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Original Paper

A Study of the Cold Cracking of Carbon Steels

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The cold cracking of some carbon steels was examined with the implant testing method. Materials used were two types of commercial carbon steels, S45C and S55C. The cold cracking susceptibilities were evaluated by the critical stress of the implant test. The conclusions were as follows. 1) The preheating decreased the cold cracking susceptibility, and when the preheating temperature exceeded 200°C, the cracking didn't occur. Under this condition, martensite was not observed in the heat affected zone. 2) To dry the electrode is effective in the case with the preheating, compared with no preheating. It is desired that the welding is carried out using dried electrode with the preheating. 3) The blowholes were scarcely occured when the preheating is not employed. When the preheating temperature exceeded 300°C, however the blowholes were remarkably increased.

1. Introduction

The carbon steels have widely used because of their lower cost for the machine parts, such as shafts, cranks, nuts and bolts. These parts have been usually joined together by the mechanical joining processes, such as bolts and nuts. Some parts are however required to be joined by the welding process from the point of view of the productivity. But the carbon steels have the poor weldabilities. That is, martensite of hard and low ductility is produced in the heat affected zone of their steels during the welding. It causes the cold cracking together with the hydrogen and the welding residual stress are coexisted in the heat affected zone. Because of the above reason high carbon content is undesirable for the welding.

Following three factors affect the cold cracking susceptibility.

1) microstructure of the heat affected zone

2) hydrogen content in the weld

3) welding residual stress

Microstructure of the heat affected zone is dependent on the chemical compositions of the steel plate and the cooling rate of the heat affected zone. The cooling rate is decreased by the preheating and the slow cooling rate avoids the formation of martensite. The slow cooling rate is also desirable to remove the diffusible hydrogen from the weld.

It is also desired that electrodes are dried to decrease the hydrogen content in the weld. And the preheating helps for the hydrogen to diffuse from the weld.

The welding residual stress is dependent on the dimentions of the welding joint and the welding procedure. The welding design should be considered so that the welding residual stress is decreased.

A reasonable method has been required to determine the welding conditions for welding the carbon steels without the cold cracking. So in this paper, the implant testing method, which is possible to control the welding residual stress, was introduced to determine the suitable preheating temperature for carbon steels of 0.45 to 0.55% carbon. The influence of electrode types was also investigated.

While it was reported that the blowholes were produced during the welding high carbon steels with the preheating. The examination of the blowholes was added.

2. Materials and implant test specimens

Two types of the carbon steels, S45C and S55C were examined. Their chemical compositions and mechanical properties were tabulated in Table 1 and Table 2 respectively.

The shapes of the implant test specimens were shown in Fig.1. The distance from the implant head to the circumferential notch is 3 mm so that the notch portion is located in the grain growth region in the heat affected zone. The same materials were used both for the implants and the backing plates for each steel.

Table 1 Chemical compositions of carbon steels wt%

steel	C	Si	Mn	P	S
S45C	0.42-0.48	0.15-0.35	0.60-0.35	0.03	0.035
S55C	0.52-0.58	0.15-0.35	0.60-0.90	0.03	0.035

Table 2 Mechanical properties of carbon steels

steel	yield point (kg/mm^2)	tensile strength (kg/mm^2)	elongation (%)	reduction of area (%)
S45C	54.7	70.0	26.7	66.9
S55C	67.5	81.0	23.7	65.8

