研究論文

Fatigue Strength Improvement of Carbon Steel by Rapid Cooling from 700℃

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加熱急冷에 의한 低炭素鋼의 疲勞强度 向上

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Key Words : 低炭素鋼(Low Carbon Steel), 疲勞强度(Fatigue Strength), A_1점(A_1 Point), 時效(Aging), 析出(Precipitation), 炭素含有量(Carbon Content)

초 록

용접 이음부는 토우부의 應力集中에 의해 疲勞强度가 저하된다는 것은 잘 알려져 있는 사실이다. 이 때문에 용접 이음부의 疲勞强度 개선을 위하여 여러 방법이 제안되어 있으나 본 연구에서는 강을 가열후 急冷하여 극저탄소강의 疲勞强度 개선에 미치는 시효의 영향을 조사하였다.

탄소함유량 0.019-0.080% 범위의 8종의 炭素鋼을 용해 제조하여 압연한 후 피로시험편을 가공하였다. 이 시험편을 A_1점 이하 700℃로 가열하여 急冷 時效에 의한 低炭素鋼의 疲勞强度에 미치는 炭素含有量의 영향을 조사하였다.

700℃로부터의 급랭 및 시효에 의하여 인장강도 및 피로강도는 노랭, 공랭재의 경우에 비하여 훨씬 높아짐을 알 수 있었다.

또한 급랭후의 시효에 의한 피로강도 향상 효과가 가장 크게 나타나는 것은 페라이트의 炭素固溶限度 0.02%에 가까운 합금 조성을 갖는 경우이었다.

1. Introduction

The effect of rapid cooling into water at a temperature below A_1 point to improve the fatigue strength of steel welded joint has previously reported and the mechanism has been deduced to be mainly aging [1)~8)]. And the effect of carbon content on this phenomenon was preliminarily studied and extremely low carbon steel (0.003 % C) has not revealed such imp-

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rovement of fatigue strength. In this report, the effect of carbon content of low carbon steel on the effect to improve its fatigue strength is further studied to know the carbon content limit for the effect. Eight laboratory melted heats which contained different levels of carbon were provided. And all the specimens from these heats were heat treated under the A_1 point, 700℃, following furnace cooling, air cooling and rapid cooling into water. And tension, fatigue and metallographic tests were carried out.

2. Experimental procedures

2.1 Heat and specimens

The heats were melted by high frequency induction furnace under argon gas atmosphere.

A 99.8% purity electrolytic iron was melted and pig iron containing 4% C and carbon steel SM 50A were added to adjust carbon content of the melt. Metallic silicon and electrolytic manganese was added to deoxidize the melt. The size of ingot was 90×76×48 mm, and the weight was about 3 kg. The ingot was hot rolled at 950℃ and then finished to be 4 mm thick sheet. After rolling, the sheets were heat treated at 950℃ not only to eliminate the stress by rolling but also to obtain a uniform grain size of all the sheets. The tension and fatigue test specimens were prepared from the heat treated sheets.

Table 1 shows the chemical composition of the eight sheets. Half of each sheets from C-1 to C-4 were furnace-cooled from 700℃ and the rest were heated to 700℃ and then rapidly cooled into iced water. The sheets from D_1 to D_4 were also heated to 700℃ and then air cooled. The carbon content was varied from 0.017 to 0.08%. Manganese contents showed a small scatter and nitrogen content in the sheets ranged from 29 ppm to 60 ppm.

2.2 Heat treatment of the specimens

Fig.1 shows the shape and dimension of the tension and fatigue test specimens. All the specimens were heated to 700℃ for 25 minutes, then all of them were furnace cooled in order to eliminate any residual stress caused by machining. Half of each sheet from C－1 to C-4 were tested under this condition and are referred to be furnace-cooled-specimen hereafter. After furnace cooling, the rest of the sheets from C-1 to C-4 were reheated to 700℃ for 25 minutes and then rapidly cooled into iced water. These are referred to be rapid-cooled-specimens hereafter. The test specimens from D-1 to D-4 were all reheated to 700℃ for 25 minutes after furnace-cooling and then air cooled. All test specimens were put in cast steel powder to prevent them from decarburization during heating.

