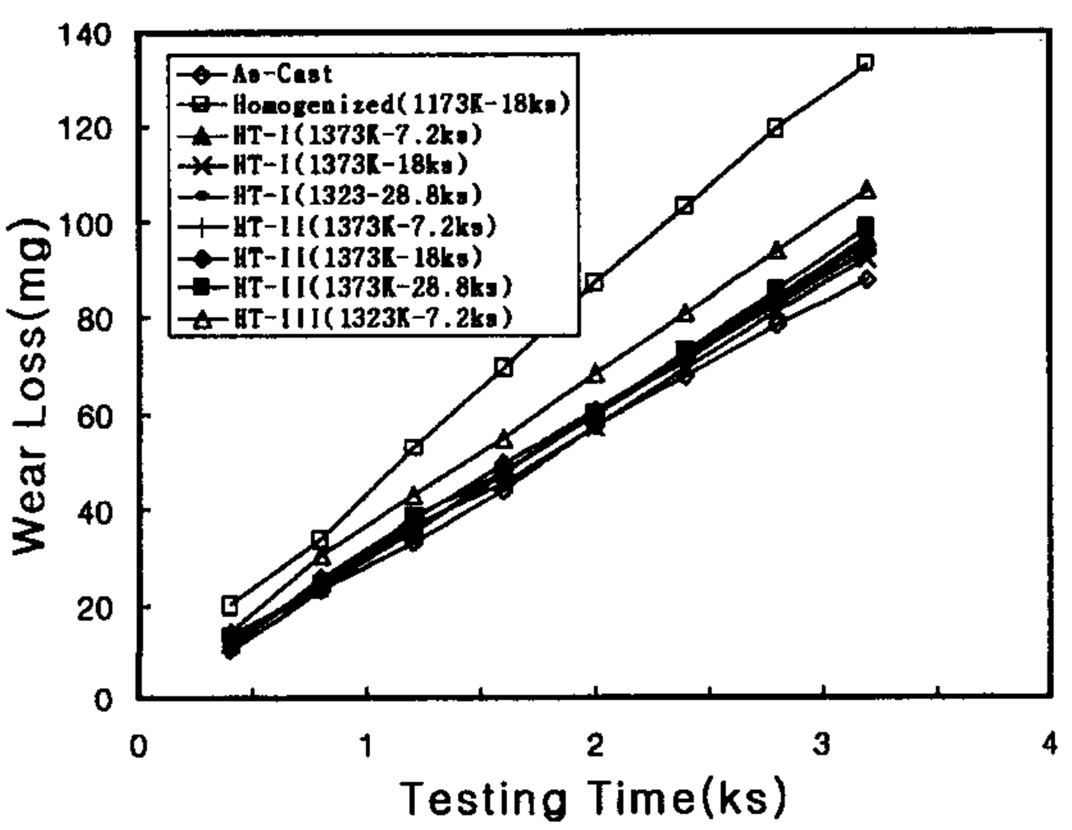

Fig. 4. The relationship between wear loss and testing time.

Table 2. Macro-and micro-hardness of all the specimens

Specimen Type	Hardness (HV)	
	Macro	Micro
As-Cast	530	385
Homogenized	656	641
HT-I(a) (1373K-7.2ks)	629	490
HT-I(b) (1373K-18ks)	637	531
HT-I(c) (1373K-28.8ks)	656	532
HT-II(a) (1373K-7.2ks)	652	575
HT-II(b) (1373K-18ks)	669	518
HT-II(c) (1373K-28.8ks)	726	583
HT-III(a) (1323K-7.2ks)	785	756

3.3 Hardness Test

Macro- and micro-hardness values are listed in Table 2. While the range of micro-hardness is from HV 358 to HV 756, the macro-hardness ranges from HV 529 to HV 785 due to the involvement of eutectic M_7C_3 carbides in measurements. The highest macro- and micro-hardness values are obtained in the specimen heat-treated by homogenizing, and then fan-air hardening with austenitizing condition of 1323 K for 7.2 ks. On the other hand, the lowest ones are obtained in as-cast specimen because of the matrix structure with large amount of austenite and less martensite, and without secondary carbides.

4. Discussions

4.1 Relationship between Vr and Heat-Treatment Conditions

The relationship between Vr and holding time in the cases of HT-I and HT-II are shown in Figs. 5 and 6, respectively.

