Weld Cold Cracking in HAZ of Engineering Carbon and Low Alloy Steel (Report IV)†

Susceptibility and Crack Free Condition to Quenching Crack Type Cold Cracking under Various Cooling Conditions

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Abstract

For fifteen kinds of commercial steels with phosphorus content about 0.012-0.026wt.% to be susceptible to quenching crack type cold cracking in weld HAZ, the variation in hardness, fracture stress and their correlations were studied by the simulated cold cracking test under the various cooling conditions. Consequently, the crack free condition was attributed to hardness and fracture stress.

The fracture stress has an excellent correlation with the fraction of intergranular fracture which indicates the cold cracking susceptibility of quenching crack type. The hardness has a good correlation with the fraction of intergranular fracture, too. However, the fraction of intergranular fracture within Hv600 to 700 is largely influenced by cooling rate, i.e., the fracture stress is remarkably improved by decreasing the cooling rate, although the loss of hardness is little. It was thought that this type of cold cracking is avoidable by adoption of the materials or welding conditions giving the maximum hardness in HAZ less than about Hv600 or the fracture stress more than about 950MPa.

KEY WORDS : (LOW Alloy Steels) (Carbon Steels) (Tool Steels) (Cold Cracking) (Quenching Cracking) (Crack Susceptibility)

1. Introduction

In the previous report[1], the effect of chemical compositions on the cold cracking susceptibility of quenching crack type had been studied by means of the simulated cold cracking test under constant cooling condition causing no bainite or troostite. According to those results, it was clarified that hardness and phosphorus have the main influences on this type of cold cracking. Thus it was expected that quenching crack type cold cracking can be improved by reducing the hardness and phosphorus content. Now, it is very interesting how to prevent this type of cold cracking with respect to the welding fabrication.

Therefore, the improving behaviors, namely, the changes in hardness, fracture stress and intergranular fracture surface and their correlations have been studied in detail under a wide range of the cooling conditions by means of the simulated cold cracking test for fifteen kinds of commercial steels with phosphorus content about 0.012-0.026wt.%. Furthermore, the crack susceptibility of quenching crack type and its crack free condition have been discussed in terms of hardness and fracture stress.

2. Materials Used and Experimental Procedures

2.1 Materials used

Table 1 shows the chemical compositions of fifteen kinds of commercial medium/high carbon low alloy steels which have different carbon contents in the range from

Table 1 Chemical compositions of materials used

Material*	Chemical composition (wt.%)								Ms temp. (K)
	C	Si	Mn	P	S	Ni	Cr	Mo	
SNCM420	0.21	0.24	0.61	0.020	0.011	1.61	0.46	0.21	649
SCM435	0.36	0.23	0.80	0.022	0.013	0.10	1.11	0.15	563
S40C	0.39	0.25	0.70	0.026	0.028	0.02	0.12	0.01	563
SCr440	0.40	0.29	0.76	0.025	0.012	0.07	1.09	0.02	559
SCM440	0.40	0.27	0.71	0.018	0.028	0.08	1.05	0.16	562
SNCM439	0.39	0.28	0.73	0.012	0.007	1.72	0.69	0.17	553
S45C	0.44	0.24	0.72	0.026	0.016	0.01	0.11	0.01	542
SCr445	0.49	0.26	0.78	0.020	0.024	0.07	1.03	0.02	559
SCM445	0.45	0.24	0.78	0.017	0.018	0.07	1.07	0.15	550
SNCM447	0.44	0.22	0.69	0.015	0.007	1.68	0.71	0.16	533
S55C	0.54	0.26	0.69	0.022	0.011	0.05	0.19	0.02	503
SK6**	0.72	0.22	0.75	0.025	0.023	0.07	0.22	0.01	487
SK5	0.89	0.24	0.29	0.022	0.020	0.04	0.12	-	466
SUJ2	0.96	0.26	0.46	0.015	0.009	0.05	1.46	0.01	427
SK3**	1.05	0.33	0.98	0.020	0.018	0.05	0.47	-	422

* Designations follow JIS.
** Mn and Cr contents are a little higher than JIS specification.

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about 0.2 to 1.0wt.% with and without low contents of alloying elements, such as Ni, Cr and Mo and so on. The tested materials are classified into machine structural alloy steels SNCM420, SCM435, SCr440, SCM440, SNCM439, SCr445, SCM445 and SNCM447, machine structural carbon steels S40C, S45C and S55C, plain carbon tool steels SK6, SK5 and SK3, and high carbon chromium bearing steel SUJ2. These steels have nearly all of the general commercial steels which are susceptible to quenching crack type cold cracking.