2.3 Tensile and fatigue specimens

All the specimens shown in Fig.1 were polished

Table 1. Chemical composition of steels

steels	elements, wt. %					
	C	Si	Mn	P	S	N
C－1	0.019	0.31	0.85	0.004	0.005	0.0041
C－2	0.029	0.30	0.80	0.005	0.005	0.0042
C－3	0.060	0.31	0.73	0.003	0.008	0.0050
C－4	0.070	0.29	0.85	0.002	0.008	0.0060
D－1	0.017	0.20	1.08	0.002	0.004	0.0029
D－2	0.029	0.24	0.76	0.006	0.005	0.0045
D－3	0.060	0.29	1.36	0.004	0.004	0.0032
D－4	0.080	0.14	0.48	0.005	0.008	0.0040

C series are furnace-cooled or rapid-cooled into iced water from 700℃
D series are air cooled from 700℃

with No. 600 emery paper. Rapid-cooled specimens were aged at room temperature for more than 1 month. The notch of fatigue specimen is located at 35.5 mm from fixed end, and the front tip radius is 0.25 mm. The stress concentration factor of the notch is 2.7.

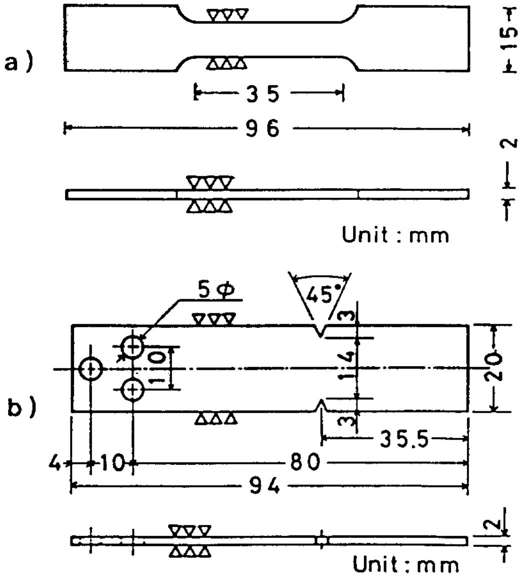

Fig. 1 Shape and dimension of test specimens
a) tension test specimen
b) fatigue test specimen

2.4 Fatigue testing

A cantilever type of bending fatigue machine with 1060 cycle and stress ratio R = −1 was used for fatigue test. The stress applied to fatigue specimen is determined by measuring the deflection of the specimen, which can be varied. Also the strain of the specimens are measured directly by strain gauge. Comparing the deflection and strain, stress applied to fatigue specimen is calculated.

2.5 Measurement of ferrite grain size

The ferrite grain sizes of the steels were measured by optical microscope, according to JIS G0552. For measuring ferrite grain size, the average of more than twenty fields were adopted. There was little difference in ferrite grain size of all specimens, which was ranged from 6.8 to 7.2.

2.6 Change of hardness on aging

The hardness change in the ferrite grain of rapidly-cooled specimens was measured by micro-Vickers tester and the average of more than 10 readings was adopted.

3. Results and discussion

3.1 Results of tensile test

Table 2 and Fig.2 show the results of tension test. As shown in Table 2, tensile strength increases from 33.40 kgf/mm^2 to 39.50 kgf/mm^2 as carbon content increases from 0.017% to 0.080% in case of the furnace-cooled specimens. Tensile strength increases linearly in proportion to carbon content as shown in Fig.2. The same tendency was shown in case of the air-cooled specimens, too. There was no remarkable difference in the tensile strength of the furnace-cooled and air-cooled specimens. The tensile strength of rapid-cooled-specimen showed the same linear relationship to carbon content as the furnace-cooled and air-cooled specimens but were 40% higher compared with the latter ones. The elongation of furnace-cooled specimens was about 46% at each carbon content, and about 44% in case of air-cooled ones. The elongation of rapid-cooled-specimens was about 30% on the average (see Fig.2).

