Hydrogen-Induced Cracking Susceptibility in High-Strength Weld Metal

A formula is proposed to estimate minimum preheat and interpass temperatures which help prevent hydrogen-induced cracking

N. OKUDA, Y. OGATA, Y. NISHIKAWA, T. AOKI, A. GOTO AND T. ABE

ABSTRACT. The hydrogen-induced cracking (HIC) susceptibility of weld metals of high-tensile strength ranging from 70 to 100 kgf/mm^2 (100 to 143 ksi) was investigated to estimate the lowest possible preheat and interpass temperatures to prevent cracking. The investigation was conducted using a multipass submerged arc welding (SAW) process with several types of electrodes and a highly basic flux of the bonded type. The flux was prepared at several baking temperatures to change the diffusible hydrogen contents ($[H]_D$) in the weld metals without changing any other characteristics peculiar to the flux. It was found that the critical preheat and interpass temperatures required to prevent HIC were in proportion to the tensile strength of the weld metal and the logarithm of diffusible hydrogen content of the weld metal as measured by gas chromatographic method ($[H]_{D\text{-}GC}$), and that they could be safely estimated within those variables.

Introduction

As welded structures such as penstocks, bridges, pressure vessels and offshore drilling rigs become larger, higher tensile strength steels, such as HT80 and HT100, as well as thicker steels, are increasingly used in their construction.

In accordance with the development of higher tensile strength steels for such projects, research and development is being carried out on welding materials.

Some welding consumables have become available that meet the requirements for mechanical properties, such as strength and notch toughness, even for low-temperature service. However, particular attention should be paid to preventing HIC, because in general, susceptibility to cracking tends to increase as the plate thickness and/or tensile strength increases.

Recently, the weldability of steels has improved significantly. Therefore, welding precautions to prevent HIC in both the heat-affected zone and the weld metal should be considered. For the base metals of HT60 and HT80, many studies of HIC in multipass weld metals were carried out, and some quantitative analysis for the prevention of cracking was reported (Refs. 1–3). However, as far as the tensile strength of weld metals up to 100 kgf/mm^2 (143 ksi) is concerned, there have been few studies of HIC.

In general, the susceptibility to HIC is affected by the tensile strength, diffusible hydrogen content, microstructure and residual stress in the weld metal, and for more accurate evaluation, those factors should be investigated at the crack initiation site of the weld metal. For instance, local hydrogen accumulation during multipass welding should be taken into account, as has been proposed (Ref. 4).

KEY WORDS

Weld Metal Cracking
Hydrogen Cracking
Induced Cracking
Crack Susceptibility
SAW Cracking Tests
Basic Bonded Flux
Diffusible Hydrogen
Flux Bake Temperature
Critical Temperature
100–140 ksi Steel

In this investigation, the HIC susceptibility of multipass high-tensile strength weld metals ranging from 70 to 100 kgf/mm^2 (100 to 143 ksi) was estimated with reference to the variables of tensile strength and diffusible hydrogen content in the weld metal. The welding variables and plate thickness were fixed so as to simplify the evaluation and to establish an evaluation that can conveniently be performed in industry.

Experiment Procedure

Electrodes and Fluxes Used

Several types of electrodes were used to change the tensile strength of the weld metal from 70 to 100 kgf/mm^2 (100 to 143 ksi). The chemical compositions of the electrodes are shown in Table 1. The diameter was fixed at 4 mm (5/32 in.). The electrodes ranging from A through D are commercially available for HT70 and HT80 steels, and the electrode E was produced experimentally to obtain a high-tensile strength weld metal of 100 kgf/mm^2.

A commercially available flux of the bonded type was modified to produce experimental fluxes which would change the diffusible hydrogen content in the weld metals. The weld metal deposited with the basic flux had a very low hydrogen content, up to 1.5 mℓ/100 g, as measured by the gas chromatographic method. Therefore, the potential hydrogen content of the fluxes for this test was increased by reducing the flux baking temperatures or by adding raw materials containing crystal water. The ranges of baking temperature and times were 150°–600°C (310°–1120°F) and 30–120 min, respectively. Talc [$Mg_3Si_4O_{10}(OH)_2$] and/or Kaolinite [$Al_2Si_2O_5(OH)_4$] were added in order to increase the potential hydrogen content of the fluxes in this experiment.