2.2 Experimental procedures

The fracture stress during cooing was measured by thesimulated cold cracking test whose applicability had been established in the previous report[2]. The shape and size of the specimen with notch in the center is shown in **Fig.1.** The cooling mtage of the thermal cycles are shown in **Fig.2.** which were programmed so to agree with those measured in the y-slit cracking test. The specimens with 25mm thickness plate, GTA welding under the condition of welding current 300A, arc voltage 19V and welding speed 2mm/sec coupled with and without preheating were prepared. The thermal cycles represented $\Delta t_{1073\text{-}773K}$ (Δt) as cooling time from 1073 to 773K. The cooling time was changed according to the welding conditions as follows; Δ t:3.5sec for the specimens which welded without preheating and Δt:6, 9, 14 and 21sec for the specimens which welded after preheating at 323, 373, 473 and 573K, respectively. The cooling time of Δt:2sec corresponds to that with SMA welding for 25mm thickness plate under the welding condition of heat input 10KJ/cm[3]. The peak temperatures (Tp) were set to the liquation temperatures of the grain boundaries in each material in order to the crack initiation stress in the RRC test[4]. Heating time to Tp is 12sec, and holding time at Tp is 6sec. The loading method used was also the same as that of the previous reort[2], the displacement was fixed from the start of cool-

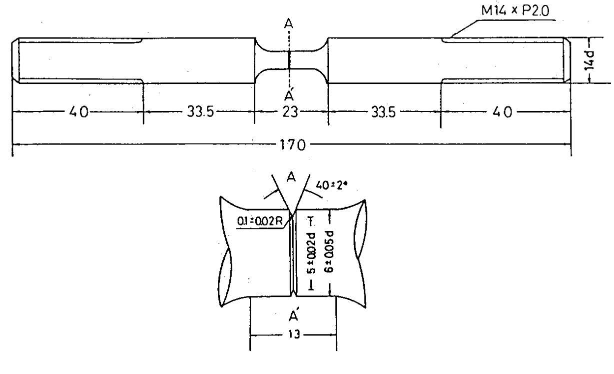


Fig. 1 Configuration of the simulated cold cracking test specimen

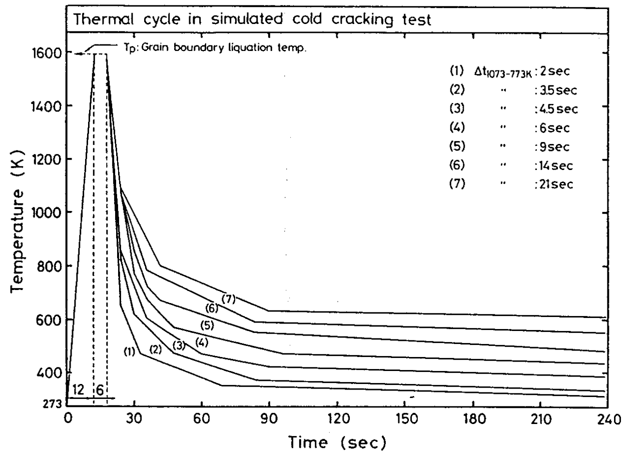


Fig. 2 Thermal cycles used in the simulated cold cracking test

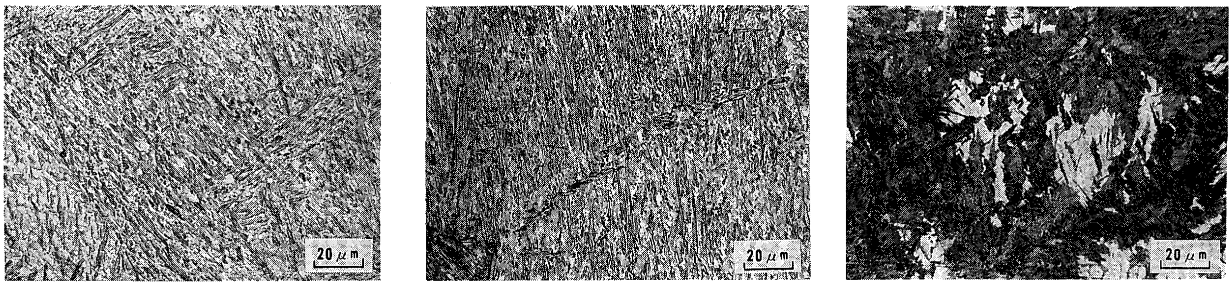
ing to the temperature just above Ms point, and then was increased under different C. H. S.. The fracture stress is equal to the average values which obtained within 323-373K during cooling.

The measurement conditions of the area fraction of intergranular fracture surface (IG fraction) and hardness(Hv) using load 9.8N were the same as the previous report[1].

