The University of Osaka
Institutional Knowledge Archive

Title	Effect of Hydrogen Content on Cold Crack Susceptibility of Various Steels with the Implant Test
Author(s)	Matsuda, Fukuhisa; Nakagawa, Hiroji; Tsuji, Tatsuo et al.
Citation	Transactions of JWRI. 1978, 7(2), p. 195-201
Version Type	VoR
URL	https://doi.org/10.18910/10270
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

The University of Osaka

Effect of Hydrogen Content on Cold Crack Susceptibility of Various Steels with the Implant Test†

Fukuhisa MATSUDA*, Hiroji NAKAGAWA**, Tatsuo TSUJI***
and Muneyasu TSUKAMOTO***

Abstract

Susceptibilities of various plain carbon steels and alloy steels to cold crack are estimated by the implant test. Furthermore, fractographic investigation is also made on fracture surfaces obtained by the implant test. Main conclusions are as follows: (1) Increase in applied stress decreases an area of intergranular fracture mode in HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels. (2) In weldable high strength and low carbon alloy steels nearly linear relations between lower critical stress and maximum hardness of HAZ are obtained in each hydrogen content but results are rather scattering. (3) Being estimated by an "embrittlement index I" (I = NTS-LCS/NTS), susceptibility of alloy steels to cold crack is increased according to a following order; 3.5% Ni < SM50 < 9% Ni < 2¼Cr-1Mo < 1¼Cr-½Mo < HT80 < HY130 < SCM4 ≒ SNCM8 steel. (4) Based on results in this study, the authors propose a following formula for a estimation of lower critical stress affected by hydrogen embrittlement in weldable high strength steels such as SM50, HT60, HT80 and HY130 and low carbon alloy steels such as 3.5% Ni, 9% Ni, 1¼Cr-½Mo and 2¼Cr-1Mo steels, which is determined by a regression analysis.

$$\sigma_{cr} = -268\,P_{CM} - 23.3 \log H_{JIS} + 138 \qquad \textit{(heat input ; 17 kJ/cm, without preheating)}$$

1. Introduction

In the previous report[1] the implant cracking test was applied to investigate the susceptibility to cold crack of various carbon steels, various weldable high strength steels, medium and high carbon low alloy steels, varying the diffusible hydrogen content and the applied stress. The lower critical stress and the fractograph with a SEM (scanning electron microscope) which were obtained by the implant test were investigated. As the result, it became clear that the quenching crack was one of the important factors of cold crack in plain carbon steels whose carbon content was more than about 0.50% and in medium and high carbon low alloy steels.

In this report the implant cracking test has been continuously applied to investigate the susceptibility to cold crack of 3.5% Ni, 9% Ni, HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels in addition to the materials used in the previous report[1], varying the diffusible hydrogen content and the applied stress. Then, from the results of these two researches the susceptibility of cold crack and the morphology of fracture surface of the steels used have been generally investigated.

On the other hand, the formulas[2),3)] which are able to estimate the lower critical stress in the implant test have been reported so far. Then, it has been investigated if the results of this study can be applied to the formulas. As a result, it has become clear that the lower critical stress in various weldable high strength steels and various low carbon alloy steels are also estimated by the formula as a function of P_{CM} value. However, the results of measurement didn't entirely correspond to those calculations using the formulas. It was considered that the reason was mainly due to the difference in the notch radius between this study and the other studies.

Then, based on this test results, the authors proposed a new formula determined by the regression analysis.

2. Experimental Procedures

The chemical compositions of the additional materials to the previous study are shown in **Table 1**. The other materials and the electrodes used were described in the previous report[1]. In order to apply the formulas which have been reported for the lower critical stress in the implant test, the diffusible hydrogen contents by IIW method in Table 2 of the previous report[1] were measured by JIS method (using a glycerin as a confining liquid), which were 1.1, 2.7, 10.1 and 28.5 ml/100g of deposited metal, respectively.

The conditions of the implant cracking test were also described in the previous report[1].