The relationship between the square

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Table 1—Chemical Composition of Electrode (wt-%)

Wire	C	Si	Mn	P	S	Ni	Cr	Mo	Base Material[a]
A	0.10	0.12	1.84	0.012	0.005	–	0.59	0.53	HT70
B	0.09	0.14	2.35	0.008	0.003	–	0.44	0.78	HT80
C	0.10	0.20	2.40	0.010	0.005	–	0.79	0.87	HT80
D	0.12	0.11	1.99	0.006	0.005	2.67	–	0.75	HT80
E	0.12	0.07	1.90	0.007	0.005	2.78	0.61	0.76	HT100

[a]Minimum tensile strength of steel: HT70 70 (kgf/mm²) 100 (ksi)
HT80 80 114
HT100 100 143

root of the moisture content of the fluxes measured at 1000°C (1832°F) and the diffusible hydrogen content of the weld metals is shown in Fig. 1.

It was found that the diffusible hydrogen content is proportional to the square root of the moisture content of the flux, precisely in accordance with Sieverts' Law. In such a manner, the diffusible hydrogen content of the weld metal changed from 1.0 to 5.1 mℓ/100 g, depending on the moisture content of the fluxes and no changes in any other characteristics. The measurement of the hydrogen content was conducted by the gas chromatographic method in accordance with WES 1003-1984. This method has the same collect rate as the mercury method standardized by the IIW (Ref. 5). The difference in diffusible hydrogen content as measured by the glycerin method (JIS) and the gas chromatographic method is shown in Fig. 2. The gas chromatographic method seems to be a more suitable method for the accurate evaluation of diffusible hydrogen content, especially when the hydrogen is at low levels.

Base Metal Used

Only one kind of base metal was used, even though numerous combinations of electrodes and fluxes were used. Its chemical composition is shown in Table 2. In this investigation, the base metal had little influence on the cracking susceptibility, since the cracking susceptibility was estimated directly from the tensile strength of the weld metal in the multipass weldments.

Experimental Process

The test assembly used to evaluate the multipass weld metal cracking is shown in Fig. 3. Fillet welds restrained the plate to prevent distortion. However, after the welding was completed, considerable residual stress remained in the weld metal because the distortion caused by the stress from this process was restricted after the first several passes. It is reported that the maximum residual stress in the weld metal tends to level off to a constant value with plates of a thickness of more than 50 mm (2 in.) (Ref. 6). Therefore, it seems that the cracking susceptibility can be estimated accurately by using U-groove prepared test plates.

Welding was conducted under the conditions shown in Table 3. All welding was performed with AC power. The temperature of the test assembly was maintained within a tolerance of ±5°C (±9°F) from the designated temperature during welding. These temperatures appear in Fig. 4. After the groove joints were filled, the test plates were left for more than 96 h in the atmosphere. The cracking in the weld metal of the plates, from which the reinforcement and restraint plates had been removed, was then investigated.

The investigation was conducted mostly by using an ultrasonic detector. In some cases, dye penetrant tests and visual observation tests with a magnifying glass were carried out on the longitudinal and transverse sections of the weld metal. It is well known that the tensile strength of the weld metal depends on the cooling rate, and the cooling rate is influenced by the preheat and interpass temperatures when the materials and welding variables are the same. Therefore, all the weld metal tensile specimens were taken from the sound portion of the test coupon, and they were tested after evaluation for HIC. Additionally, in order to ascertain the influence of the hydrogen, the diffusible hydrogen content of the weld metal deposited from each combination of electrode and flux was measured. The flux was also removed once it had been used so as to keep the potential hydrogen in the flux constant. Furthermore, the influence of the welding variables on the diffusible hydrogen content of the weld metal was

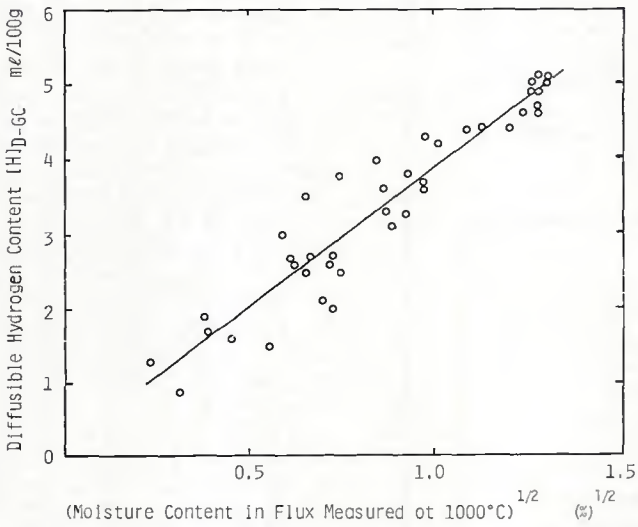


Fig. 1—Relationship between square root of moisture content in flux measured at 1000°C (1832°F) and diffusible hydrogen content in the weld metal

