論 文

Effect of Silicon on the Fracture Characteristics of Austempered Ductile Iron

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Summary

The effects of Si and austempering temperature on the fracture characteristics and the microstructures of austempered ductile irons were investigated. As Si content increased from 2.28% to 3.0%, the precipitation of carbides during bainitic transformation and was suppressed the amount of retained austenite increased resulting in the increase in the fracture toughness. It is believed that the high Si limited the formation of martensite in the microstructure and minimized the segregation of the other elements at cell boundaries. But in samples with too high Si content as 3.3%, the formation of islands of free ferrite in the bainitic structures was observed and the fracture toughness was measured to have degraded.

Résumé

Nous avons étudié les effets du Si et de la temperature de trempe sur les caractéristiques de la rupture et sur la microstructure d'.échantillons d'acier ductible trempés. Losque la quantité de Si a été accrue de 2.28% à 3%, la précipitation de carbures pendant la transformation bainitiques est trouvée réduite et la quantité d'.austenite retenue s'est trouvée augmentée, avec pour conséquence une plus grande résistance à la rupture. Nous pensons que la quantité accrue de Si a limité la formation de martensite dans la microstructure et a réduit l' agglutination des autres éléments dans les espaces intercistallins. En revanche, dans des échantillons où le contenu de Si avait été porté à 3.3%, on a observé la formation d' ilots dispersés de ferrite dans les structures bainitiques et on a constaté que leur résistance à la rupture s' était dégradée.

Zusammenfassung

Der EinfluB von Si-Gehalt und der Zwischenstufenvergütungstemperatur auf die Brucheigenschaft und auf die Gefüge des zwischenstufenvergüteten DuktilguBeisens wurde untersucht. Beim Zunahme des Si-Gehaltes von 2.28% zu 3.0% wurde die Ausscheidung der Karbiden während der Bainitumwandlung unterdruckt, und auch wurde die Bruchduktilität wegen der Eröhung des Restaustenitanteils verbessert. Die hohe Si-Gehalte scheinen die Mar

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tensitumwandlung zu unterdrücken und zugleich die Ausscheidung der dritten Elementen an der wegen der freien Ferritbildung in Bainitgefüge abenommen.

1. Introduction

Austempered ductile iron (ADI) has emerged as a new economic material for making machinery and vehicles which can replace cast steels and forged steels.

Meanwhile, silicon which influences the microstructure of the cast iron the most along with carbon among alloying elements is know to suppress the precipitation of various carbides and promote the stabilization of the retained austenite and thus increase the amount of it. It also decreases the distance between nodular graphites and thus prevents the formation of microsegregation and improves the toughness of the matrix.

In this study, Mo-Cu nodular ductile cast irons with Si content 2.28%, 2.68%, 3.0%, and 3.3% were prepared and austenited at 900℃ for 1.5hr and then austempered at several temperatures between 300℃ and 400℃. The effect of Si on the fracture toughness of ADI was investigated by following the microstructral change.

2. Experimental

Steel scraps and pig irons were used as raw materials and melted in a high rfequency induction furnace. Ductile cast iron was prepared by adding 1.3% of Fe-Si-8% Mg to the base iron and innoculated by 0.3% of Fe-75% Si. It was further alloyed with Fe-Mo and electrolytic Cu and Fe-75% Si. The Si content was Varied by the amount of Fe-75% Si and the melt was cast in a 3 inch CO_2 Y-block (ASTM A-536). The compositions of the prepared specimens and the microstructure distributions are listed in Table 1 and Table 2, respectively.

The specimens for tension, CVN impact, and fracture toughness tests were machined out of the bottom part of the castings. Compact tension specimen(CTS) were used for the fracture toughness tests according to ASTM E-399. The width(W) and the thickness of the specimens were 54mm and 27mm, respectively. The specimens were grouped by the austempering temperature and heat tre-

Table 1. Chemical composition of ductile cast irons. (wt %)

Specimem	TC	Si	Mn	P	S	Mg	Cu	Mo
A	3.68	2.28	0.22	0.032	0.005	0.06	0.56	0.24
B	3.64	2.68	0.22	0.033	0.004	0.06	0.56	0.21
C	3.67	3.0	0.22	0.003	0.005	0.059	0.57	0.29
D	3.62	3.3	0.21	0.036	0.006	0.065	0.54	0.22

Table 2. Structure analysis of ductile cast irons.