It is understood from Fig. 5 that the Vr value of 70.2% in as-cast specimen decreases significantly when the specimen is destabilized at 1373 K for 7.2 ks. This can be attributed to the facts that (1) the austenite retention in as-cast specimen is favored by fast cooling rate after solidification and presence of

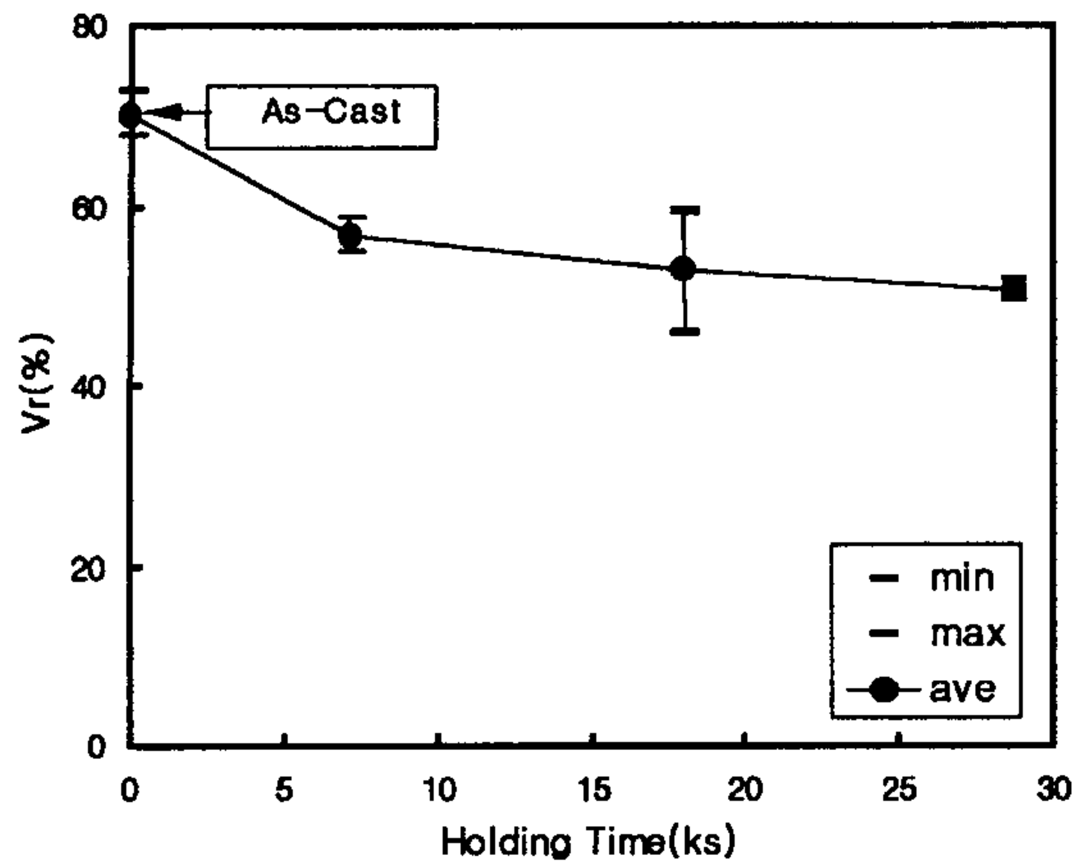

Fig. 5. The relationship between volume fraction of retained austenite(Vr) and holding time in HT-I.

austenite-stabilizing element such as nickel, whereby Ms temperature is lowered. (2) the destabilizing heat-treatment reduces carbon and chromium content in austenite matrix by precipitating secondary carbides, and hence raises Ms temperature, resulting in mixed austenite-martensite matrix. It can be also said from Fig. 5 that the Vr value does not change so much even if the holding time is extended more than 7.2 ks. This is because the concentration of the alloying elements in the matrix might have reached an equilibrium state over the holding time of 7.2 ks.