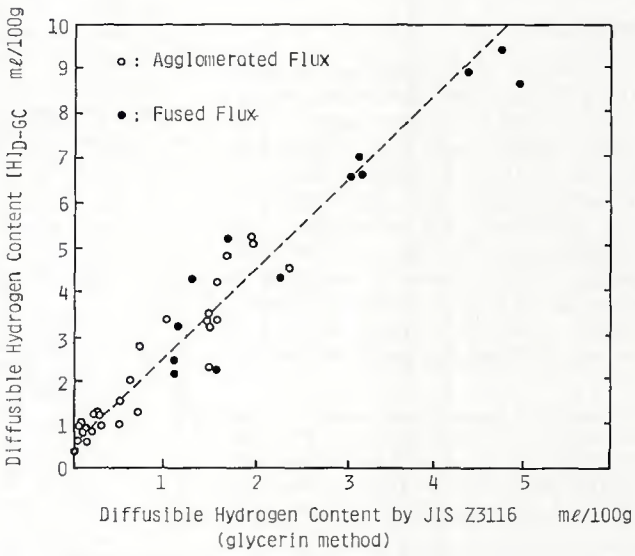


Fig. 2—Relationship between diffusible hydrogen content as measured by the glycerin (JIS) and gas chromatograph methods

Table 2—Chemical Composition of Base Material

Base material	Thickness (mm)	Chemical Composition (wt-%)											Ceq[a] (WES)	Pcm[b]
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B		
HT80	50	0.14	0.28	0.78	0.005	0.005	0.27	0.99	0.46	0.39	0.042	0.0010	0.50	0.276

[a] Ceq (WES) = C + 1/24Si + 1/6Mn + 1/40Ni + 1/5Cr + 1/4Mo + 1/4V
[b] Pcm = C + 1/30Si + 1/20Mn + 1/20Cu + 1/60Ni + 1/20Cr + 1/15Mo + 1/10V + 5B

investigated. The welding variables such as current, voltage and travel speed had negligible effects on the diffusible hydrogen content. The effect of voltage is shown in Fig. 5.

Test Results and Discussion

The influence of the tensile strength (σB) and the diffusible hydrogen of the weld metal were investigated to establish the critical preheat and interpass temperatures for the prevention of HIC. The welding was multipass using the SAW process and several electrodes and preheat and interpass temperatures. An example of a typical transverse weld crack which was found in the longitudinal cross-section of the weld metal, with a tensile strength of 101 kgf/mm^2, is shown in Fig. 6. The SEM fractograph of the transverse crack near the initiation site is shown in Fig. 7. An intergranular fracture surface and a quasi-cleavage fracture surface with a secondary crack are observed on the crack surface. This is the typical fracture morphology caused by HIC. This type of cracking tended to propagate with increases in the tensile strength or the diffusible hydrogen content of the weld metal, and in extreme cases, the cracking reached the surface of the plates. On the other hand, the cracks had the tendency to contract as those factors diminished.

The majority of the cracks in the weld metal were observed within a range of 5 to 15 mm (0.2 to 0.6 in.) below the plate surface, a location in which the residual stress and local hydrogen accumulation are said to reach a maximum. Finally, no cracking was evident even when the preheat and interpass temperatures were maintained at 50°C (122°F), provided that those two factors were kept to a minimum. The length and frequency of HIC in the weld metal depended on the tensile strength, diffusible hydrogen content and preheat and interpass temperatures. However, the critical preheat and interpass temperatures for the prevention of HIC were readjusted in accordance with the diffusible hydrogen content of the weld metal.

The relationship between diffusible hydrogen content and the critical preheat and interpass temperatures for 89.2 to 93.8 kgf/mm^2 (127 to 133 ksi) weld metals is shown in Fig. 4A. It was found that the critical temperature is proportional to the logarithm of the diffusible hydrogen content when the tensile strength of the weld metal is almost the same. In the same manner, the relationship between diffusible hydrogen and the critical temperature for preventing HIC for each level of tensile strength in the weld metal is shown in Fig. 4B. It was found that the critical temperature increased in proportion to the logarithm of diffusible hydrogen, and the gradient for each strength level was the same, irrespective of the tensile strength levels in the weld metals. Tensile strength level E (77.0 to 79.3 kgf/mm^2) resulted in a very low cracking susceptibility compared with other tensile strength levels. It was estimated that the difference in the cracking susceptibility resulted from the varying microstructures of the weld metals (Ref. 7). Bainitic structure was observed mainly in strength level E, while