Specimen	Ferrite (%)	Pearite (%)	Graphite (%)	Average diameter of graphite(㎜)	Deegree of spheroidization(%)	Number of graphite (#/㎟)
A	12.15	77.0	10.85	0.062	90.1	62
B	24.77	54.26	20.97	0.065	91.4	71
C	35.87	50.67	13.46	0.057	89.4	77
D	41.18	48.63	10.19	0.043	91.4	105

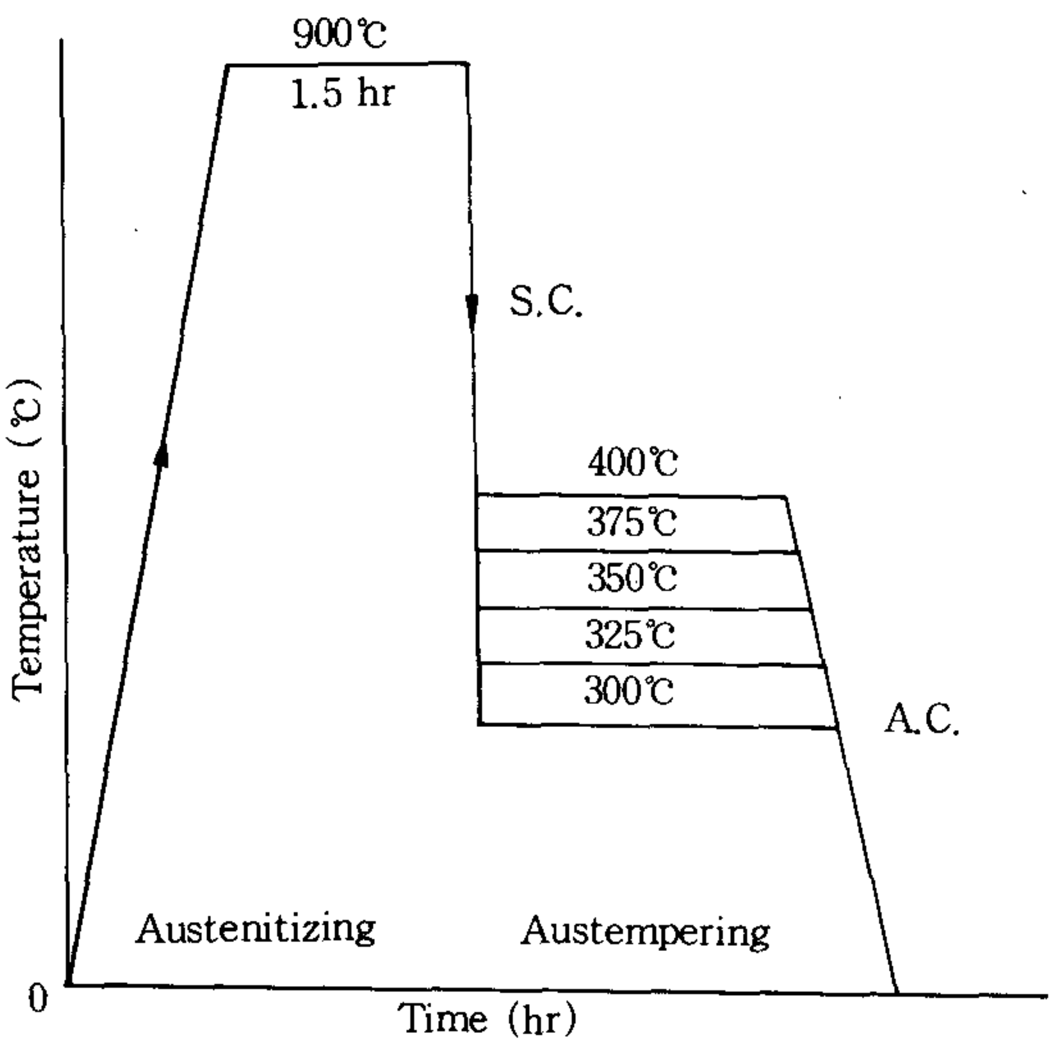

Fig. 1. Heat treatment cycle for austempering of ductile cast iron.

ated in a $NaNO_2$-KNO_3 (mol % = 54:46) salt bath following the heat treatment cycle as shown in Fig. 1.