3.2 Change of hardness by aging

Fig.3 shows the change of hardness in the ferrite grain by aging of rapid-cooled-specimens. The hardness in the ferrite grain becomes higher gradually by aging, and it becomes nearly constant after about 1 month. Consequently, rapid-cooled-tension and fa-

Table 2. Mechanical properties of test specimens

carbon content (wt. %)	heat treatment	tensile strength (kgf/mm²)	elongation (%)
0.017	f. c.	33.40	40.05
	a. c.	34.90	37.70
0.029	f. c.	33.55	44.70
	a. c.	35.90	40.10
	r. c.	51.95	24.05
0.060	f. c.	36.25	40.10
	a. c.	37.40	38.15
	r. c.	53.10	21.10
0.070	f. c.	38.80	40.40
	r. c.	53.20	23.23
0.080	f. c.	39.50	40.65
	a. c.	39.87	37.80
	r. c.	55.15	21.45

f. c. : furnace cooling, a.c. : air cooling, r.c. : rapid cooling

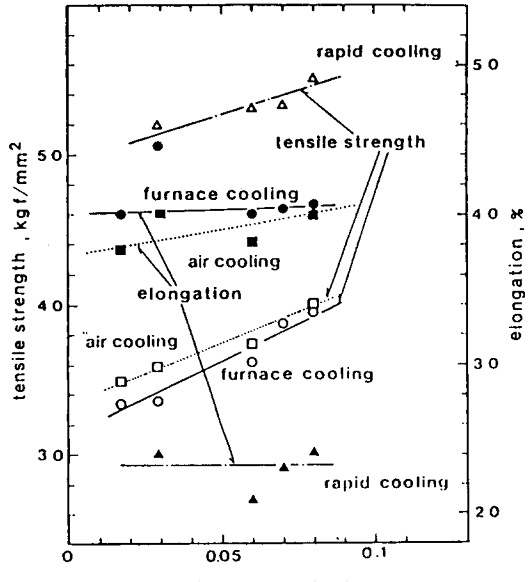

Fig. 2 Characteristics among carbon content, heat treatment and mechanical properties

tigue specimens were tested after aging for over 1 month.

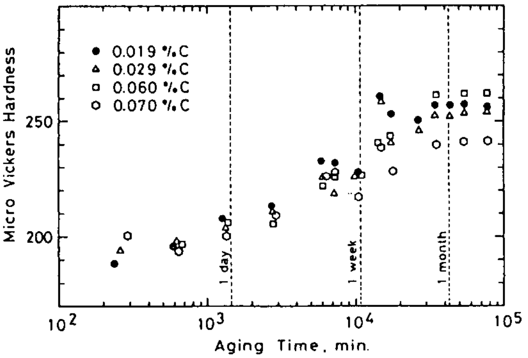

Fig. 3 Change of hardness during aging time at room temperature

Talbe 3 Fatigue test results

carbon content (wt.%)	fatigue strength (kgf/mm²)		
	f.c.	a.c.	r.c.
0.017	–	9.66	–
0.019	7.87	–	20.86
0.029	8.42	10.05	21.03
0.060	9.88	11.06	22.13
0.070	10.50	–	20.98
0.080	–	11.50	–

f.c. : furance cooling, a.c. : air cooling
r.c. : rapid cooling

3.3 Fatigue test results

The fatigue test results are shown from Fig.4 to Fig.7 and summarized in Table 3.

Fig.4 shows the fatigue test results of furnace-cooled and rapid-cooled-specimens containing 0.019% carbon, and air-cooled-specimens of 0.017% carbon. It is clear that fatigue strength increases remarkably by rapid cooling. In case of 0.019% carbon, fatigue limit in the furnace-cooled and air-cooled conditions are 7.87 kgf/mm^2 and 9.66 kgf/mm^2, respectively. But rapid-cooled-specimens show over 15 kgf/mm^2 fatigue limit.