† Received on October 28th, 1978
* Professor
** Research Instructor
*** Sumikin Welding Electrode Co., Ltd.

Table 1 Chemical compositions of additional materials

Steel	Chemical composition (wt.%)										Ceq*	P_{CM}**
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V		
3.5% Ni	0.08	0.25	0.61	0.008	0.009	0.23	3.49	0.14	0.01	—	0.31	0.196
9% Ni	0.04	0.23	0.55	0.008	0.007	0.03	8.76	0.04	0.01	—	0.37	0.225
HY130	0.11	0.31	0.84	0.004	0.009	0.04	4.93	0.50	0.46	0.06	0.61	0.308
1¼Cr-½Mo	0.15	0.60	0.55	0.010	0.003	0.01	0.03	1.38	0.55	—	0.68	0.304
2¼Cr-1Mo	0.08	0.23	0.50	0.009	0.004	0.03	0.15	2.25	0.96	—	0.87	0.293

*$Ceq = C + 1/6Mn + 1/24Si + 1/40Ni + 1/5Cr + 1/4Mo + 1/14V$

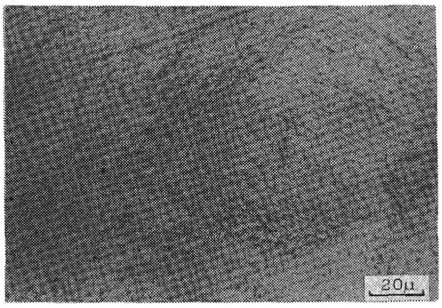
**$P_{CM} = C + 1/30Si + 1/20Mn + 1/20Cu + 1/60Ni + 1/20Cr + 1/15Mo + 1/10V + 5B$

3. Experimental Results

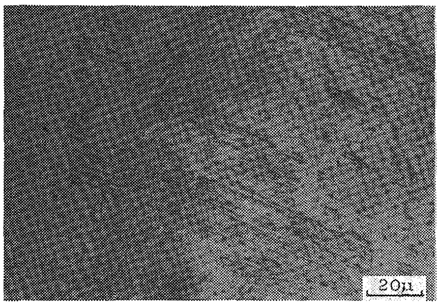
3.1 Microstructure of Heat-Affected Zone

Typical microstructures of heat-affected zone near the fusion boundaries in 3.5% Ni, 9% Ni, HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels are shown in **Fig. 1 (a), (b), (c), (d)** and **(e)**, respectively, as observed under a light microscope.

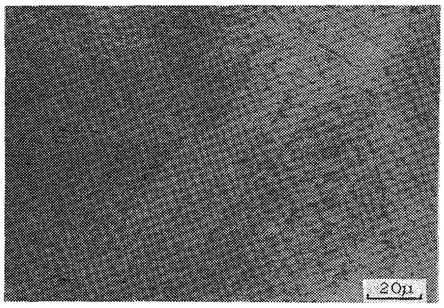
The microstructure of 3.5% Ni steel, Fig. 1 (a) was composed of sporadic ferrite and upper-bainite formed at grain boundaries of the prior austenite. On the other hand, the microstructures of the other steels were not composed of sporadic ferrite and upper-bainite formed at the grain boundaries of the prior austenite but mainly composed of lath-like martensite.



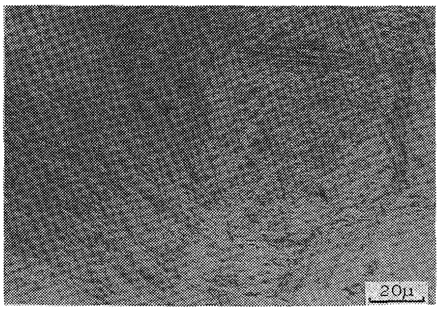
(a) 3.5% Ni



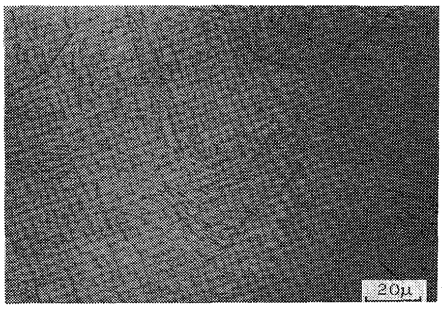
(b) 9% Ni



(c) HY130



(d) 1¼Cr-½Mo



(e) 2¼Cr-1Mo

Fig. 1 Microstructures of heat-affected zone, etchant; saturated aqueous picric acid with wetting agent