The fracture toughness test was proceeded as follows: Microcracks were formed by applying sine waves of frequency less than 20 Hz to the notch tip by a fatigue tester (Saginomiya Seisaka Co., cap. 10 ton servopac). The specimens were then fractured by a tension tester (Toyo Baldwin Co., cap 10 ton) at the cross head velocity of 2mm/min. The K_{IC} values were calculated from the P-COD curves according to ASTM E-399. Meanwhile, the amount of retained austenite was calculated by comparing the amount of α-Fe and γ-Fe which were measured by X-ray diffractometer (Philips Co., PW 1700 systems 1) using Cu Kα1.

3. Results and Discussion

Photo 1 shows the microstructures of the ADI specimens with different Si contents austempered at two different temperatures. It is observed that the upper bainite structures are coarser than the lower bainite structures in general. Also it is observed that as Si content increases from 2.28% to 3.0%, the upper and the lower bainite structures are getting coarser. In a specimen with 3.3% Si, however, it is shown that fine and inhomgeneous bainites and island and elongated ferrites are intermixed. It is observed that the amount of ferrite increased with Si content. The elemental Si is known to retard the precipitation of Fe_3C. But too high Si content is observed to result in a bad effect. The austenitization temperature which was used for the specimen with 3.3% Si is too low to transform the bainite. Therefore it is expected that the carbon content near the nodules in the austenite at equilibrium is lower than that away from the nodules. The lower carbon content seems to promote the ferrite formation.

The mechanical properties, fracture toughness, and the volume percentage of the retained austenite are listed in Table 3. The ultimate tensile strength, the yield strength, and the hardness of ADI were measured to be higher in the specimens austemoered at 300℃ than those austempered at 400℃. The mechanical properties were measured to have degraded in the specimen with 3.3% Si than those with 2.28-2.68% Si. The percentage elongation, the CVN values, and the fracture toughness were measured to have increased when the austempering temperature was increased from 300℃ to 375℃ but have decreased when austempered at 400℃.

The relation between the fracture toughness and the amount of retained austenite in ADI can be correlated in terms of microstructural change and the resulting mechanical properties can be inferred from it. Tensile and hardness characteristics were improved with low austempering temperatures and low Si contents. This improvement is believed to be caused by the acicular bainite structure and fine carbide dispersion.

Photo 2 shows the fractographs of specimens with different Si contents.