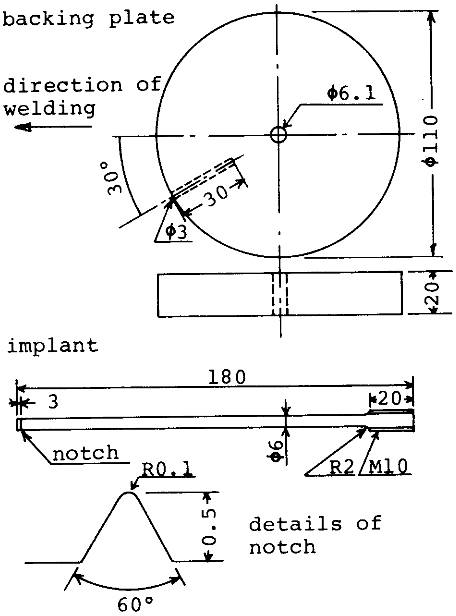


Fig.1 Shapes of implant and backing plate

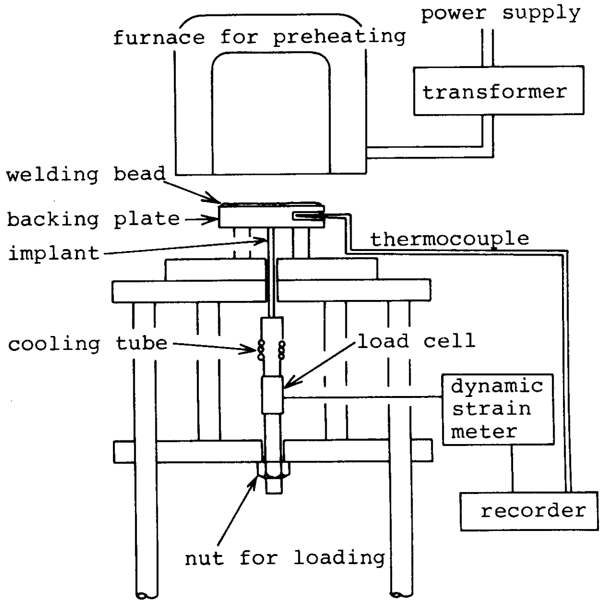


Fig.2 Apparatus for implant test

3. Apparatus for cold cracking test

Implant testing method was employed to examine the combined influences of preheating temperature, carbon content and diffusible hydrogen content on the cold cracking susceptibility. The implant testing machine was equipped with the furnace for preheating as shown in Fig.2.

Welding was carried out using D8016 and D5816 electrodes of low hydrogen types (4 mm in diameter). Welding current and arc voltage were 185 A and 25 V respectively, and the welding speed was 15 cm/min. The heat imput was about 18500 J/cm.

Preheating was carried out with following procedure. At first, the implant test specimens were heated above the desired preheating temperature by the furnace. When the furnace was turned off and the tempwrature of the backing plate fell down to the preheating temperature, welding was started. The temperature was measured by the thermocouple, which was inserted into the hole of the backing plate.

The desired stress was loaded at the time when the temperature of the heat affected zone fell down to 150°C. And the stress was held for 24 hours or nutill the implant was fractured.

The cold cracking susceptibility under some welding conditions was compared by the critical stress of the implant test. The critical stress is the critical value of the stress to cause the cold cracking.

4. Results of the implant test

The time-stress curves obtained by the implant test were shown in Fig.3 and Fig.4. The results in Fig.3 were obtained using D8016 electrode dried at 350°C for 1 hour (a and b) or in moistened condition (c and d). Moistened condition means that the electrode was exposed in air for 1 week after drying at 350°C for i hour.

When the welding was carried out without the preheating using the dried electrode, the critical stresses were 45 kg/mm² and 42 kg/mm² for S45C and S55C respectively (Fig.3-a). There was no difference in the incubation time between S45C and S55C. For S55C, the critical stress increased from 42 kg/mm² to 76 kg/mm² with the preheating at 100°C (Fig.3-a and b). When the preheating temperature exceeded 200°C, the implant was not fractured at any stress below the yield point of notched specimen of S55C. In this cases the critical stresses could not be determined because the implant was deformed during the stress loading. When the dried electrode was used, the fracture didn't occur in S45C weld with the preheating at 100°C.

Using the moistened electrode without preheating, there was 3 kg/mm² decrease in the critical stress for both steels compared with the case of the dried electrode (Fig.3-a and c). With the preheating at 100°C, the critical stress increased to 58 kg/mm² and 48 kg/mm² for S45C and S55C respectively, as