3.2 Fractography

In the previous report[1)], since the area of intergranular fracture in HT80 steel was very small, its dependence of the applied stress was not obvious. However, the area of intergranular fracture in HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels which were examined in this report was large and their dependences of the applied stress were obviously observed. For an example, the macrofractographs and their sketches in 2¼Cr-1Mo steel with the hydrogen content of 5.7 ml/100g (IIW method) are shown in **Fig. 2.** In the case of the high applied stress as 77.1 kg/mm^2 the

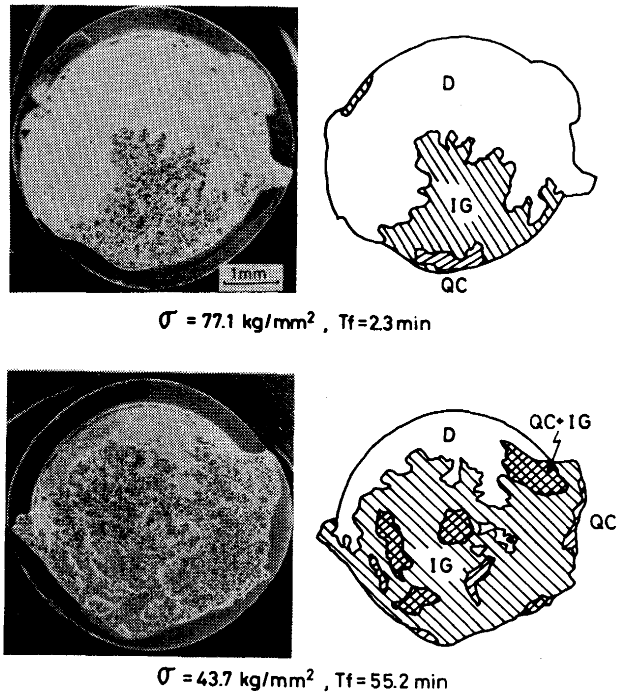


Fig. 2 Variation of macrofractograph of 2¼Cr-1Mo with decreasing applied stress, diffusible hydrogen content; 5.7 ml/100g in IIW method.

area of the intergranular fracture was not so large, and the area of the dimple fracture was large. On the other hand, in the case of the low applied stress as 43.7 kg/mm² the area of the intergranular fracture was large, and the area of the dimple fracture was small.

The relations between the applied stress and the area fraction of the intergranular fracture in the typical steels which are observed in the hydrogen content of 5.7

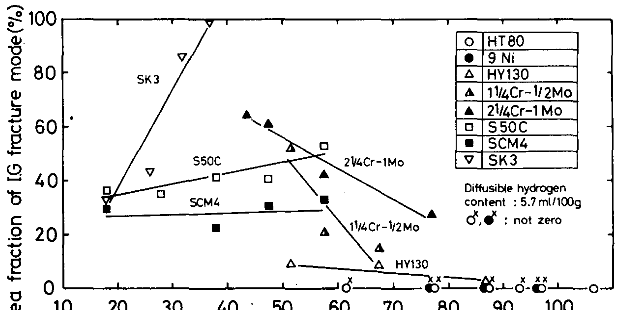


Fig. 3 Area fraction of intergranular fracture vs. applied stress in 9% Ni, HT80, HY130, 1¼Cr-½Mo, 2¼Cr-1Mo, SCM4, S50C and SK3, diffusible hydrogen; 5.7 ml/100g in IIW method.