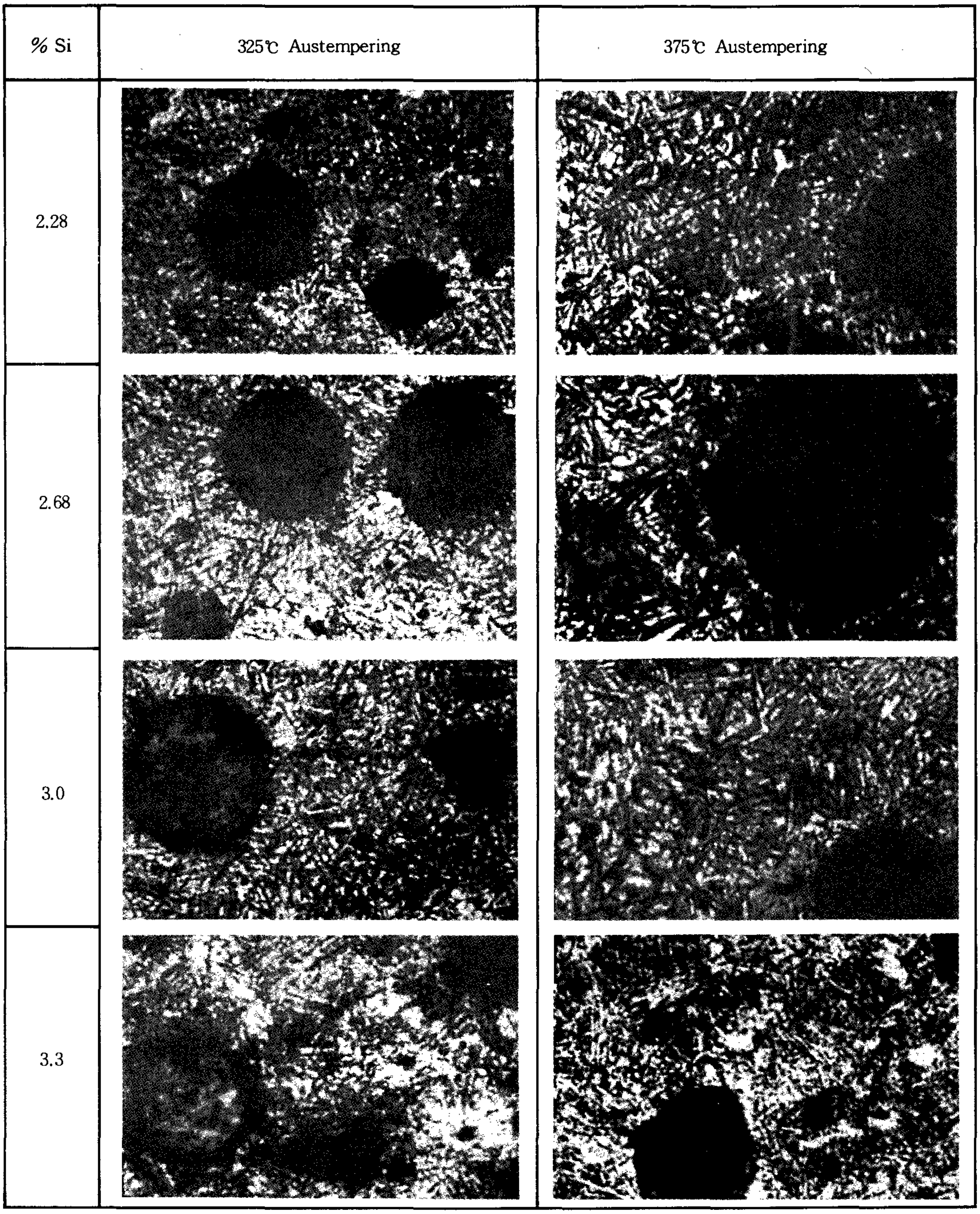

Photo 1. Mcrostructure of 2.28-3.3% Si ADI austempered at 325℃ and 375℃ (x400)

Fibrous and dimple patterns were observed in the specimens with Si content ranging from 2.28% to 3.0% due to the increase of the amount of bainite. But in the specimen with 3.3% Si, quasi-cleavage fractograph is obtained. It is believed that the amount of ret-

Table 3. Mechanical properties, amount of retained austenite and fracture toughness of austempered ductile irons.

A; 2.28% Si, B; 2.68% Si, C; 3.0% Si, D; 3.3% Si *; K_Q

austempering temp.(℃)	speci-men	YS (MPa)	UTS (MPa)	EL. (%)	VHN	CVN value(J/cm²)	Rγ (%)	K_{IC} (MRa $m^{1/2}$)
300	A	1324	1460	3.7	438	8.3	21.2	74.1
	B	1331	1491	3.8	435	8.8	24.0	79.7
	C	1353	1378	4.1	433	9.8	31.3	89.2
	D	1286	1342	2.1	425	6.2	14.3	53.3
325	A	1229	1363	4.1	415	8.9	22.1	74.6
	B	1235	1391	4.3	410	9.7	25.7	80.7
	C	1239	1426	4.7	408	10.5	32.3	90.1
	D	785	810	2.8	406	7.3	17.1	69.7
350	A	1031	1204	5.8	381	11.6	25.1	75.9
	B	1042	1216	6.1	380	12.0	31.8	88.6
	C	1072	1256	6.8	375	13.3	36.0	88.6
	D	647	673	3.0	370	8.5	19.4	*72.5
375	A	931	1109	8.2	349	12.9	28.8	83.4
	B	952	1163	8.5	345	14.7	34.6	90.9
	C	911	1043	8.9	332	15.9	38.2	94.1
	D	616	636	4.0	313	8.9	18.1	*74.1
400	A	738	941	8.8	289	10.5	20.0	72.4
	B	724	863	9.0	287	9.0	20.3	72.1
	C	713	840	9.3	279	8.3	22.2	71.2
	D	581	628	4.5	257	7.0	11.1	*62.5