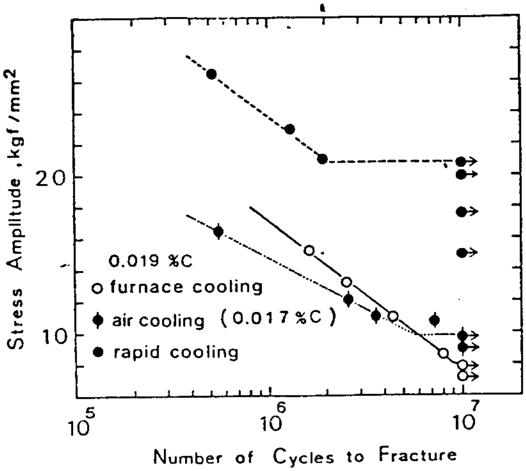

Fig. 4 Fatigue test results of 0.017 and 0.019%C specimens

Fig.5 shows the fatigue test results of 0.029% carbon specimens which were subjected to the three different heat treatments. The results are similar to those shown in Fig.4. The fatigue limits of the furnace-cooled, air-cooled and rapid-cooled conditions are 8.42, 10.05 and over 16 kgf/mm^2, respectively.

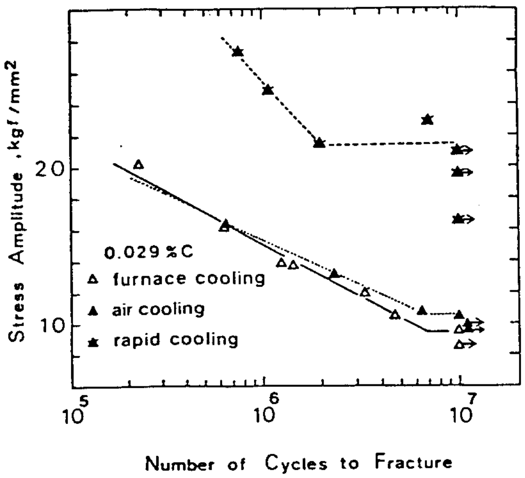

Fig. 5 Fatigue test results of 0.029%C specimens

Fig.6 shows fatigue testing results of 0.060% carbon specimens, which has the same tendency as in Fig.4 and Fig.5. The fatigue limits in the three different conditions, i.e., furnace-cooled, air-cooled and rapid-cooled are 9.88, 11.06 and 22.13 kgf/mm^2, respectively.

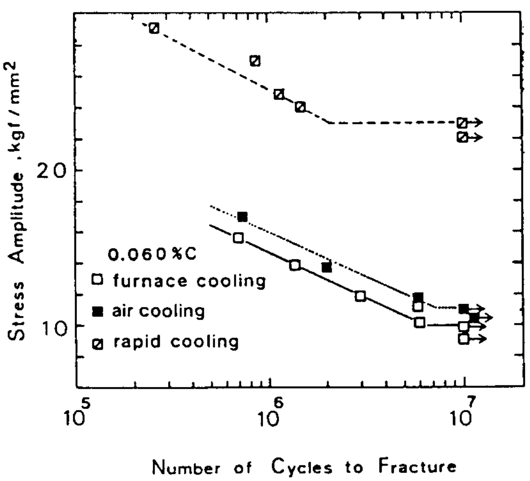

Fig. 6 Fatigue test results of 0.060%C specimens

Fig.7 shows the fatigue test results of the 0.07% carbon specimens which underwent the furnace-cooling and rapid-cooling heat treatments, together with the result of air cooled 0.080% carbon specimens. In this case, fatigue limits of the furnace-cooled and

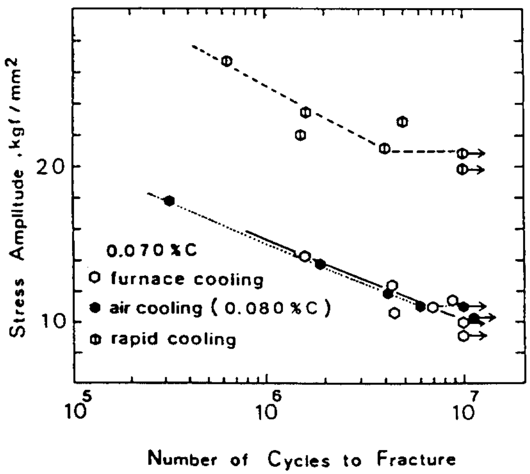

Fig. 7 Fatigue test results of 0.070 and 0.80%C specimens

rapid-cooled conditions are 10.50, 20.98 kgf/mm^2, respectively. And the fatigue limit of air-cooled 0.080% carbon specimens is 11.50 kgf/mm^2.