Fig. 6 shows that the Vr value is almost zero in homogenized specimen because of ferritic matrix due to slow furnace cooling to the room temperature. Subsequent treatment for austenitizing at 1373 K for 7.2 ks allows to redissolve the precipitated secondary carbides into the matrix, whereby the matrix with the retained austenite forms during fan-air cooling. The Vr value shows about 65% by austenitizing for 7.2 to 12.6 ks. Then, it decreases to about 55% at 18 ks and becomes constant when the holding time is prolonged to 57.6ks. The reason why such higher Vr values obtained at an early stage of austenitizing is considered that the overdissolution due to the inertia might have occurred. Therefore, this suggests that the Vr value in equilibrium condition could be about 55%. When this diagram is compared with that in Fig. 5, it is clear that the equilibrium Vr value obtained by austenitizing from the homogenized state is very close to that destabilized from the as-cast state.

4.2 Relationship between Hardness and Heat-Treatment Conditions

The variation of macro- and micro-hardness with holding time in HT-I is shown in Fig. 7.

It is evident from this figure that in comparison with the as-cast specimen, a significant increase in both macro- and micro-hardness is shown by destabilizing heat-treatment at 1373 K for 7.2 ks. As the same manner as the case of Vr vs. holding time, the hardness remains approximately constant after 7.2 ks with an increase in holding time up to 28.8 ks. The primary increase in the hardnesses is attributed to the martensite transformation of retained austenite and the precipitation of secondary carbides

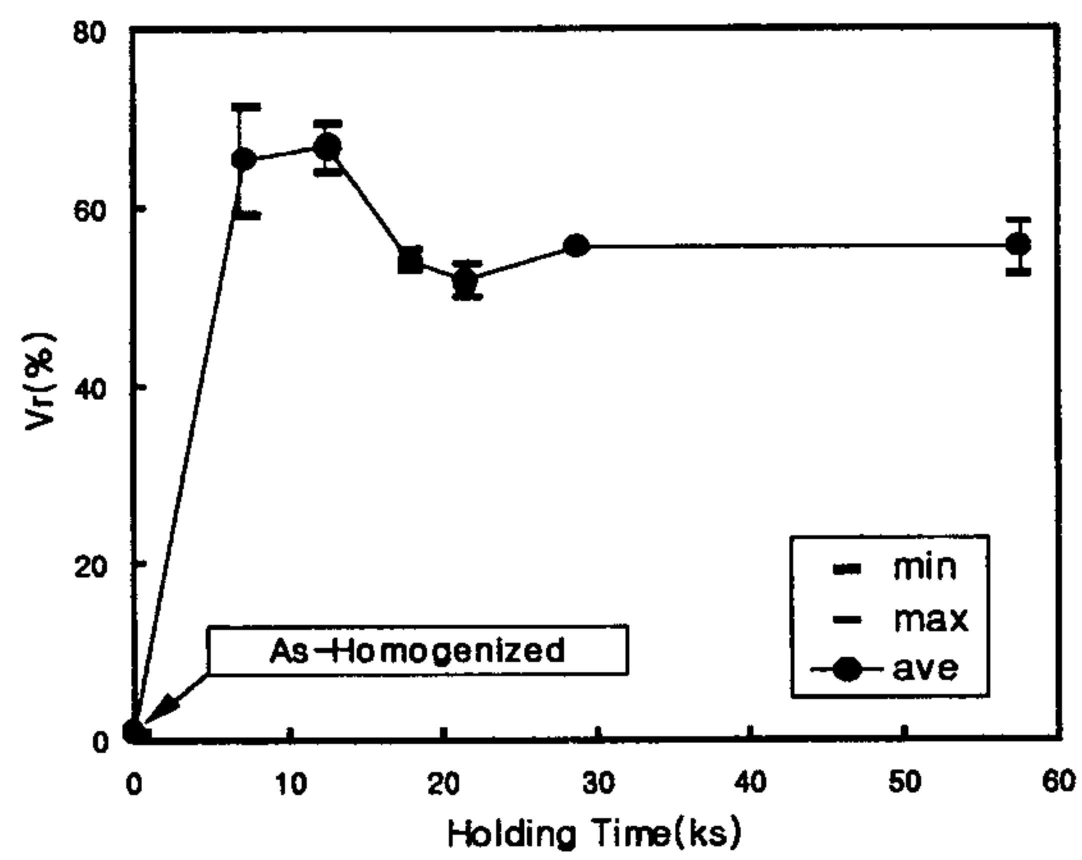

Fig. 6. The relationship between volume fraction of retained austenite (Vr) and holding time in HT-II.