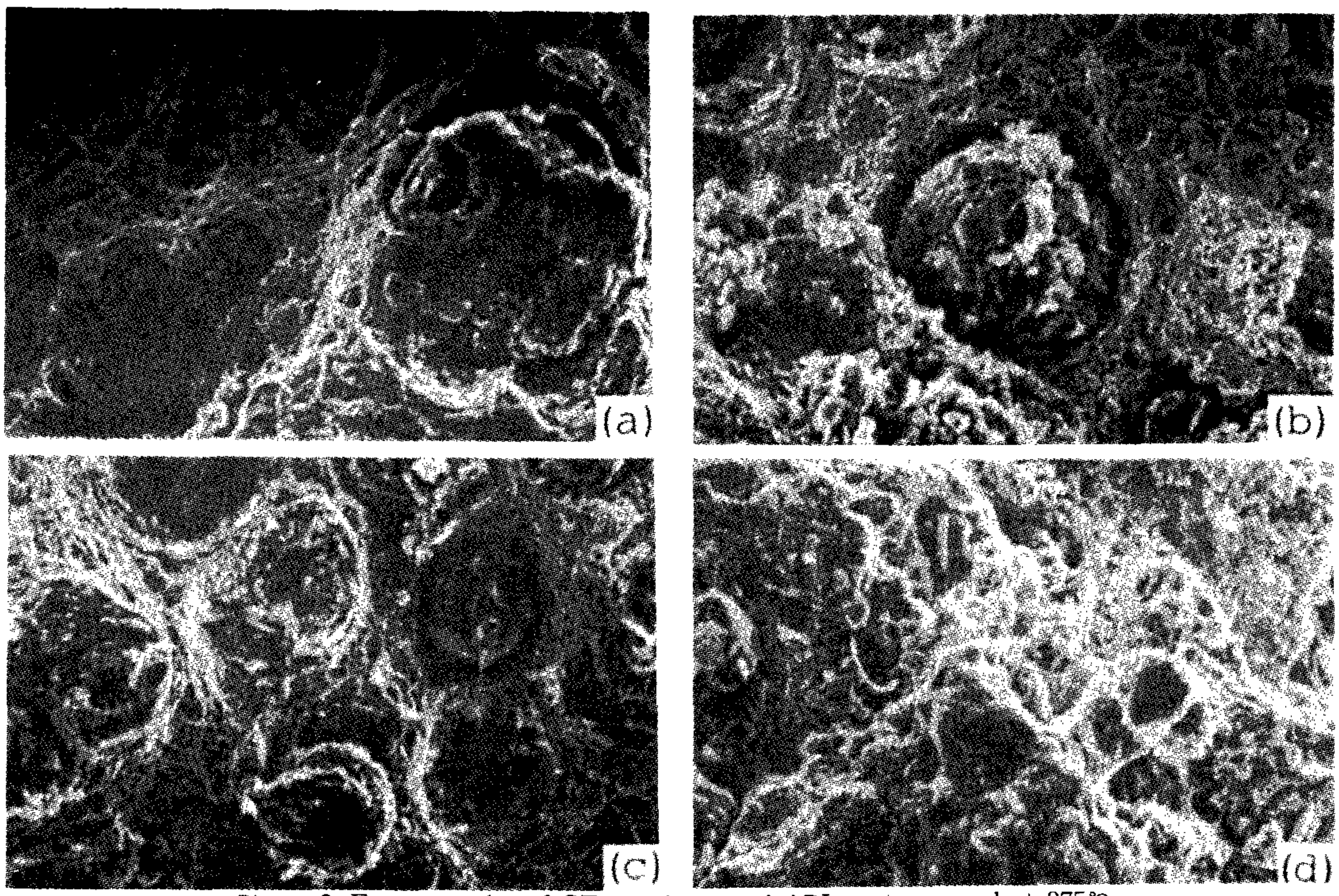

Photo 2. Fractographs of CT specimens of ADI austempered at 375℃
(a) 2.28% ADI, (b) 2.68% ADI, (c) 3.0% ADI, (d) 3.3% ADI