ml/100g (IIW) is shown in **Fig. 3**. Considering the results of Fig. 3, the relation between the applied stress and the area fraction of the intergranular fracture can be classified into 3 types. In one of these three types the dependence of the applied stress is not obvious because the area of the intergranular fracture are very small, such as in HT80 and 9% Ni steels. The second type shows that the area of the intergranular fracture is decreased with the increase in the applied stress, such as in HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels. The last type shows that the area of the intergranular fracture is increased with the increase in the applied stress, such as in S50C and SK3. In SCM4 the dependence is not obvious.

About the first two types it is well considered that the cracks are caused by hydrogen-induced delayed crack. On the other hand about the last type, as described in the previous report[1)], it is considered that the cracks may be dominated with the quenching crack in high applied stress.

Considering both the microstructures and the maximum hardness of HAZ in the steels which are dominated with hydrogen-induced delayed crack, it is supposed that the intergranular fractures easily occur in the steels in which the prior austenitic grain boundaries are clearly observed and the maximum hardness of HAZ is more than about 350 in Hv.

3.3 Lower Critical Stress

The relations between the lower critical stress and the maximum hardness of HAZ in all materials used are shown in **Fig. 4**. In both the plain carbon steels and the alloy steels, the lower critical stress are decreased with the increase in the maximum hardness of HAZ. However, the degree of the decrease in the lower critical stress is considerably different from each other and the lower critical stress in the plain carbon steels usually shows the higher value at the same hardness compared to those in alloy steels. This reason is considered that the microstructures in the plain carbon steels are easily composed of proeutectoid ferrite and/or troostite along the grain boundaries of the prior austenite and are difficult to be transformed to uniform martensite since the susceptibility of quenching is worse than that in alloy steels. That is, it is considered that the lower critical stress in the plain carbon steels is higher than those in the alloy steels since the microstructures in the plain carbon steels are mixed with the martensite of higher susceptibility to hydrogen-induced crack in the midst of the prior austenitic grains and the ferrite and/or troostite of lower susceptibility along the grain boundaries. Consequently the susceptiblity to hydrogen-induced crack in the steels may be affected by the microstructure along the grain boundaries.

Considering the results from 3.5% Ni to 1¼Cr-½Mo steels as shown in Fig. 4, the linear relations between the lower critical stress and the maximum hardness of HAZ are nearly obtained in each hydrogen content but the results are rather scattering.

The relations between the lower critical stress and the logarithm of the IIW hydrogen content are shown in