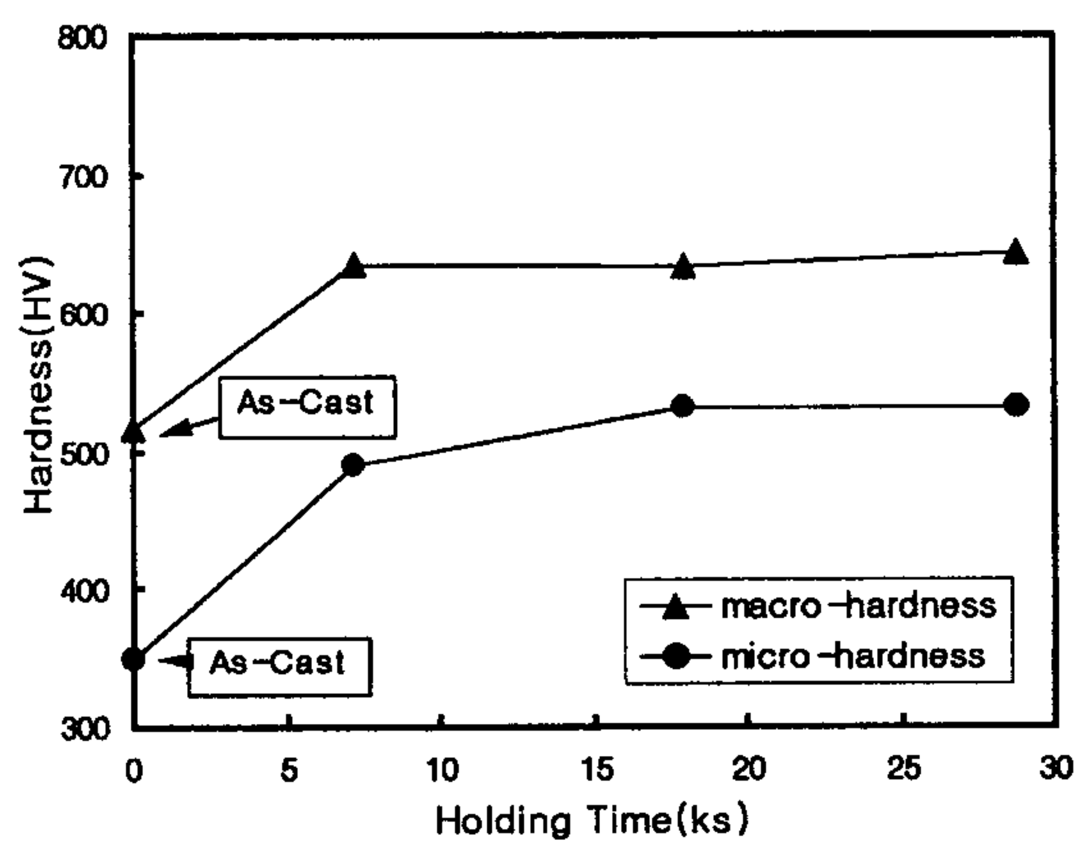

Fig. 7. The relationship between hardness and holding time in HT-I.