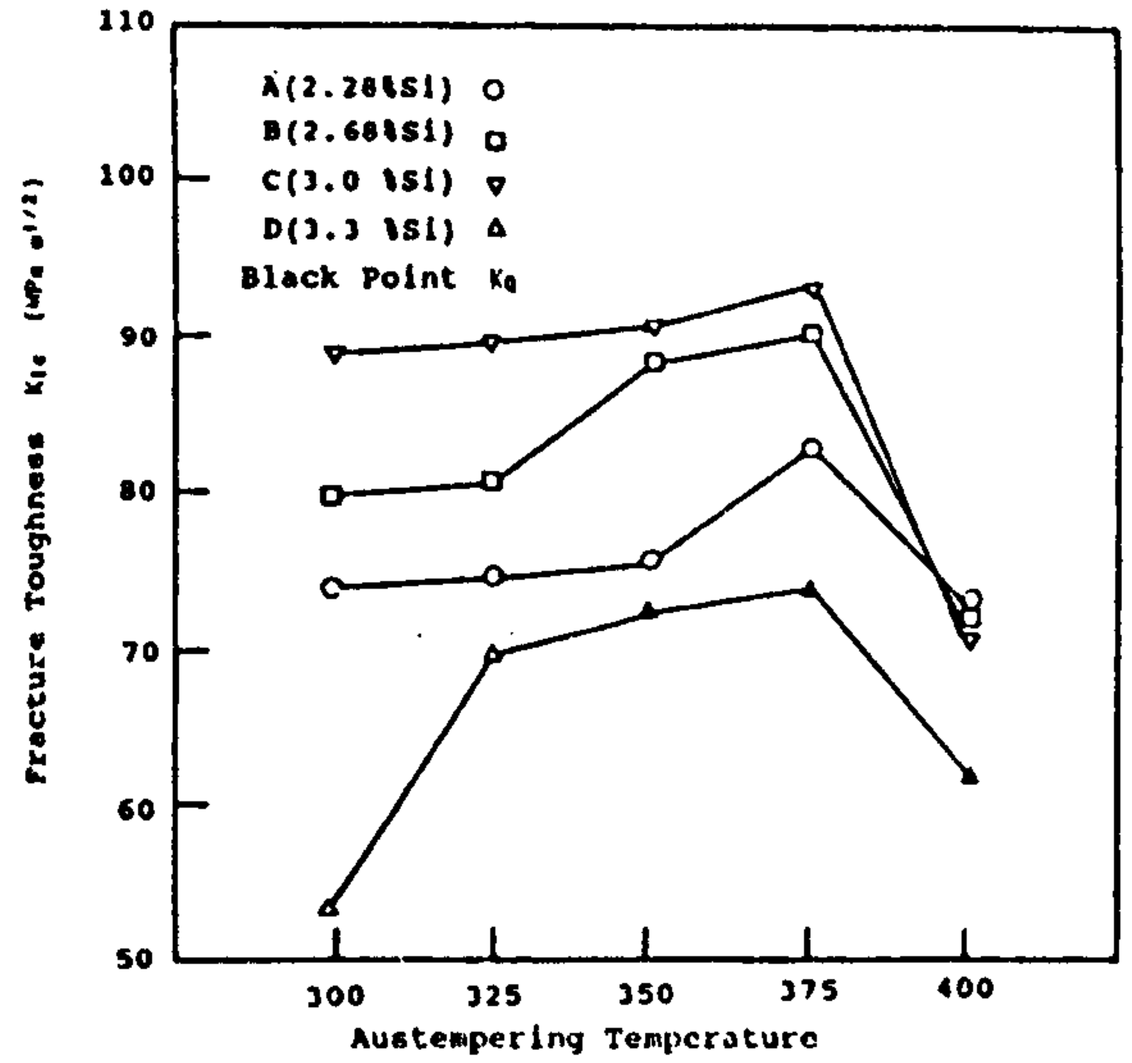

Fig. 2. The effect of Si contents and austempering temperature on the fracture toughness of A DI austenitized at 900℃ Austempening Tem perature Facture Toughness KIc(MPa $m^{1/2}$)