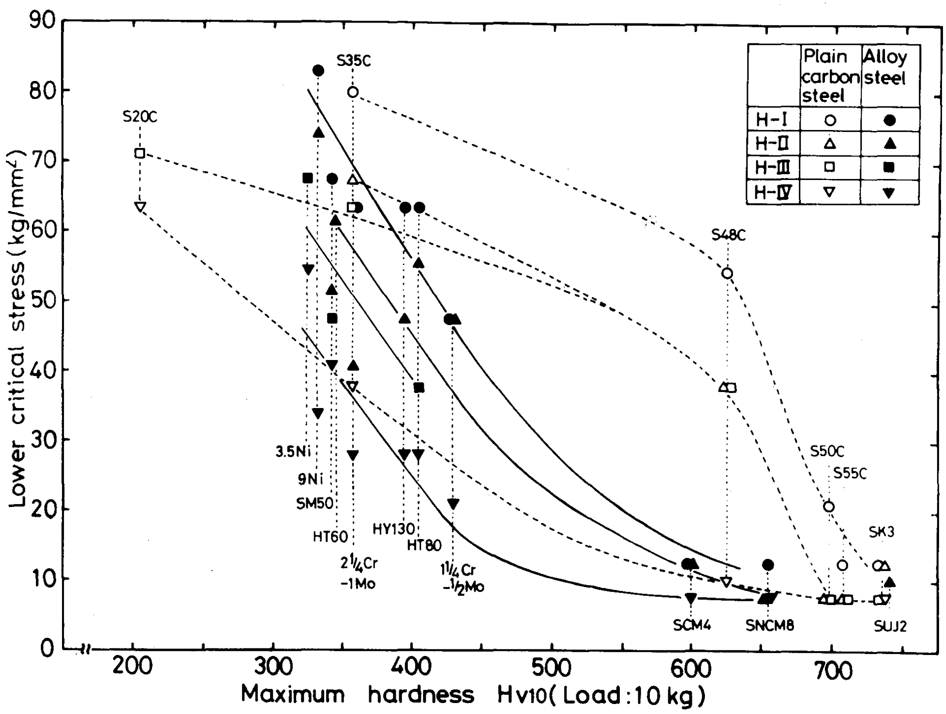
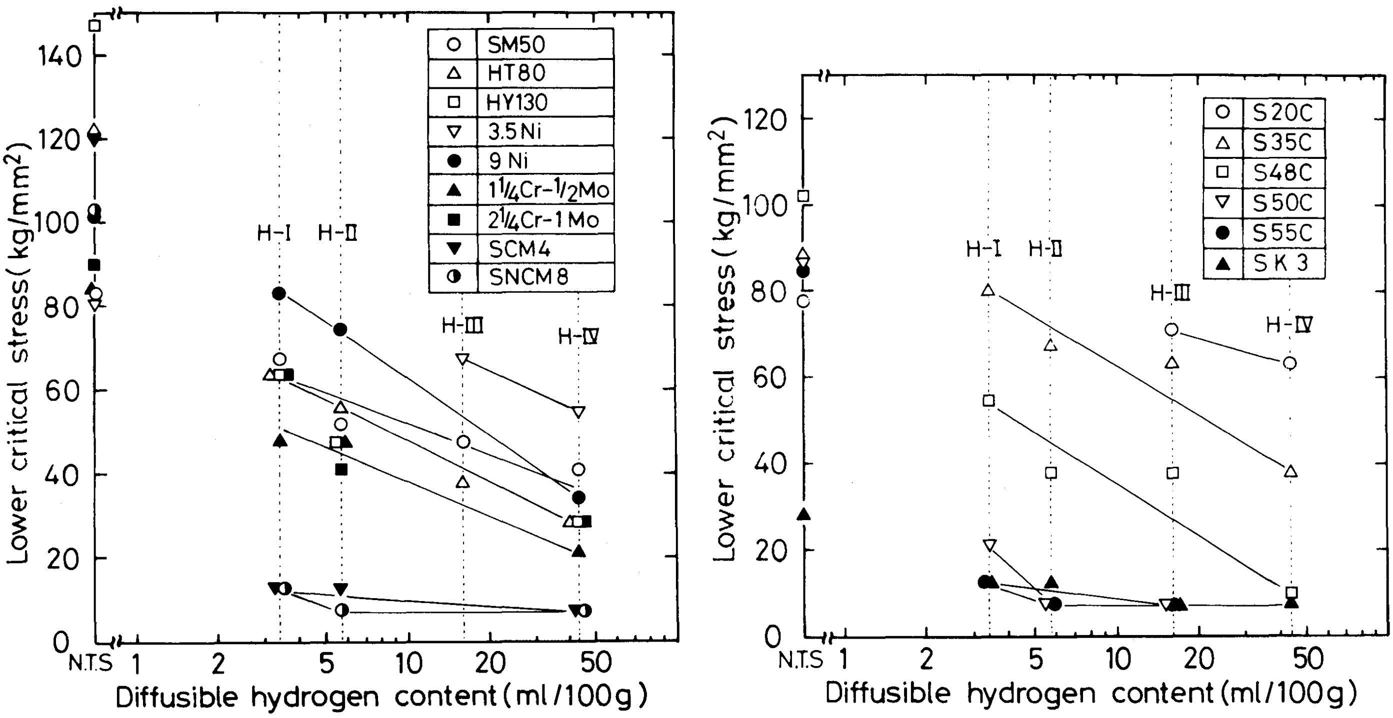