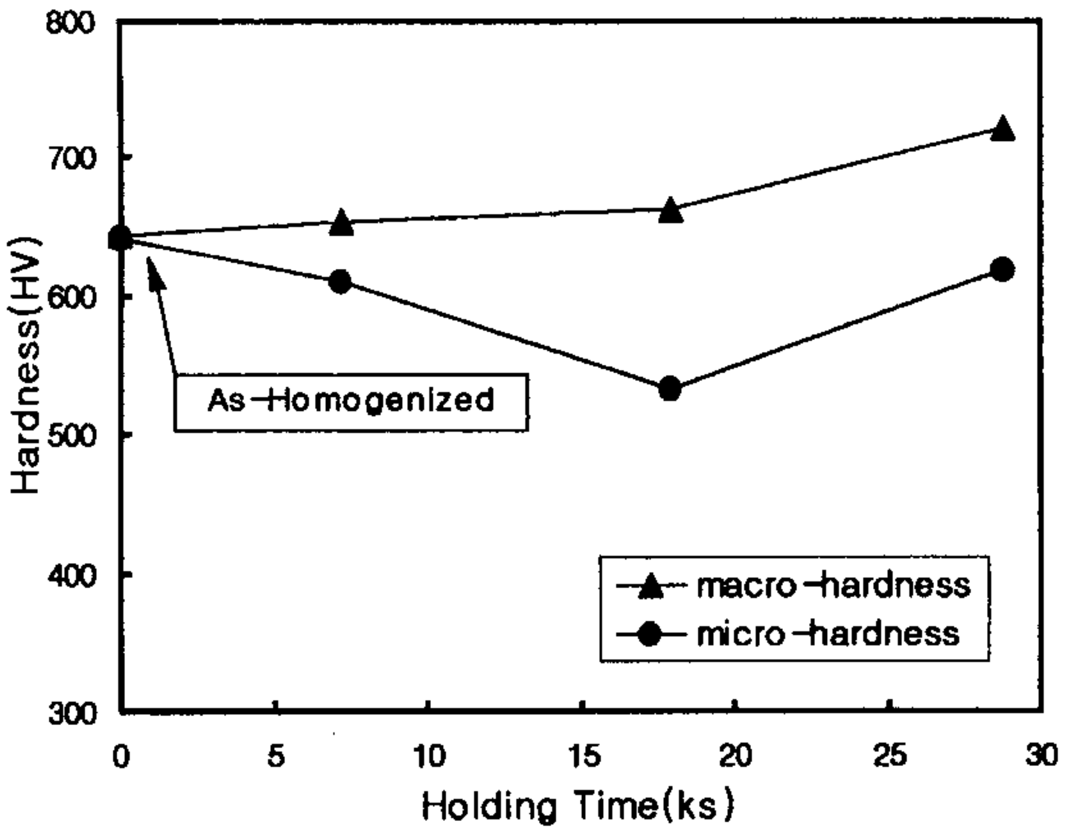

Fig. 8. The relationship between hardness and holding time in HT-II.

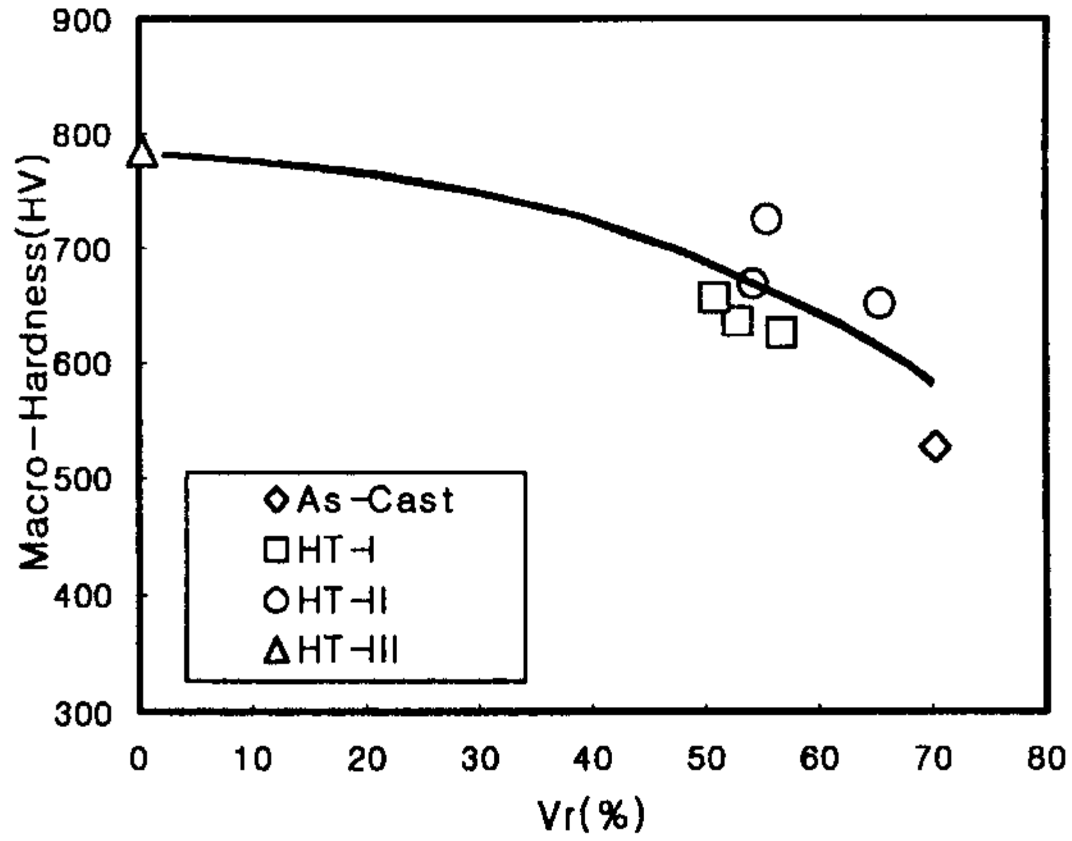

Fig. 9. The relationship between macro-hardness and volume fraction of retained austenite (Vr).