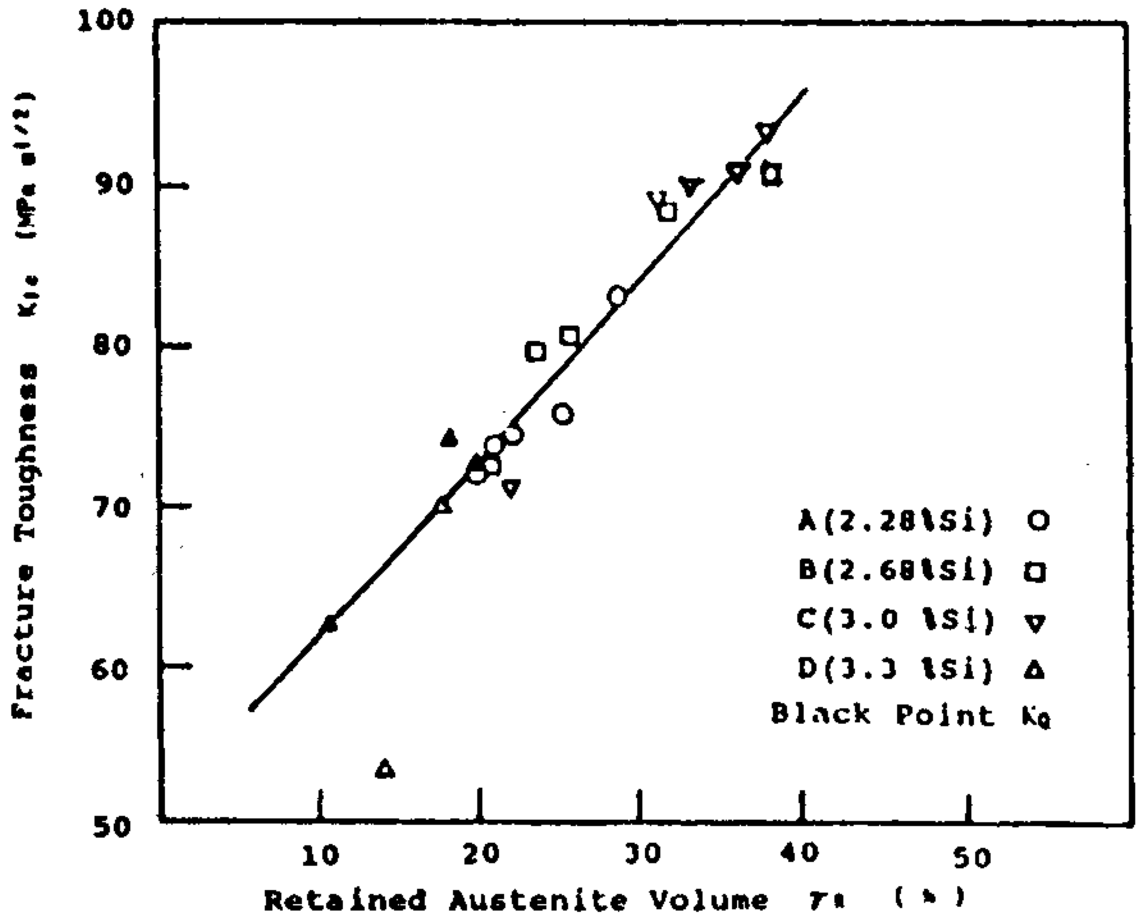

Fig. 3. The relation between fracture toughness and retained austenite voluse of ADI austenitized at 900 C and austempered at 300−400℃.

ained austenite decreased due to partial bainite transformation. Fig. 2 shows the fracture toughness as a function of Si content and austempering temperature. The fracture toughness was measured to increase with Si in the range of 2.28% to 3.0% when austempered at the temperature between 300℃ and 375℃. The specimen with 3.3% Si showed the lowest fracture toughness. In this specimen, the fraction toughness was pro-