3. Experimental Results and Discussions

3.1 Variations in microstructure, intergranular fracture surface and fracture stress under the various cooling conditions

Under the various cooling conditions, bainite and/or troostite with martensite (and partial retained austenite) were formed with decreasing the cooling rate. The improvement behaviors of the hardness and fracture stress also showed various behaviors attributed to the differences of the transformation characteristics for each material. However, the characteristics can be roughly classified into three groups having the similar behaviors as follows. (i)Group I, the steels such as SNCM439 and SNCM447 of medium carbon low alloy steel. An example of the icrostructural change near notch of SNCM447 is shown in **Fig.3. Figure 4** shows the SEM microstrostructure of bainite near grain boundary of SNCM447 under the cooling condition of Δt:9sec which was obtained by electrolytic etching crosssection of the specimen. In this group, the microstructure at Δt:3.5sec showed lath martensite. The microstructure remained without changes at Δt:6sec, but bainite was formed formed at Δt:9sec. (ii)Group II, the steels such as S55c, SK6 and SK5 of medium/high carbon steel. In this group, troostite was rapidly formed by a



(a) Δt:3.5sec, M, Hv700 (b) Δt:6sec,M,Hv680 (c) Δt:9sec,M+B, Hv605

Fig. 3 Variation in microstructure of SNCM447 with increasing cooling time

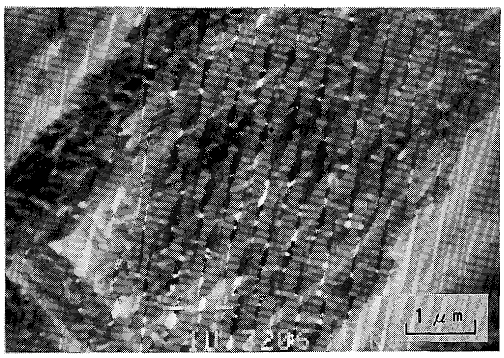
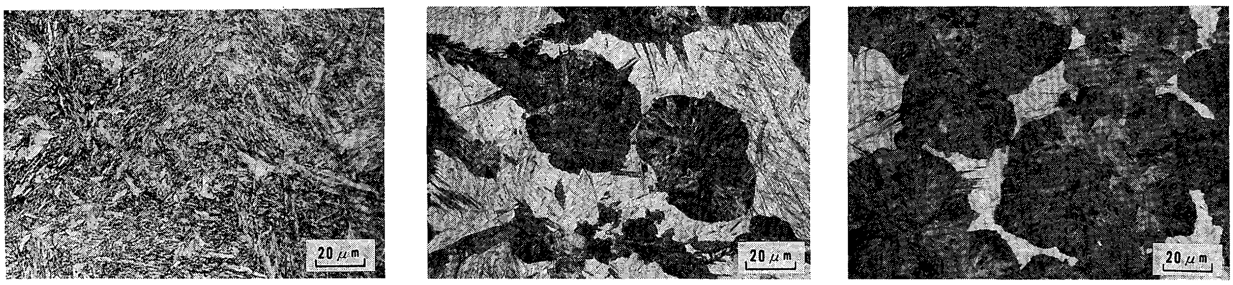


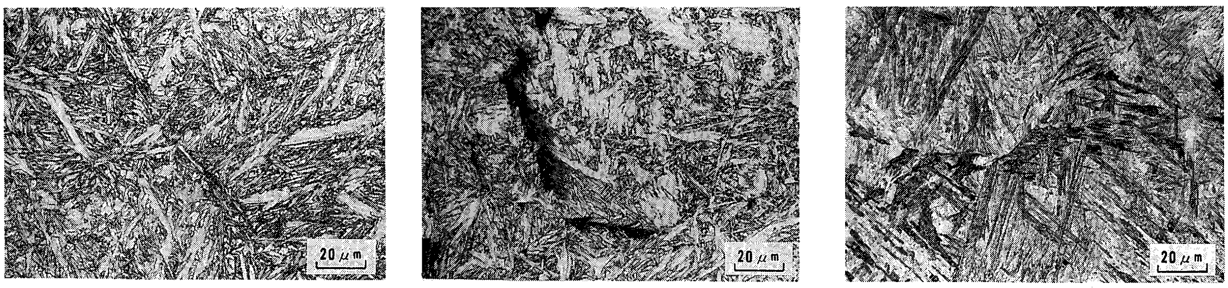
Fig. 4 SEMmicrostructure of bainite of SNCM447 under the cooling condition of Δt:9sec

slight decrease in cooling rate as shown in **Fig.5.** (iii)Group III, the steeis such as SK† and SUJ2 of high carbon low alloy steel. Both microstructures at Δt:3.5 and 6sec werelens martensite, and then bainite started to form at prior austenite grain boundary from about Δ t:9sec as shown in **Fig.6.** However, the rate of bainite formation was relatively much slower in comparison with the other groups. These microstructural changes in each group are normally dependent upon the characteristics of precipitation curves of bainite and troostite in C.C.T. diagram. However, the C.C.T diagrams for these steels were not