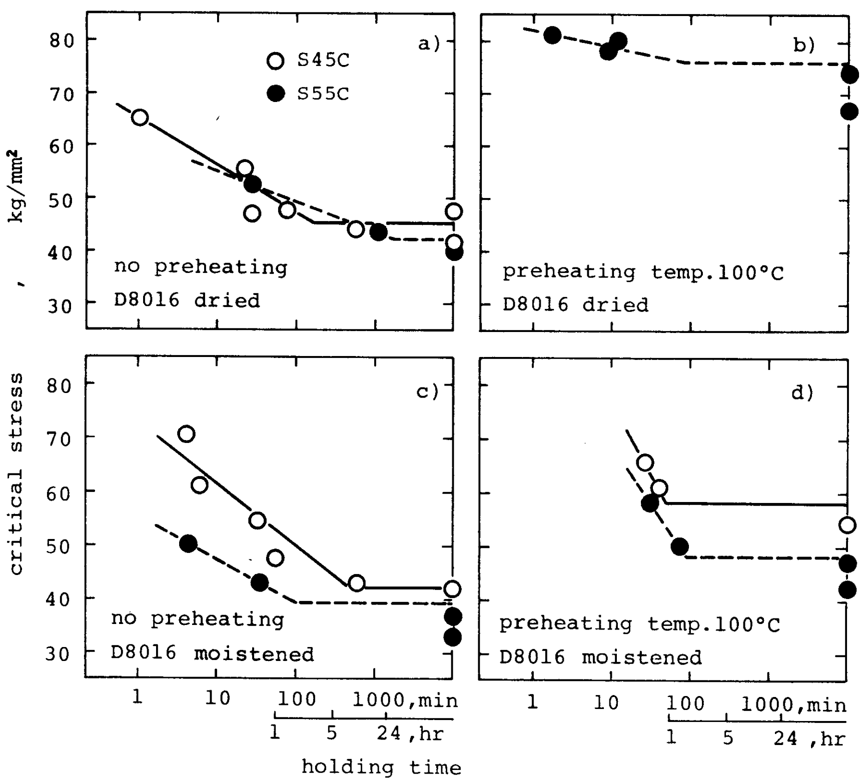


Fig. 3 Results of the implant test : electrode D8016

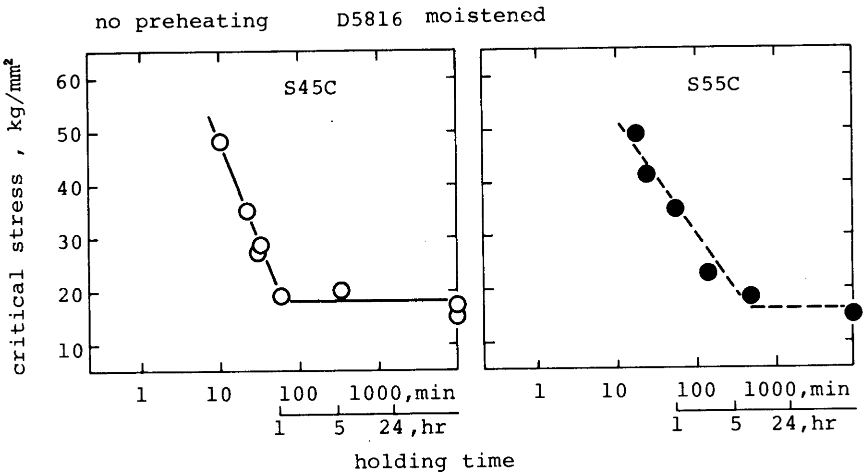


Fig. 4 Results of the implant test : electrode D5816

shown in Fig.3-d. When the preheating temperature exceeded 200°C, the fracture didn't occur for both steels.

Fig.4 shows the time-stress curves of the implant test using moistened D5816 electrode. Welding was carried out without the preheating. The critical stresses were 18 kg/mm^2 and 16 kg/mm^2 for S45C and S55C respectively. Theses critical stresses were extremely small as compared with that D8016 electrode was used. There was about 20 kg/mm^2 decrease in the critical stress between D8016 and D5816 electrodes. D8016 and D5816 electrodes are both low hydrogen type electrodes. However the weld of D5816 electrode has larger diffusible hydrogen content than that of D8016 electrode. It is considered that the difference in the diffusible hydrogen content caused the extreme decrease in the critical stress. The diffusible hydrogen will be considered later.

5. Measurement of the diffusible hydrogen content

The hydrogen content is the important factor affecting the cold cracking susceptibility. The diffusible hydrogen contents were measured for a ilmenite type electrode and three kinds of low hydrogen type electrodes by the glycerin hydrogen test (JIS Z 3113). The mild steel was used for the base metal. The welding condition was same as the implant test. The results were tabulated in Table 3. The testing was carried out using dried and moistened electrodes.