These results reveal that the fatigue limit is increased remarkably by rapid cooling compared with air cooling or furnace cooling.

Fig.8 shows the relationship between carbon content and fatigue limit. Fatigue limit increases linearly with carbon content in case of furnace-cooling and air-cooling, but that of rapid-cooled-specimens shows only a small change with increasing carbon content.

Based on the tension and fatigue test results, the equations between tensile, fatigue limit and carbon contents were obtained by the least squares method and are shown as follows :

$$\sigma_{Bf}=31.06+102.28\times(C\%) \qquad (1)$$

(tensile strength of furnace cooling)

$$\sigma_{Ba}=33.59+73.65\ (C\%) \qquad (2)$$

(tensile strength of air cooling)

$$\sigma_{Br}=50.16+53.33\ (C\%) \qquad (3)$$

(tensile strength of rapid cooling)

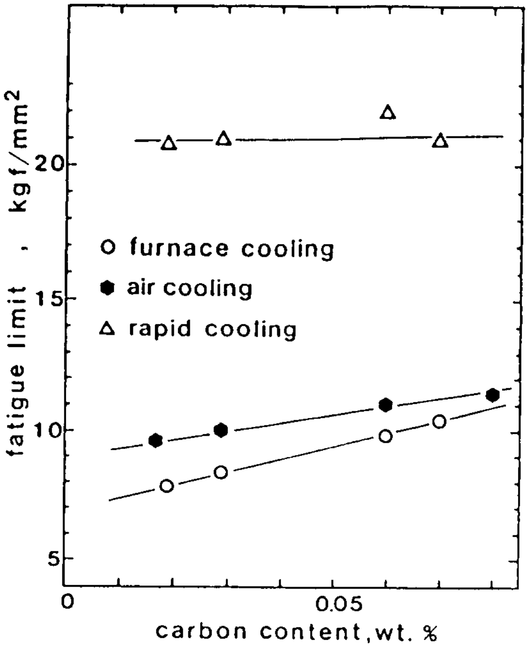

Fig. 8 The relationship between carbon content and fatigue limit

$$\sigma_{Lf}=6.93+50.36\ (C\%) \cdots\cdots\cdots\cdots\cdots\cdots \quad (4)$$

(fatigue limit of turnace cooling)

$$\sigma_{La}=9.19+29.71\ (C\%) \cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

(fatigue limit of air cooling)

$$\sigma_{Lf}=20.75+11.29\ (C\%) \cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

(fatigue limit of rapid cooling)

The equations from (1) to (3) are the relationship between tensile strength and carbon content, and the correlation coefficients are 0.97, 0.98 and 0.89, respectively. The correlation coefficient of rapid-cooled condition is lower than that of furnace-cooled and air-cooled condition.

The equations from (4) to (6) are the relationship among fatigue limit and carbon content and the correlation coefficients are 0.999, 0.997 and 0.5, respectively. Good correlationship is recognized for furnace-cooled and air-cooled condition, but in case of rapid-cooled condition is small.

The effect of carbon content and heat treatment on fatigue strength improvement may be evaluated by the following factor. The fatigue limit increasing rate (FLIR) is defined as follows;

$$\mathrm{FLIR}=\frac{\sigma_{Lr}-\sigma_{Lf}}{\sigma_{Lf}}\times 100(\%) \cdots\cdots\cdots\cdots\cdots (7)$$