(a) Δt:3.5sec, M, Hv850 (b) Δt:4.5sec, M+B/T, Hv695 (c) Δt:6sec, M+B/T, Hv550

Fig. 5 Variation in microstructure of SK5 with increasing cooling time



(a) Δ t:3.5sec, M, Hv810 (b) Δ t:9sec, M+B, Hv740 (c) Δt:21sec, M+B, Hv535

Fig. 6 Variation in microstructure of SK3 with increasing cooling time

† SK3 is normally classified into one of high carbon steel, however, in this study, the contents of Mn and Cr in SK3 are a little higher than that of JIS specification.

prepared for the purpose of this study.

The hardness changes for each group under the various cooling conditions are summarised in **Fig.7.** The initial hardness of Group I is relatively lower than that of the other groups. Also, with decreasing cooling rate the hardness is slightly changed. In Group II, the initial hardness is as high as that of Gro III. However, the loss of hardness in Group II is significant while in Group III is a

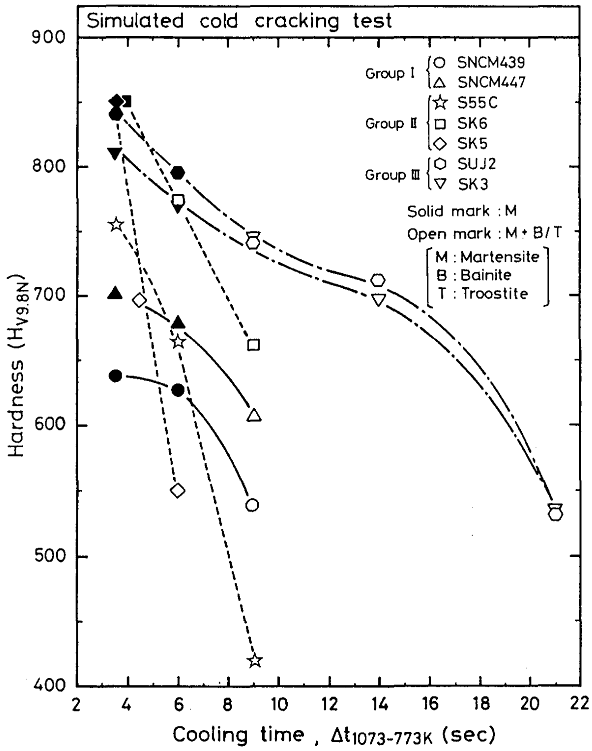


Fig. 7 Relationship between cooling time and hardness

little within Δt:14sec. These tendencies of the hardness change in each group correspond to those of the microstructural changes.

Figure 8 shows the changes of hardness, fracture stress and IG fraction in SNCM447 under the various cooling conditions as an example of Group I. The marks , andin Fig.8 symbolize fracture stress, the mean hardness(Hv) and IG fraction, respectively, while the microstructure represented by solid marks for martensite and open marks for bainite and/or troostite with martensite. From this figure, it is obvious that with decreasing the cooling rate the fracture stress is increased rapidly and TG fraction is also decreased rapidly, although the hardness is decreased a little. In particular, it was noted that the improvement of fracture stress can be achieved by increasing the cooling time from Δt:3.5 to 6sec with nearly same hardness. The IG fraction appeared to reach 0% at Δt:9sec which gived a little bainite. The effect of cooling time on the

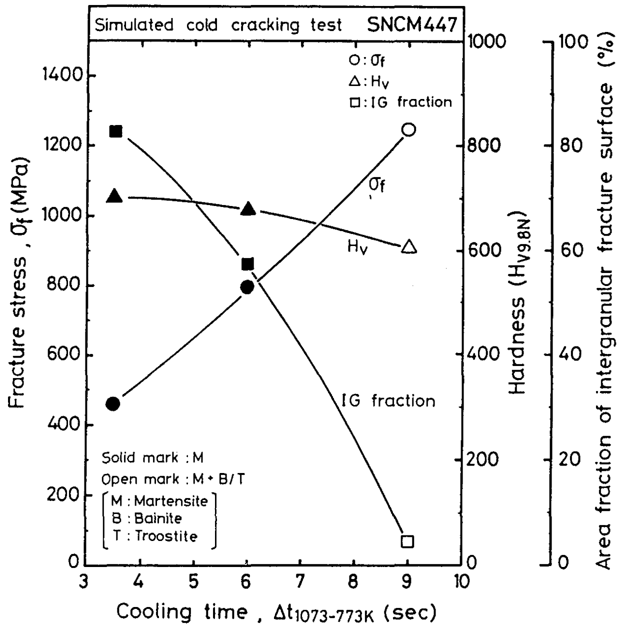
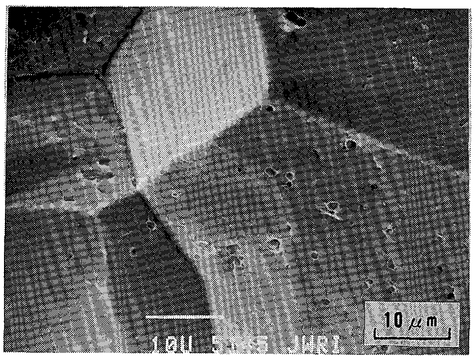