Fig. 4 Relation between maximum hardness of HAZ and lower critical stress

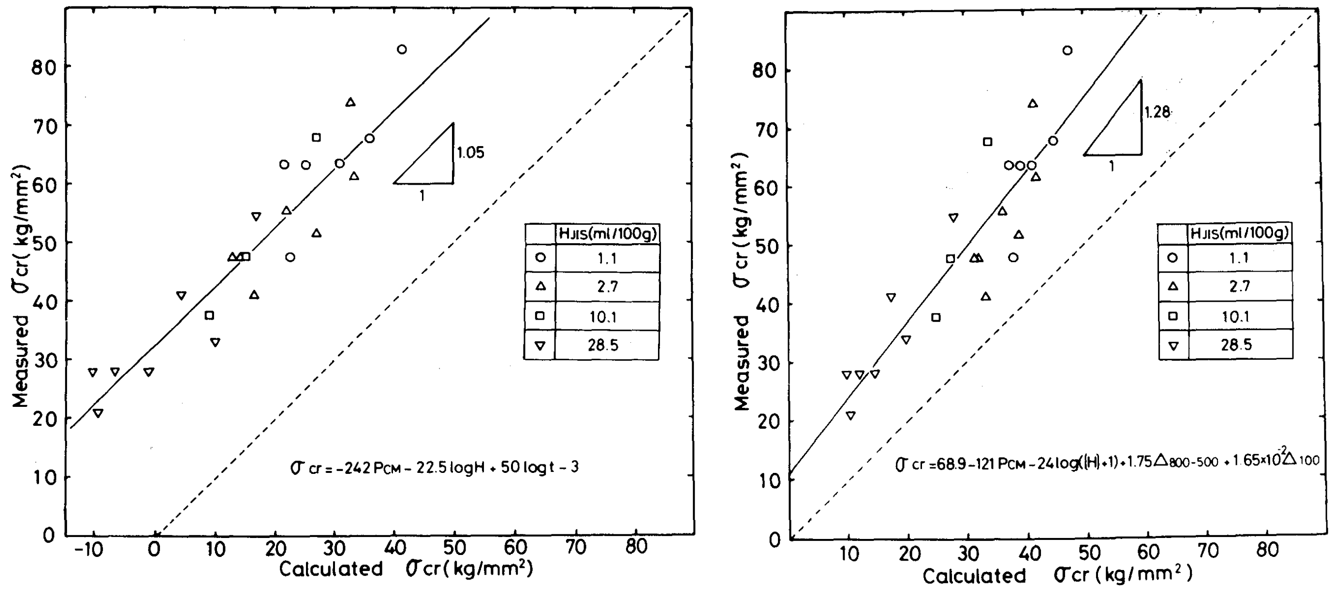


(a) Alloy steels

(b) Plain carbon steels

Fig. 5 Relation between logarithm of IIW hydrogen content and lower critical stress

Fig. 5 (a), where the results of the alloy steels are presented, and in **Fig. 5 (b)** where those of the plain carbon steels are presented. Furthermore, the notch tensile strength (NTS), which is fractured at 1 week or more after the welding and consequently is considered to be the strength of the hydrogen free condition is shown in Fig. 5 (a) and (b). The lower critical stress in the alloy steels except SCM4 and SNCM8 steels and the plain



(a) Result in application of formula by Y. Ito et al. (b) Result in application of formula by M. Inagaki et al.

Fig. 6 Relation between calculated values and measured values

carbon steels except S50C, S55C and SK3 are linearly decreased with the increase in the hydrogen content in logarithmic scale. On the other hand, the lower critical stress in SCM4, SNCM8, S50C, S55C and SK3 are almost constant and also very low. Judging from this behavior and the feature of the fracture surfaces shown in Fig. 3, it is considered that the quenching crack may act to these steels.