in the matrix. The hardness variation with holding time after 7.2 ks corresponds to the result in Fig. 5 suggesting that the alloy concentration of the matrix reaches an equilibrium state over 7.2 ks. The macro-hardness of destabilized specimen is higher than micro-hardness because eutectic M_7C_3 carbides are also involved in the measurement of macro-hardness in addition to matrix and secondary carbides, both of which are only used to measure the micro-hardness.

Fig. 8 shows a relationship between hardness and holding time in HT-II. An interesting fact to be noted is that the micro-hardness decreases with an increase in the holding time up to 18 ks, after which increases again. As shown in Fig. 3, the homogenizing of as-cast specimen at 1173 K for 18 ks prior to the austenitizing produces almost fully ferritic matrix with large amounts of secondary carbides and with a micro-hardness value of HV 641. When these matrices are austenitized, a certain portion of the numerous fine secondary carbides redissolves, resulting in austenitic/martensitic matrix with more or less and finer or coarser secondary carbides. The ratio of these phases determines the micro-hardness of the matrix, and in this case, lowest at 18 ks.

4.3 Relationship among Vr, Hardness and Rw

Fig. 9 shows a relationship of Vr vs. macro-hardness. The macro-hardness decreases with an increase in Vr values. As shown in Figs. 2 and 3, the matrix structures of as-cast and heat-treated specimens are duplex and consist of austenite and martensite. The greater the amounts of martensite, the higher the hardness. Therefore, the point 1 in Fig. 9, which has the highest hardness, corresponds to the specimen with the greatest amount of martensite, and the point 2 indicates the specimen with the greatest amount of austenite.

The relationship between Rw and Vr is shown in Fig. 10. The Rw decreases with increasing the Vr values. This might be due to the fact that austenite on the wear surface has transformed into martensite during the test due to work-hardening [10] and this is contributive to higher wear resistance.

Figs. 11 and 12 show the relations of Rw vs. macro- and micro-hardness, respectively. It is found that the Rw increases or the wear resistance reduces as the hardness increases. Since martensite formed by