Table 3—Welding Conditions

Welding Position	Electrode Dia. (mm)	Welding Variables			Heat Input (kJ/cm)	Preheat and Interpass Temp. (°C)
		Current (A)	Arc Voltage (V)	Welding Speed (cm/min)		
Flat	4.0	600	32	30	38.4	50-175

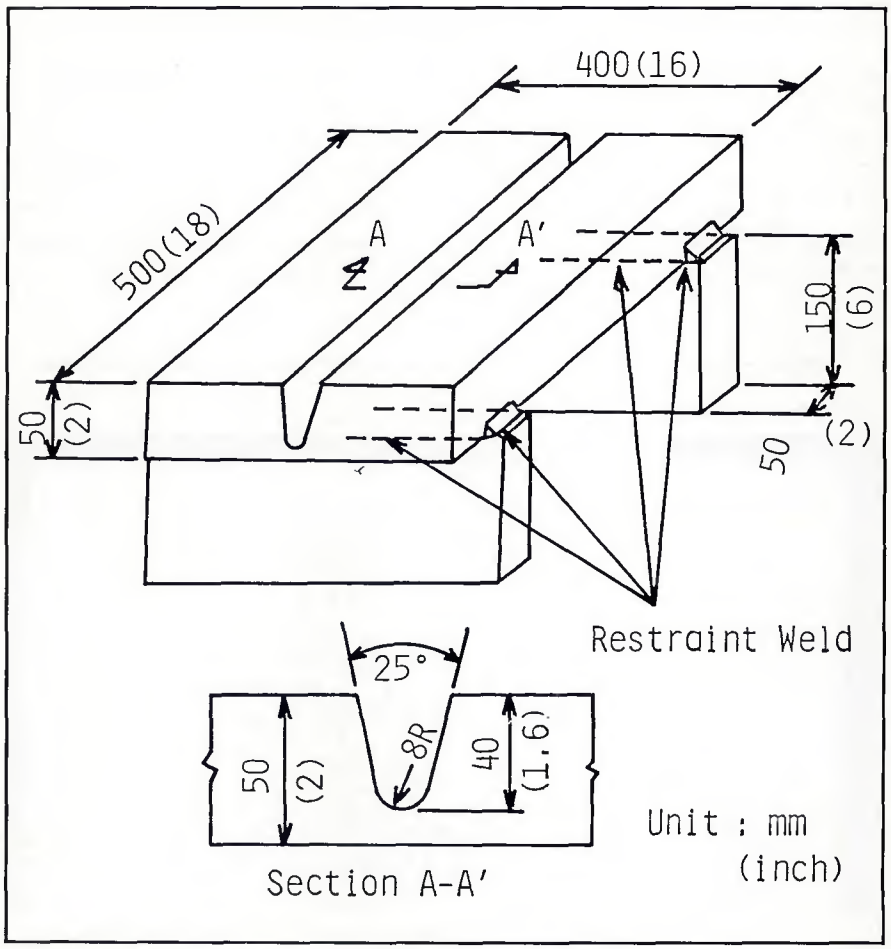
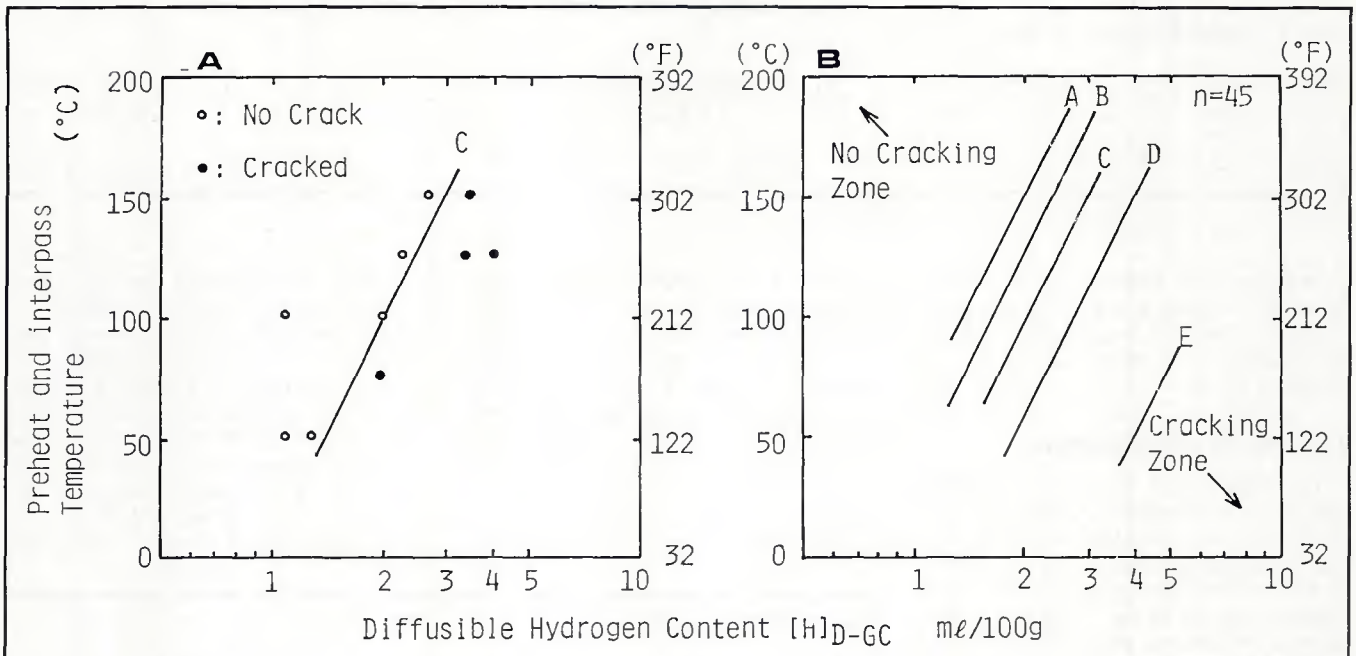