The ilmenite type electrode; D4301 has much diffusible hydrogen. There is 10 ml/100g decrease in diffusible hydrogen with drying at 100°C for 1 hour, however 40 ml/100g remains in the weld. The ilmenite type electrode is undesirable for welding the carbon steels, which renders the carbon steels high cold cracking susceptibility, even if the electrode is dried.

While, three low hydrogen type electrodes have very small hydrogen content under moistened condition, and this values are decreased to about 1/4 by drying at 350°C for 1 hour. The effect of the drying is remarkably, because in this case the drying temperature is higher than that in the ilmenite type electrode.

The low hydrogen type electrode should be used for welding the carbon steels. And from the point of view of the hydrogen content, D8016 electrode is most desirable among them.

Table 3 Results of the measurement of diffusible hydrogen content by the glycerin hydrogen test (JIS Z 3113)

electrode	condition	
	moistened	dried
D4301	50	40
D4316	9	2
D5816	5.5	2
D8016	4	1

unit; ml/100g deposited metal
drying; D4301 at 100°C for 1 hour
other electrodes at 350°C for 1 hour
note; the mean values of each 5 times

6. Influences of the factors on the critical stress of the cold cracking

1) The preheating temperature The influence of the preheating on the critical stress was shown in Fig.5. D8016 electrode was used to obtained the results of the figure. In all cases, the critical stresses increased with the increase of the preheating temperature. The preheating at 100°C is more effective in the case of the dried electrode compared with that of moistened electrode. Such the effect is more remarkable for S45C steel than S55C steel. The cold cracking was prevented by using the dried D8016 electrode and the preheating at 100°C, because the critical stress is as large as the yield point of S45C and the welding residual stress will never exceed the yield point.

When the preheating temperature exceeded 200°C, the cold cracking was not observed in all cases. Even if S55C steel was welded by the moistened electrode

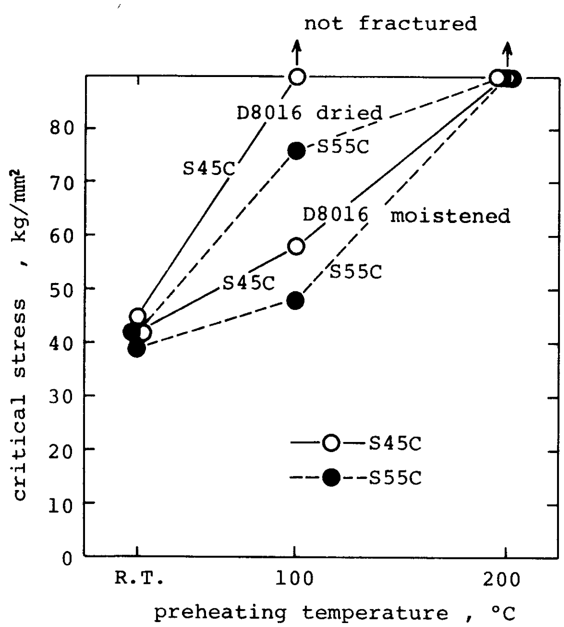


Fig.5 Influence of the preheating on the critical stress of cold cracking

the implant was not fractured. For the preheating temperature, 200°C seemed to be enough to prevent the cold cracking.

2) The diffusible hydrogen content Fig.6 shows the influence of the diffusible hydrogen content on the critical stress. Fig.6-a and Fig.6-b show the results of the tests with or without the preheating respectively. The marks △ and ▲ means that the welding was carried out using the moistened D5816 electrode.

When the diffusible hydrogen content incresed from 1 ml/100g to 4 ml/100g in Fig.6-a, the critical stress scarcely decreased. But when the diffusible hydrogen content exceeded 5 ml/100g, the critical stress remarkably decreased. It is considered that this steep decrease in the critical stress was caused by the increase in the diffusible hydrogen content. This tendency is the same for both S45C and S55C.

In the case of employing the preheating at 100°C (Fig.6-b), the influence of the diffusible hydrogen is more remarkable. There was about 30 kg/mm^2 increase in the critical stress with drying the D8016 electrode. Then, it is desired that both the drying electrode and the preheating should be used at the same time.