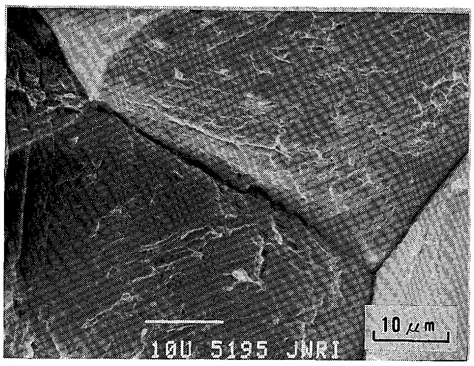
Fig. 8 Effect of cooling time on fracture stress, hardness and IG fraction in SNCM447

variation in the feature of IG fracture facet for SNCM447 is shown in **Fig.9.** The IG facet at Δt:3.5sec is very brittle, however, the traces of plastic deformation on IG facet at Δt:6sec are observed much more than at Δt:3.5sec. It is obvious that IG fracture tends to be suppressed by an increase in cooling time. First, it was thought that the improving effect of IG fracture may be attributed to the carbide precipitation at grain boundary. However, no carbide were observed by using SEM up to x30000 magnification with electrolytic etching crosssection of the specimen. Therefore, it was thought that the improvement of fracture stress and IG fraction is mainly caused by the changes of the phosphorus segregation to grain boundaries. The effect of grain boundary segregation of phosphorus on the quenching crack type cold cracking will be discussed in detail in another paper[5)]. SNCM439 showed the same behaviors in SNCM447. According to the resulte, it was suggested that this type of cold cracking in medium carbon low alloy steels can be prevented by relatively lower preheating temperatures causing no bainite, and this was confirmed by the y-slit cracking test in SNCM439[6)]. Besides, the phenomenon agrees with that[7)] reported for machine structural steel using electron beam welding.

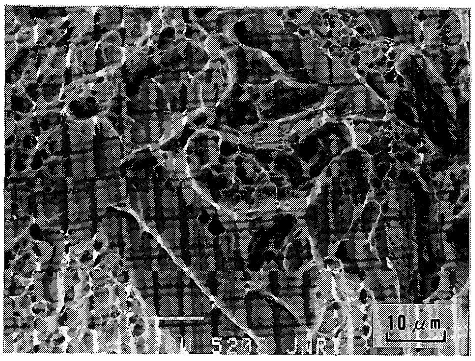
The results of SK5 are shown in **Fig.10,** as an example of Group II. The hardness is decreased largely with the rapid formation of troostite and bainite. The fracture stress is sharply increased and IG fraction is sharply decreased corresponding to to the hardness change. An example of fracture surface at Δt:4.5sec is shown in **Fig.11,** the transgranular part at the triple point corresponded to



(a) Δt:3.5sec



(b) Δt:6sec



(c) Δt:9sec

Fig. 9 Variation in SEM microfractograph of SNCM447 with increasing cooling time

the part of troostite. Therefore, it was found that troostite has an affect too retard the occurrencs of IG fracture.

The results of SK3, as an example of Group III, are shown in **Fig.12.** The hardness change from Δt:3.5 to 9sec has a similar tendency to that of SNCM447 showed in Fig.8. The improvement of IG fraction and fracture stress is a little within that cooling rate, and then the fracture stress tends to increase gradually with decreasing the hardness. The cleavage and quasi-cleavage fracture surfaces were increased with the improvement of the fracture

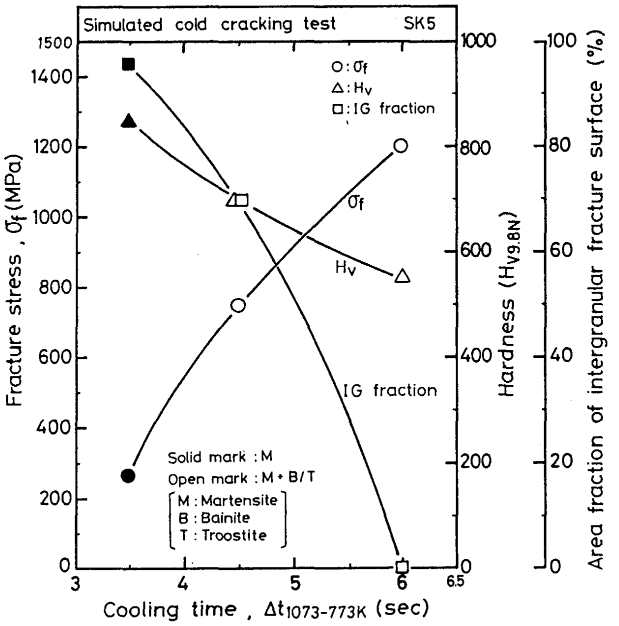


Fig. 10 Effect of cooling time on fracture stress, hardness and IG fraction in SK5