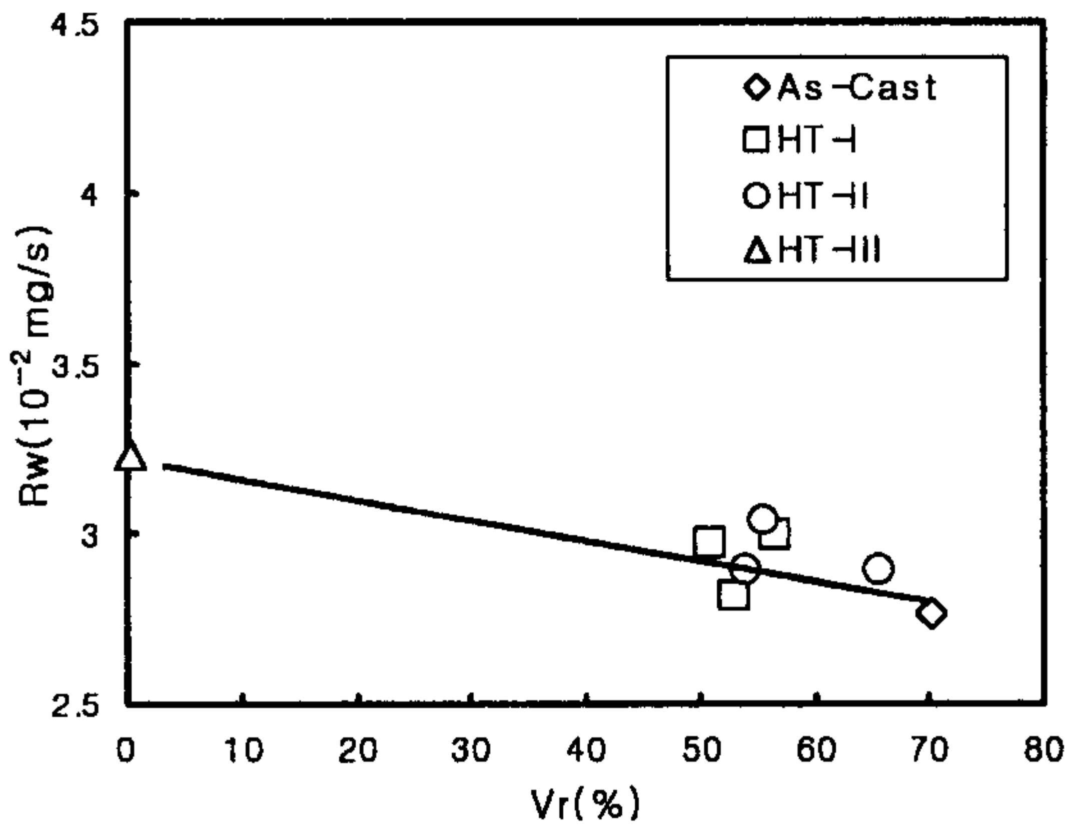

Fig. 10. The relationship between wear rate (Rw) and volume fraction of retained austenite (Vr).

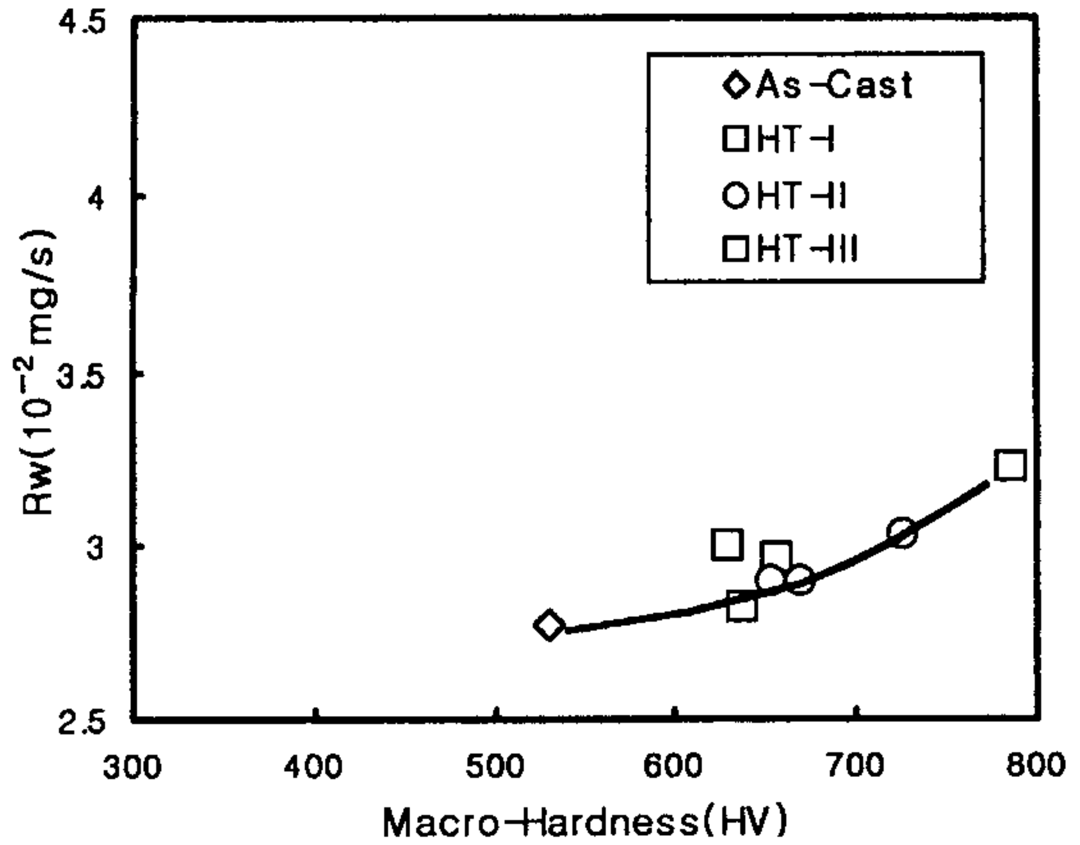

Fig. 11. The relationship between wear rate (Rw) and macro-hardness.