3) The carbon content The comparison between S45C and S55C welds was shown in Fig.7. The critical stress of S45C was generally greater than that of S55C. This results was expected from the carbon content. However, the difference of the critical stress between both steels was small without the preheating, on three levels of the diffusible hydrogen content. While, the difference became larger with the preheating. This is caused by the difference of the continuous cooling transformation characteristics of both steels. And the difference of this characteristics appears on the hardness and the microstructure of the heat affected zone.

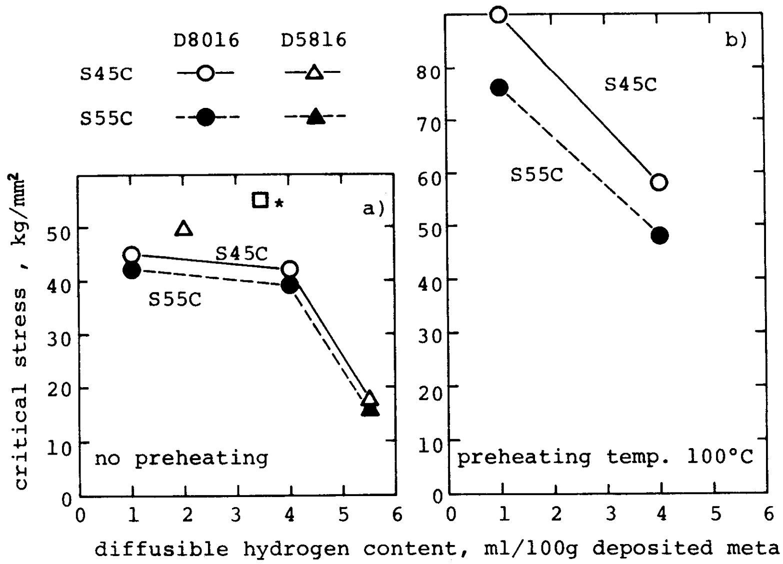


Fig. 6 Influence of the diffusible hydrogen content on the critical stress of cold cracking
(a; no preheating b; preheating temperature 100°C)
note; * the weld of S48C using the D5016 electrode[1)]

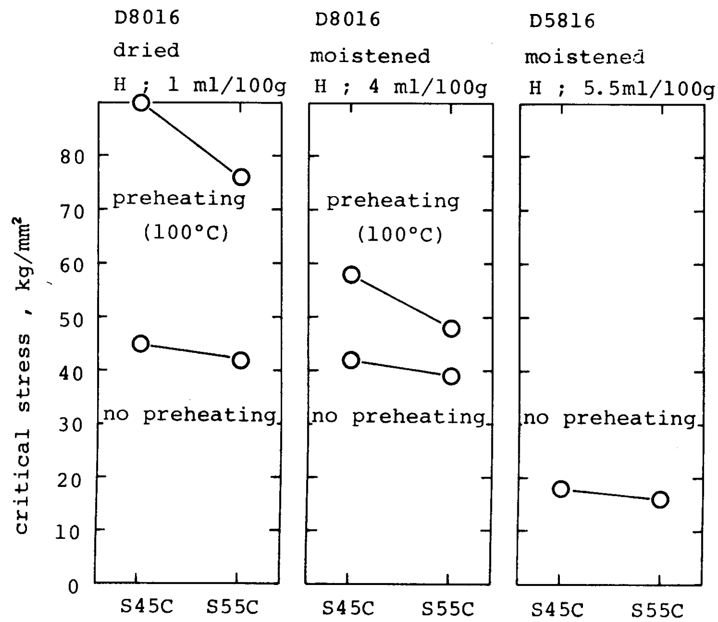


Fig.7 Influence of the carbon content on the critical stress of cold cracking

7. Microstructure of the weld

The microstructure of the welds without the preheating were tabulated in Table 4. In the weld metal and the grain growth region of both steels, the microstructure was martensite including a small amount of bainite. S45C weld had larger amount of bainite compared with S55C weld. In the unaffected zone, the microstructure was ferrite and pearlite. And the S55C weld had larger amount of pearlite than as S45C, since S55C had larger carbon content than S45C.