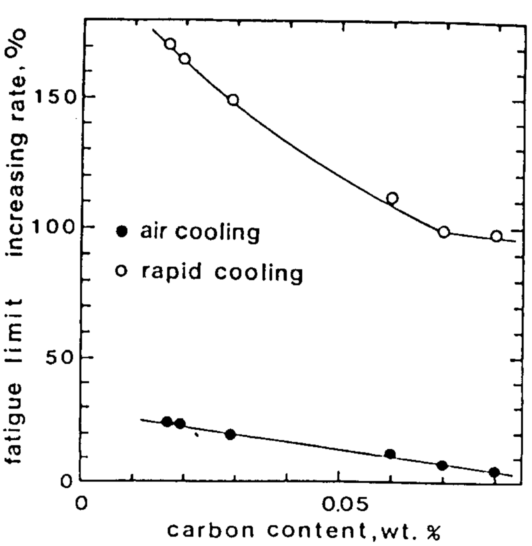

Fig. 9 The relation between carbon content and fatigue limit increasing rate

σ_{Lr} = fatigue limit of rapid-cooled condition
σ_{Lf} = fatigue limit of furnace-cooled condition

Fig.9 shows the relationship between carbon content and FLIR based on equation (7). FLIR decreases as increasing carbon content especially in case of rapid cooling. FLIR of air cooled specimens is very small compared with rapid-cooled condition. Also, similar to the rapid-cooled specimens, the FLIR of the air-cooled specimens decreases with increasing carbon content.

Fig.10 shows the relation between carbon content and endurance ratio, σ_L/σ_B. It can be seen that the endurance ratio varies only slightly with increasing carbon content for all three heat treatment conditions. The endurance ratios of furnace-cooled and air-cooled conditions range from 0.24 to 0.27 and 0.27 to 0.29, respectively. And the endurance ratio of rapid-cooled-specimen ranges from 0.38 to 0.41.

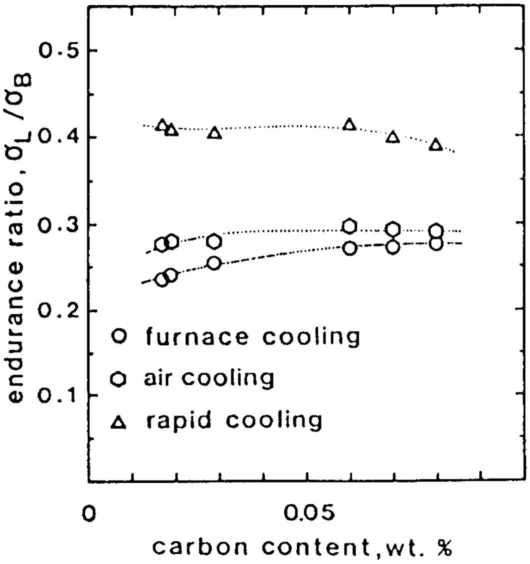

Fig. 10 Change of endurance ratio for three different heat treatments

Fig.11 shows the precipitation constituents observed by scanning electron microscope. Fig.11a and Fig.11b show the distribution of precipitates of furnace-cooled 0.019% and air-cooled 0.017% carbon specimens. No precipitates are observed in the ferrite grain. While much precipitation is observed in the ferrite grain of rapid-cooled specimens(Fig.11c to Fig.11f).

Fig.11c and d are the cases of rapid-cooled 0.019 and 0.029% carbon specimens, in which the difference in the precipitation features are recognized, compared with Fig.11e (0.06% C) and Fig.11f (0.07% C). In the former ones precipitates are observed only in the ferrite grain and those are uniformly distributed. But in the latter ones, precipitates are observed not only in the ferrite grain but also on the ferrite grain boundary or near the grain boundary. And the precipitation constituents on the grain boundary or near grain boundary are very coarsed ones.

4. Conclusions

Eight laboratory melted specimens were subjected to different heat treatments below A_1 point. The effect of aging concerned with improvement of fatigue strength was investigated.

The main conclusions obtained were as follows;

1. Tensile and fatigue limit of all specimens ranging from 0.017 to 0.08%C increased remarkably by low temperature heating (700℃) below A_1 point and rapid cooling into iced water.
2. The fatigue limit and endurance ratio of rapid-cooled-specimens were nearly the same at all levels of carbon investigated and were independent of carbon content.