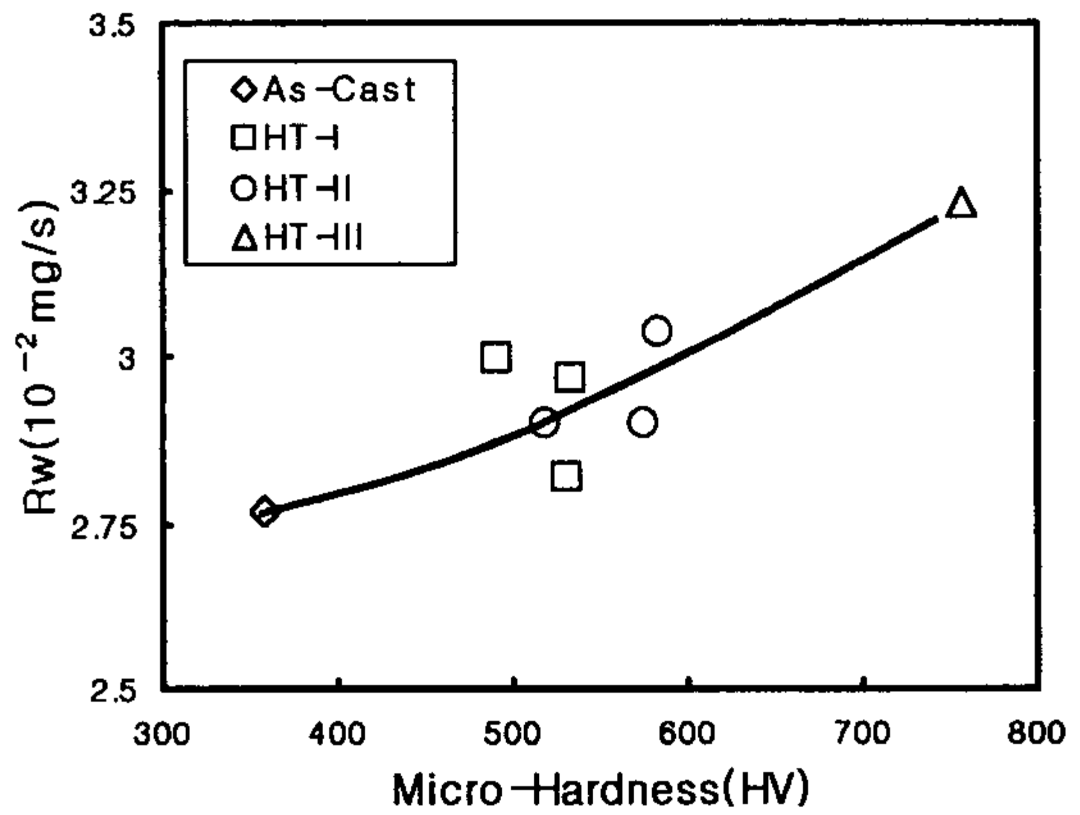

Fig. 12. The relationship between wear rate (Rw) and micro-hardness.

the heat-treatments has lower carbon content than that formed from austenite by work-hardening in as-cast specimen, the heat-treated specimens give higher Rw or lower wear resistance [11].

5. Conclusion

A hypoeutectic white cast iron of 2.3%C-26%Cr-1%Ni-0.5%Mo was heat-treated using three different procedures to obtain the specimens with different levels of retained austenite (Vr) in the matrix. Then, the effect of the Vr value on the abrasion wear resistance and the macro- and micro-hardness of the iron was investigated. The results are summarized as follows:

1) While the amounts of retained austenite are 70.2% in as-cast specimen, those of heat-treated specimens range from 0.3 to 65.4% depending upon the type of heat-treatment.

2) A linear relationship is obtained between wear loss and testing time in all the specimens after the primary stage of unsteady wear. Therefore, the rate of wear (Rw : mg/s), equivalent to the slope at the portion of the straight line, is adopted as an index of wear resistance.

3) In this wear test of scratching type, abrasion wear resistance increases with an increase in the amount of retained austenite which contributes to the wear resistance due to working hardening during test.

4) Macro- and micro-hardness decrease as the amount of retained austenite increases.

5) Abrasion wear resistance decreases with an increse in the hardness.

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