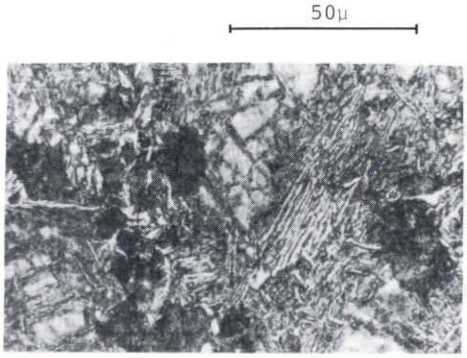
Photo.1 shows the change of the microstructure in the grain growth region, in where the cold cracking appears. The microstructure of S45C weld changed to upper bainite with the preheating at 100°C. And martensite decreased. The microstructure of S55C weld also changed to bainite with the preheating at 100°C However upper bainite was not observed in S55C weld. With the preheating at 200°C, pearlite appeared and martensite disappeared in the welds of both steels. Proeutectoid ferrite appeared and bainite disappeared in the S45C weld. While, bainite remained in the S55C weld. Generally the microstructures of both steels

Table 4 Microstructure of the welds of the carbon steels

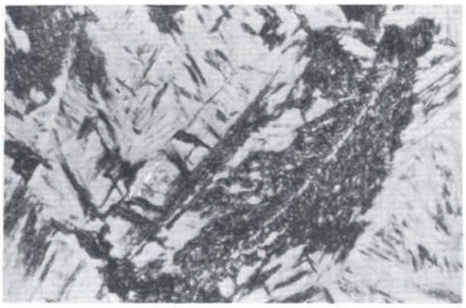
steel	weld metal		grain growth region		uneffected zone	
S45C	martensite	90%	martensite	90%	ferrite	40%
	bainite	10%	bainite	10%	pearlite	60%
S55C	martensite	95%	martensite	95%	ferrite	30%
	bainite	5%	bainite	5%	pearlite	70%

note; without the preheating

S45C preheating temp. 200°C
proeutectoid ferrite
pearlite

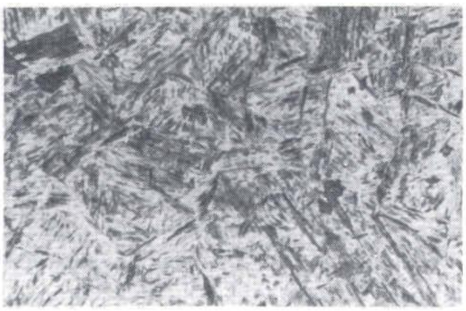


S55C preheating temp. 200°C
pearlite
bainite

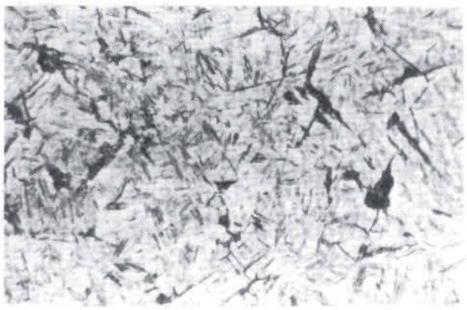


S45C preheating temp. 100°C
bainite
martensite

S55C preheating temp. 100°C
martensite
bainite



S45C without preheating
martensite
bainite (a small amount)



S55C without preheating
martensite
bainite (a small amount)

Photo.1 Microstructures of the heat affected zone
(grain growth region)

changed to the soft structure with rising the preheating temperature. There was little difference between S45C and S55C in the microstructure of the weld without the preheating.

8. Hardness of the heat affected zone

Fig.8 shows the influence of the preheating temperature on the maximum hardness of the heat affected zone for both steels. The number in this figure is the vickers hardness. The maximum hardness is 595, and the same for both steels without the preheating. S45C weld had slightly larger amount of bainite than that S55C did, however this difference in the microstructure did not appear on the hardness. The maximum hardness decreased to about 400 with the preheating at 100°C. There is 20 difference between both steels. With the preheating at 200°C, the maximum hardness decreased further, and the difference became large. Generally the hard microstructure represents the high cold cracking susceptibility. However the critical stress increased remarkably when the hardness decreased from 420 to 400. This increase of the critical stress was caused by the kinds of bainite. This results indicates that the hardness is not enough for the microstructure to represent in the point of the cold cracking.