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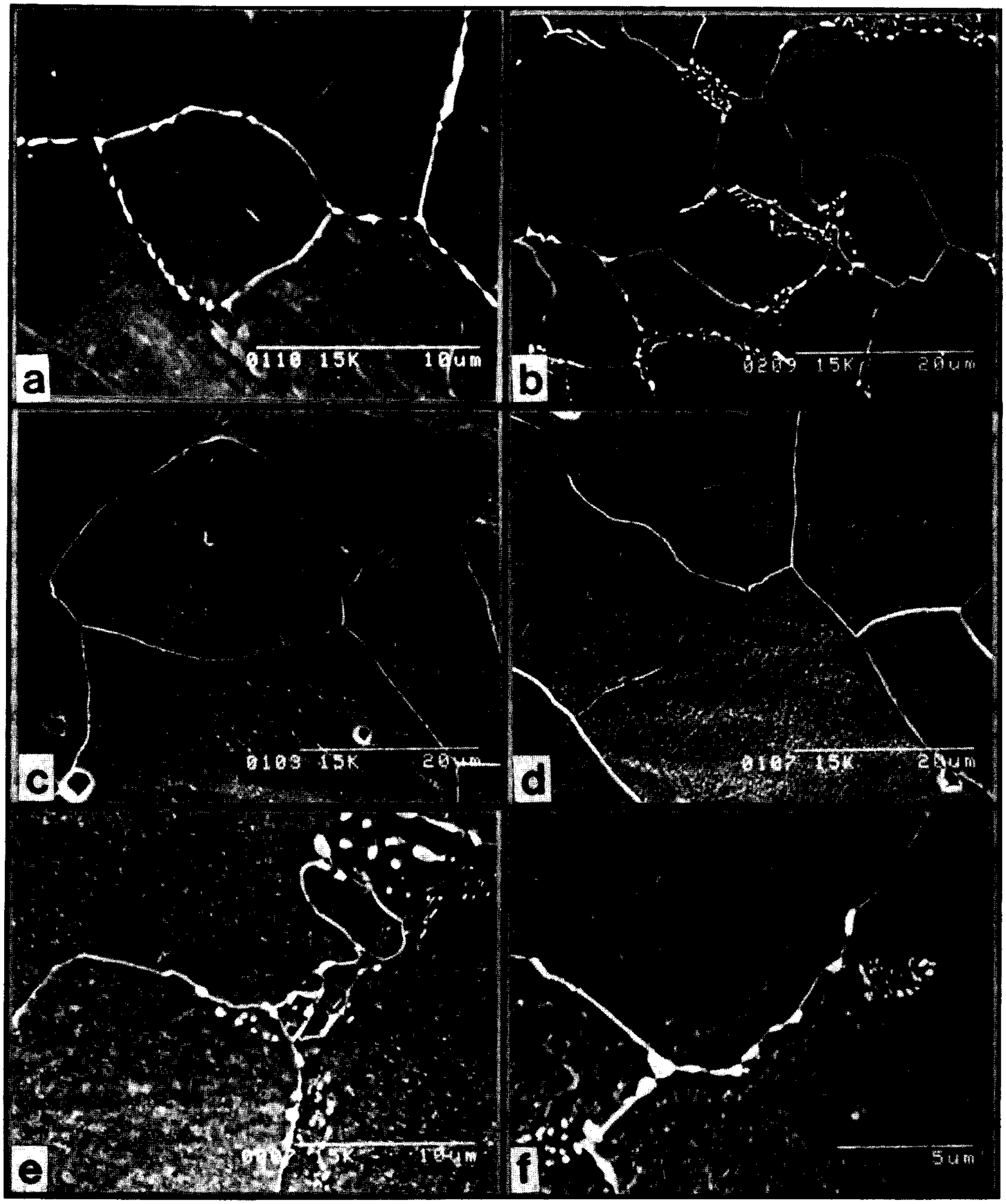

Fig. 11 SEM microstructures of heat treated specimens

a) 0.019%C(furnace-cooled)
b) 0.017%C(air-cooled)
c) 0.019%C(rapid-cooled and aged)
d) 0.029%C(rapid-colled and aged)
e) 0.060%C(rapid-colled and aged)
f) 0.070%C(rapid-colled and aged)

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