Considering the susceptibility of the materials used to cold crack, it is obvious that the susceptibility to cold crack in the plain carbon steels are increased with the increase of the carbon content, as shown in Fig. 5 (b). On the other hand, it is difficult to estimate the susceptibility of the alloy steels to cold crack by means of the lower critical stress, since the tensile strength in hydrogen free condition and the chemical compositions are different from each other.

An "embrittlement index I" which has been proposed by T. Boniszewski et al[4)] is calculated from the relation;

I = (NTS - LCS)/NTS.

where NTS ; notch tensile strength in hydrogen free condition

LCS ; lower critical stress for hydrogen charged condition.

Then, estimating the susceptibility of the alloy steels to cold crack by means of the index I, the results of the susceptibility are increased according to the following order;

3.5% Ni < SM50 < 9% Ni < 2¼Cr-1Mo < 1¼Cr-½MO < HT80 < HY130 < SCM4 ≑ SNCM8 steel.

3.4 Application of the Formulas to the Lower Critical Stress

The formulas which are able to estimate the lower critical stress of the implant test have been proposed so far[2,3)]. The lower critical stress is expressed in the formulas as functions of P_{CM} value, diffusible hydrogen content, cooling time from 800 to 100°C (or from peak temperature to 100°C) and cooling time from 800 to 500°C. However, since the formulas are proposed to apply to the weldable high strength steels, there are few applications to the low carbon alloy steels such as 3.5% Ni, 9% Ni and 2¼Cr-1Mo steels and so on. Then, it has been investigated if the results for the weldable high strength steels and the low carbon alloy steels in this study can be applied to the formulas proposed.

Figure 6 (a) shows the result of application to the formula by Y. Ito et al, and **Figure 6 (b)** shows the result by M. Inagaki et al. The welding condition in this study was 17 kJ/cm of heat input without preheating. Then the cooling time from 800 to 500°C measured was about 6 seconds and the cooling time from 800 to 100°C about 100 seconds. In this study the cooling time from 800 to 100°C and from peak temperature to 100°C were considered as the same.

In both cases the results of measurement are higher than those of calculation, as shown in Fig. 6 (a) and (b). It is considered that the reason was mainly estimated due to the difference in the notch radius of the specimen between this study and other studies. However, since the results of measurement aren't entirely proportional to those of calculation but the linear correlation between the measurement and the calculation is almost obtained, it is suggested that the results of this study can be estimated by a formula as functions of P_{CM} value and diffusible hydrogen content.

Then, based on these test resuts, the authors propose the following formula for the weldable high strength steels and the low carbon alloy steels as SM50, HT60, HT80, HY130, 3.5% Ni, 9% Ni, 1¼Cr-½Mo and 2¼Cr-1Mo steels, which was determined by the regression analysis.

$$\sigma_{cr} = -268\, P_{CM} - 23.3 \log H_{JIS} + 138$$

where σ_{cr} (kg/mm^2) ; lower critical stress in the implant test

P_{CM} (%) ; chemical composition for cold crack susceptibility of steel in $0.196 \leqq P_{CM} \leqq 0.308$, where

$$P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Cr/20 + Ni/60 + Mo/15 + V/10 + 5B$$

H_{JIS} (ml/100g); diffusible hydrogen content (JIS method) in $1.1 \leqq H_{JIS} \leqq 28.5$

The results which are calculated by using the above exprimental formula are shown in **Fig. 7**, where a good correlation between the results of the measurement and the calculation is observed.