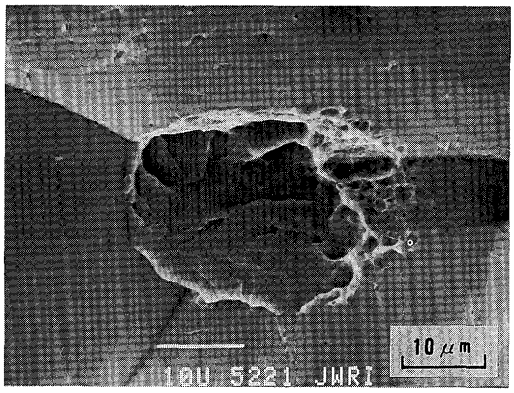


Fig. 11 SEM microfractograph of SK5 under the cooling condition of Δt:4.5sec

stress.

3.2 Correspondence of fracture stress and hardness with IG fraction

The relationship between fracture stress and IG fraction for all materials and the used cooling conditions is shown in **Fig.13,**where triangular and circular marks mean the results obtained under the cooling conditions of Δ t:3.5sec(partly 2sec) and Δ t:6-21sec (partly 4.5sec), respectively. The fracture stress and IG fraction have an excellent correlation regardless of the cooling rates, except IG fraction giving about 0%. Therefore, in the case of the various cooling conditions, it was found that the susceptibility to this type of cold cracking can be evaluated with not only IG fraction but also fracture stress. The reason why the scatter of fracture stress is large near IG fraction

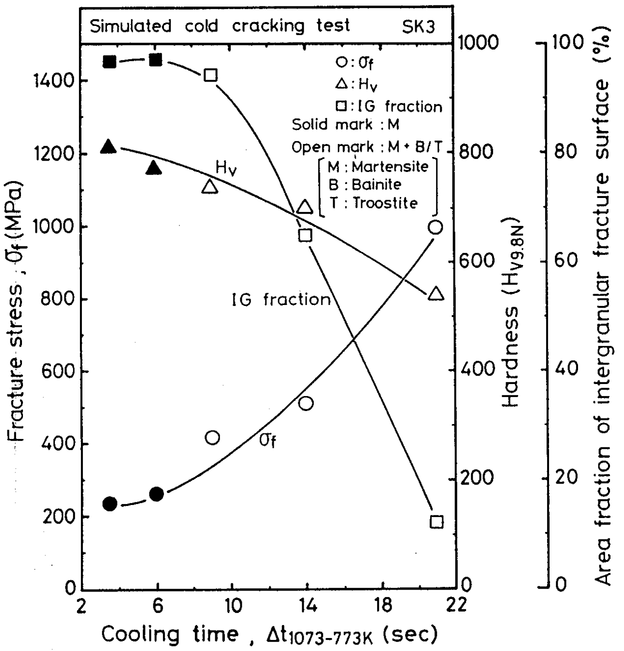


Fig. 12 Effect of cooling time on fracture stress, hardness and IG fraction in SK5

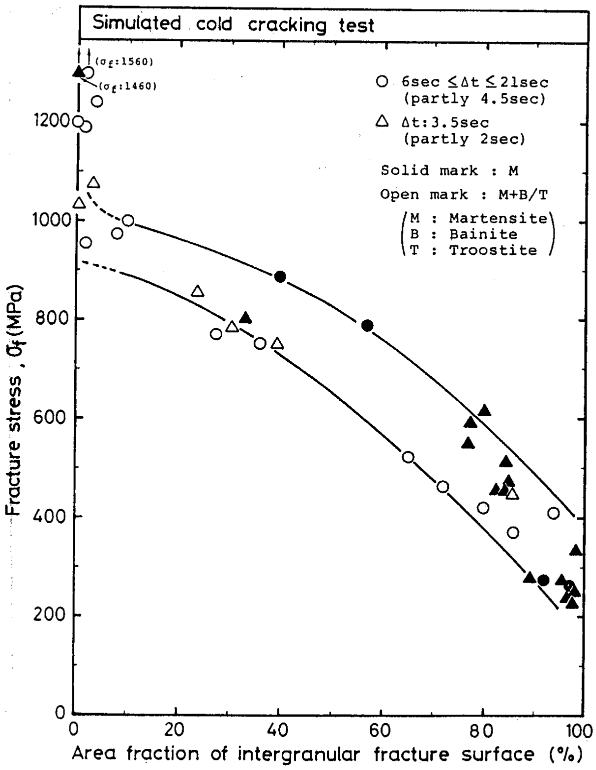


Fig. 13 Relationship between IG fraction and fracture stress

about 0% is dus to the difference of the fracture toughness in the matrix. The fracture stress is baout 900-1000MPa when IG fracture is not occurred.