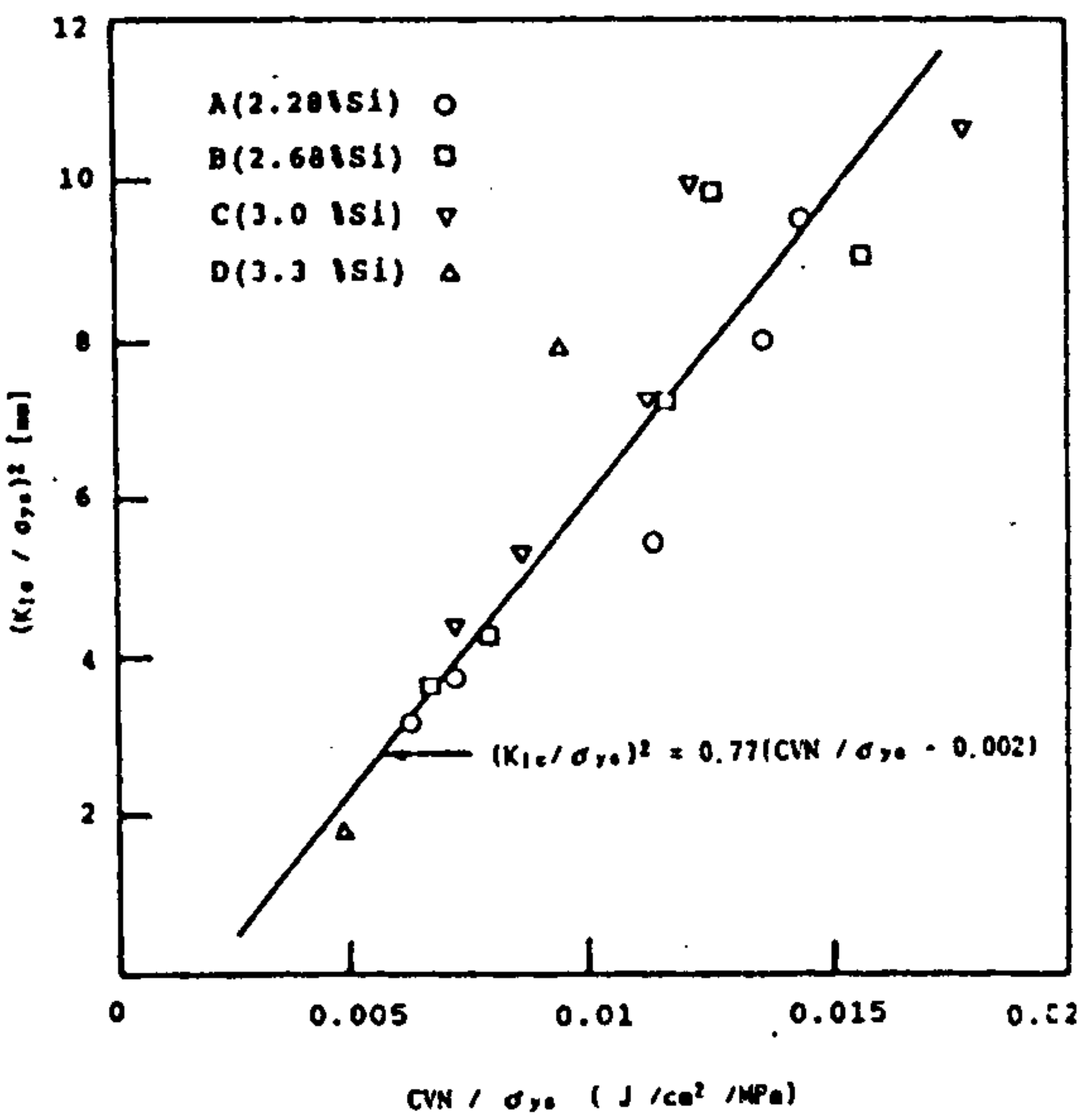

Fig. 4. The relation between KIc and CVN value in ADI.

porxtial to the retained austenite volume fraction which increased from 10% to 40%. The retained austenite improves the fracture toughness since it reduces the strain which is induced by martensite transformation at the crack tip. The relation between the amount of retained austenite and fracture toughness is shown in Fig. 3 and Fig. 4. In these specimens, the relation between the fracture toughness, the yield strength, and the CVN when austempered at 380℃ can be expressed in the form of Rolfe-Novac-Barson's equation as

$$(K_{IC}/\delta_{ys})^2=0.77(CVN/\delta_{ys}-0.02)$$

4. Conclusion

The mechanical properties, the volume of the retained austenite, and the fracture characteristics of the Mo-Cu ADI observed in this experiment can be correlated with the austempering temperature and the Si content and can be summarized as follows;

1. Bainitic laths become coarser and the retained austenite volume increases with Si

content. Therefore the tensile strength, the yield strength, and the hardness decrease but the elongation and the toughness increase.

2. When too high content of Si is alloyed as in specimen with 3.3%, the islands of free ferrite are formed in the bainite structures and it degrades the mechanical properties are formed in the bainite structures and it degrades the mechanical properties and the fracture characteristics.

3. The highest plain strain fracture toughness was obtained in the specimen austempered at 375℃ and with Si content of 3.0%. The fractograph of this specimen shows a dimple a pattern with fibrous and microvoid.

4. The maximum fracture toughness was measured to be 94 MPa/m for the specimen austempered at 375℃ and with 3.0% Si. In this specimen the volume fraction of the retained austenite was measured to be 38%.

5. The relation between the K_{IC} and the CVN can be expressed as

$$(K_{IC} / \delta_{ys})^2 = 0.77(CVN / \delta_{ys} - 0.02)$$

The units used for the expression are MPa/m for K_{IC}. MPa for δ_{ys} and joule for CVN.

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