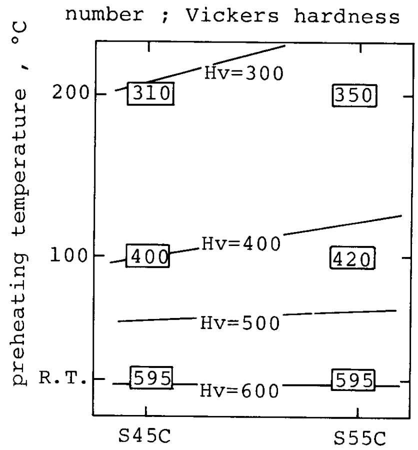


Fig. 8 Influence of preheating temperature on the maxmun hardness of the heat affected zone

9. The welding using D5816 electrode

It was mentioned that the weld using the moistened D5816 electrode had the high cold cracking susceptibility. This weld had 5.5 ml/100g diffusible hydrogen. The increase of only 1.5 ml/100g diffusible hydrogen decreased the critical stress as much as 25 kg/mm^2. While the critical stress was about as high as 50 kg/mm^2 in the case of the dried D5816 electrode, which contained 2 ml/100g diffusible hydrogen (See Fig.6). And M.Matuda had reported that the critical stress of S48C was as high as 55 kg/mm^2 using the D5016 electrode (the diffusible hydrogen content was 3.4 ml/100g)[1]. From these results it seems that D5816 and D5016 electrodes are more desirable than D8016 electrode for the welding of the carbon steels, if the electrodes are dried.

10. Blowholes in the weld

From the view of the cold cracking it is desired that the preheating temperature is high. But M.Kawahara had reported that the blowholes were observed in the weld of the carbon steels with the preheating[2]. So the suitable preheating temperature was examined from the point of view of both the cold cracking and the blowhole. The observation of the blowholes was carried out by X-rays non-destructive inspection. S45C and S55C plates in thickness of 6 mm were

Table 5 Number of the blowholes per 100 mm welding bead

steel	electrode	preheating temperature (°C) 100	200	300
S45C	D4316	0	0	7
	D5816	0	0	7
	D8016	0	3	6
S55C	D4316	0	2	8
	D5816	2	3	9
	D8016	2	3	6

used for the base metals. Welding condition as same as that of the implant test. There were many blowholes in the start and the crater of the welding bead because of the poor arc stability of the low hydrogen type electrode. Then the measurement of the blowholes were carried out over the welding bead except the start and the crater. The results were tabulated in Table 5. The extent of the blowholes are represented by the number of the blowhole per 100 mm welding bead. All blowholes were 1 mm in diameter except that they were produced in the start and the crater. With the preheating at 100°C, the blowholes scarcely occured, however the number of blowholes increased with the rising the preheating temperature. Particularly the large number of blowholes occured with the preheating at 300°C.

The blowholes occured more frequently in S55C than S45C, and there was no difference among the types of the electrodes.

The high carbon content and high preheating temperature were related to the occurence of the blowholes, however the cause to the blowholes was not yet obvious.

11. Conclusions

The cold cracking susceptibility of the carbon steels was studied employing the implant testing method. And the following conclusions were obtained.

(1) The preheating was effective to prevent the cold cracking of the carbon steels. When the preheating temperature exceeded 200°C, the cold cracking was not occured. The effect of the preheating was larger in the case of lower diffusible hydrogen or lower carbon content.

(2) The preheating decreased remarkably the maximum hardness of the heat affected zone. And the change of the hardness corresponded to the change of the critical stress of the cold cracking.

(3) In the point of view of the diffusible hydrogen content the low hydrogen type electrodes were desirable for the welding of the carbon steels. And the drying the electrode increased the critical stress of the cold cracking. There was a large increase in the critical stress in the case of employing the preheating. Therefore it is desired that both the drying electrode and the preheating should be used at the same time.

(4) The blowholes occured frequently when the preheating temperature exceeded 300°C. The preheating temperature should be below 300°C.

References

1) M.Kawahara, I.Takahashi; Preprints of the national meeting of J.W.S. No.15 (1974) P22-23.
2) H.Mastuda; Preprints of the national meeting of J.W.S. No.23 (1978) P18-19.