Figpre 14 shows the relationship between hardness and IG fraction. The hardness and IG fraction have a good correlation. IG fraction at hardness higher than Hv700 gives more than 80%, even bainite and/or trostcte may be formed. The hardness which gives little IG fracture surface is less than about Hv600. However, within Hv600 to 700, it was noted that the IG fraction is largely influenced by cooling rate, i.e., the IG fraction is fairly low at lower cooling rate, although the hardness is nearly the same compared with that of the higher cooling rate. This is due to the fact that IG fracture was suppressed with increasing the cooling time in spite of nearly the same hardness as mentioned in Fig.8. Therefore, within the range of Hv600 to 700, the evaluation of the crack susceptibility by hardness is liable to produce large errors. This will be represented in more detail in section 3.3.

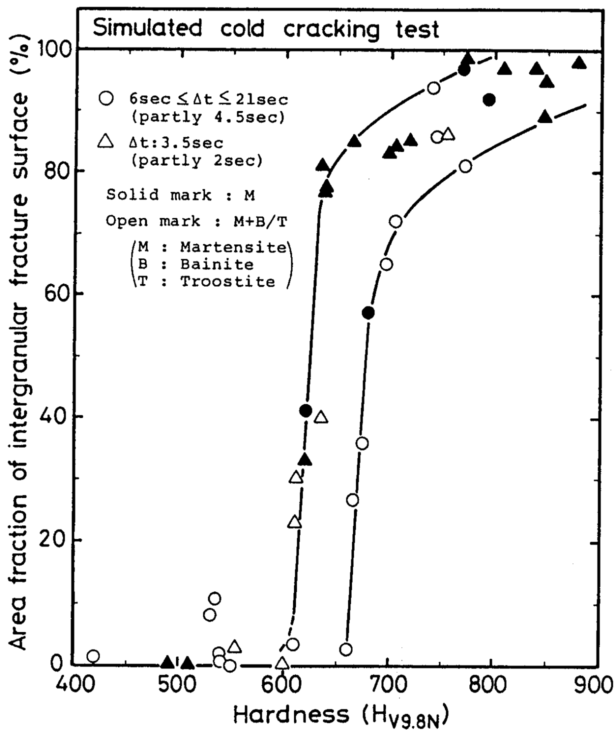


Fig. 14 Relationship between hardness and IG fraction

The hardness illustrated in Fig.14. is the mean hardness in matrix. In addition, the various factors, namely, the maximum and minimum hardness in matrix, the possession of bainite and/or troostite along prior austenite grain boundaries and so on were also taken into consideration for the correlation with fracture stress and IG fraction. However, none of them were more satisfactable in comparison with the case of the mean hardness. This reveals that the stress concentration at grain boundaries mainly depends on the mean hardness in matrix.

3.3 Correlation with hardness and fracture stress, and suggestion of the crack free condition

According to the results in the above section 3.2, it was seen that the susceptibility to quenching crack type cold cracking can be evaluated well with the relationship between IG fraction and fracture stress. The crack susceptibility can be also evaluated with hardness but, in this case, the scatter will be large in the hardness range of Hv600 to 700. However, with respect to the welding fabrication, hardness is obviously desirable method for evaluating the crack susceptibility. Also, fracture stress can be oboained more easily than IG fraction. Therefore, the relationship between hardness and fracture stress was examined, and then the cold cracking susceptibility of quenching crack type and the crack free condition have been discussed on the basis of the experimental results.