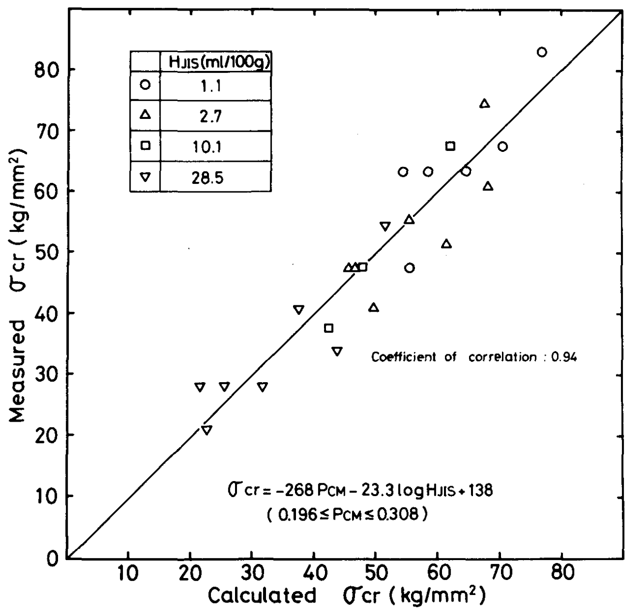


Fig. 7 Relation between calculated values by formula in this study and measured values

4. Conclusions

The susceptibility of various plain carbon steels and alloy steels to cold crack are estimated by the implant test. Furthermore, fractographic investigation is also made on the fracture surface obtained by the implant test. Main conclusions are as follows:

(1) The relation between the applied stress and the area fraction of the intergranular fracture can be classified into 3 types.

(a) One of these does not show the dependence of the applied stress because the area of the intergranular fracture are very restricted, in which HT80 and 9% Ni steels are contained. (b) The second type shows that the area of the intergranular fracture is decreased with the increase in the applied stress, in which HY130, 1¼Cr-½Mo and 2¼Cr-1Mo steels are contained. (c) The last shows that the area of the intergranular fracture is increased with the increase in the applied stress, in which S50C and SK3 steels are contained.

In the first two types the cracks are considered to be caused by hydrogen-induced delayed crack. On the other hand, in the last type it is considered that the crack may be dominated with the quenching crack in high applied stress.

(2) In the weldable high strength and the low carbon alloy steels the linear relations between the lower critical stress and the maximum hardness of HAZ are nearly obtained in each hydrogen content but the results are rather scattering.

(3) Being estimated by the embrittlement index I (NTS-LCS/NTS), the susceptibility of the alloy steels to cold crack is increased according to the following order; 3.5% Ni < SM50 < 9% Ni < 2¼Cr-1Mo < 1¼Cr-½Mo < HT80 < HY130 < SCM4 ≒ SNCM8 steels.

(4) Based on the results in this study, the authors proposed the following formula for the estimation of the lower critical stress affected by hydrogen embrittlement in the weldable high strength steels such as SM50, HT60, HT80 and HY130 and the low carbon alloy steels such as 3.5% Ni, 9% Ni, 1¼Cr-½Mo and 2¼Cr-1Mo, which was determined by the regression analysis.

$$\sigma_{cr} = -268\, P_{CM} - 23.3 \log H_{JIS} + 138$$

(heat input ; 17 kJ/cm, without preheating)

A good correlation between the exprimental and the estimated values was obtained.

References

1) F. Matsuda, H. Nakagawa, T. Tsuji and M. Tsukamoto : "Fractography of Cold Crack of Various Carbon Steels and Alloy Steels by Means of the Implant Test", Trans. JWRI, Vol. 7 (1978), No. 1 pp.71-85.
2) Y. Ito, M. Ikeda and M. Nakanishi : "Study on Estimation of Lower Critical Stress for Cold Cracking at Welds by Implant Test Method", J. Japan Weld. Soc., Vol. 45 (1976), pp.1029-1036, (in Japanese).
3) M. Inagaki, K. Satoh, S. Matsui and Y. Ohkuma : "Application of Implant Test on Cold Cracking", Preprints of the Third

International Symposium of JWS, 1978, pp.379-384.
4) T. Boniszewski, F. Watkinson, R. G. Baker and H. F. Tremlett: "Hydrogen Embrittlement and Heat Affected Zone Cracking in Low-Carbon Alloy Steels with Acicular Microstructure", Brit. Weld. J., Vol. 12 (1965), pp.14-36.