Figure 15 shows the relationship between hardness and fracture stress for all the tested materials and cooling conditions. There is a good correlation betoween hardness and fracture stress. However, the scattering which surrounded by two solid lines in the range of Hv600 to 700 is somewhat wider than that above Hv700. This corresponds to the fact that IG fraction within Hv600 to 700 changes more largely by the effect of cooling rate as mentioned in Fig.14. The scattering range can be divided into two regions, i.e., the upper region of Δt:6 to 14sec and the lower region of Δt:2 to 3.5sec as illustrated in Fig.15. Noting that, the effect of cooling rate above Hv700 is little. The relationships between hardness and fracture stress in

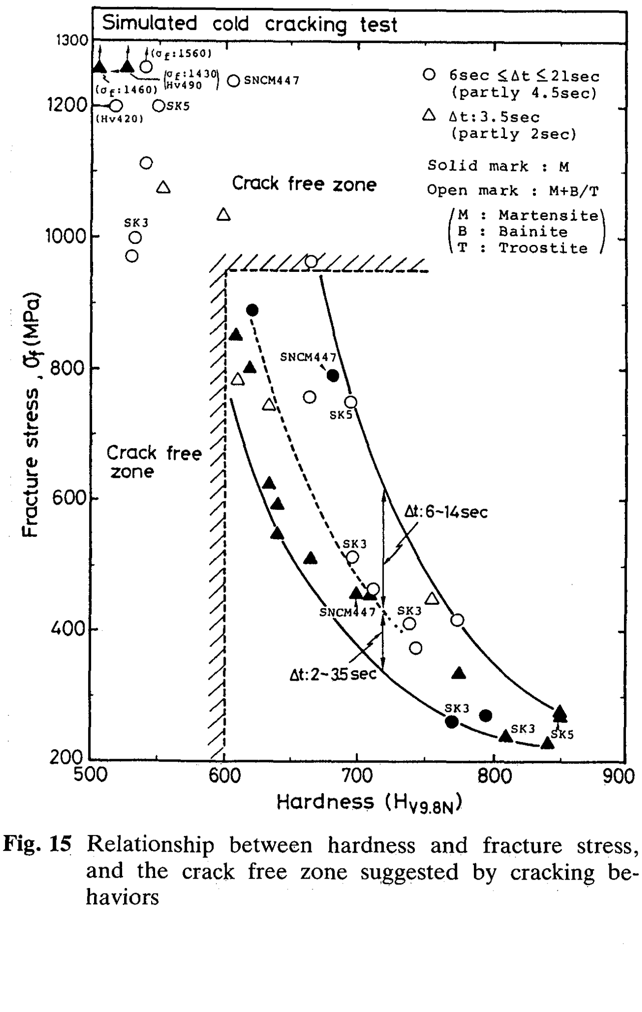


Fig. 15 Relationship between hardness and fracture stress, and the crack free zone suggested by cracking behaviors

SNCM447, SK5 and SK3 were also illustrated as an example of the Group I, II and III, respectively. The fracture stresses of SK5 and SK3 are gradully improved with decreasing the hardness. On the other hand, the fracture stress of SNCM447 increases largely with a decrease in cooling rate, although the loss of hardness is little.

The valuse of the hardness less than Hv600 and the fracture stress more than 950MPa were illustrated in Fig.14 as the crack free condition for the prevention of the quenching crack type cold cracking. The crack free conditions were based on the results of IG fracture which showed in Fig.13 and 14. Based on these results it is obvious that the fracture in the crack free zone was occurred in association with the fracture toughness in matrix, irrespective of a mechanism of the quenching crack type cold cracking.According to the welding conditions or pre- and postheating treatment which gives the maximum hardness in HAZ less than about Hv600 or the fracture stress more than about 950MPa, it was thought that the quenching crack type cold cracking is avoidable. Moreover, there is still a region giving the fracture stress more than 950MPa, even though, the hardness shows more than Hv600. This suggests that it was not necessary to reduce the hardness to less than Hv600 in certain steels. The validity of the critical conditions will be discussed in another paper[6] with the results of the y-slit cracking test.

4. Conclusions

The changes in hardness, fracture stress and intergranular fracture surface and their correlations were studied under the various cooling conditions by means of the simulated cold cracking test for fifteen kinds of commercial steels. Furthermore, the crack free conditions were proposed on the basis of the results. Main conclusions obtained as follows:

(1) The fracture stress has an excellent correlation with the area fraction of intergranular facture surface. The area fraction of intergranular fracture surface. The fracture stress which gives little intergranular fracture surface is more than about 950MPa.

(2) The hardness has a good correlation with the area fraction of intergranular fracture surface, too. The hardness which gives little intergranular fracture surface is less than about Hv600. However, the fraction of intergranular fracture within Hv600 to 700 is largely influenced by cooling rate, i.e., the fraction of intergranular fracture is fairly low at lower cooling rate, although the hardness is nearly the same compared with the higher cooling rate.

(3) There is a good correlation between hardness and fracture stress. However, in the range of the hardness

Hv600 to 700, the fracture stress at lower cooling rate is much higher in represented in the above section.

(4) On the basis of the results represented in (1), (2) and (3), by adoption of the materials or the welding conditions incorporated with adequate pre-and postheating which gives the mximum hardness in HAZ less than about Hv600 or the fracture stress more than about 950MPa, it was thought that guenching crack type cold cracking is avoidable.

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