Fig. 3—Plate preparation for multipass weld metal cracking test



	Tensile Strength of Weld Metal		n
	kgf/mm^2	ksi	
A	107.8 (106.3 ∿ 109.5)	153 (151 ∿ 156)	7
B	101.0 (98.3 ∿ 103.6)	144 (140 ∿ 147)	13
C	91.5 (89.2 ∿ 93.8)	130 (127 ∿ 133)	11
D	84.2 (82.1 ∿ 86.1)	120 (117 ∿ 123)	8
E	77.8 (77.0 ∿ 79.3)	111 (109 ∿ 113)	6

Fig. 4—Relationship between diffusible hydrogen content (H_D) and critical preheat and interpass temperature for a 70 to 100 kgf/mm^2 (100 to 143 ksi) class of high-tensile weld metal

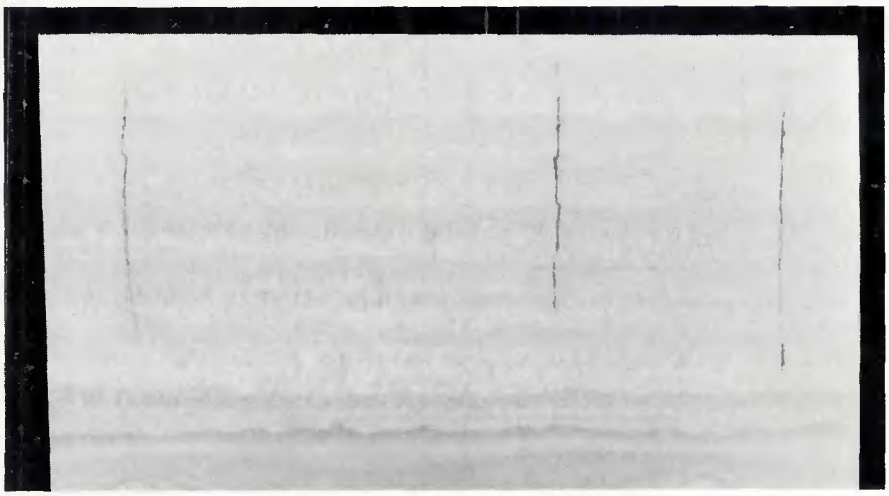


Fig. 6—Example of transverse cracks in a longitudinal section of 101 kgf/mm^2 (144 ksi) weld metal

a mixture of bainitic and martensitic structures, or a mostly martensitic structure, corresponding to the tensile strength of the weld metals, was observed for levels A to D. The typical microstructures for that group of weld metals are shown in Fig. 8.

Throughout the range of conditions encountered during the experiment, the

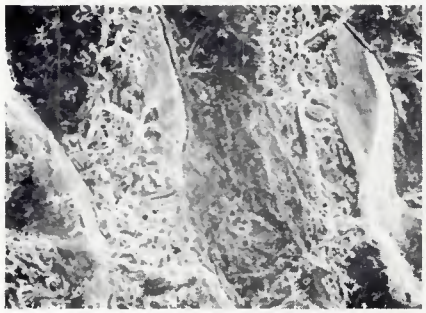


Fig. 7—Fractograph of transverse weld crack in weld metal of 101 kgf/mm^2 (144 ksi)

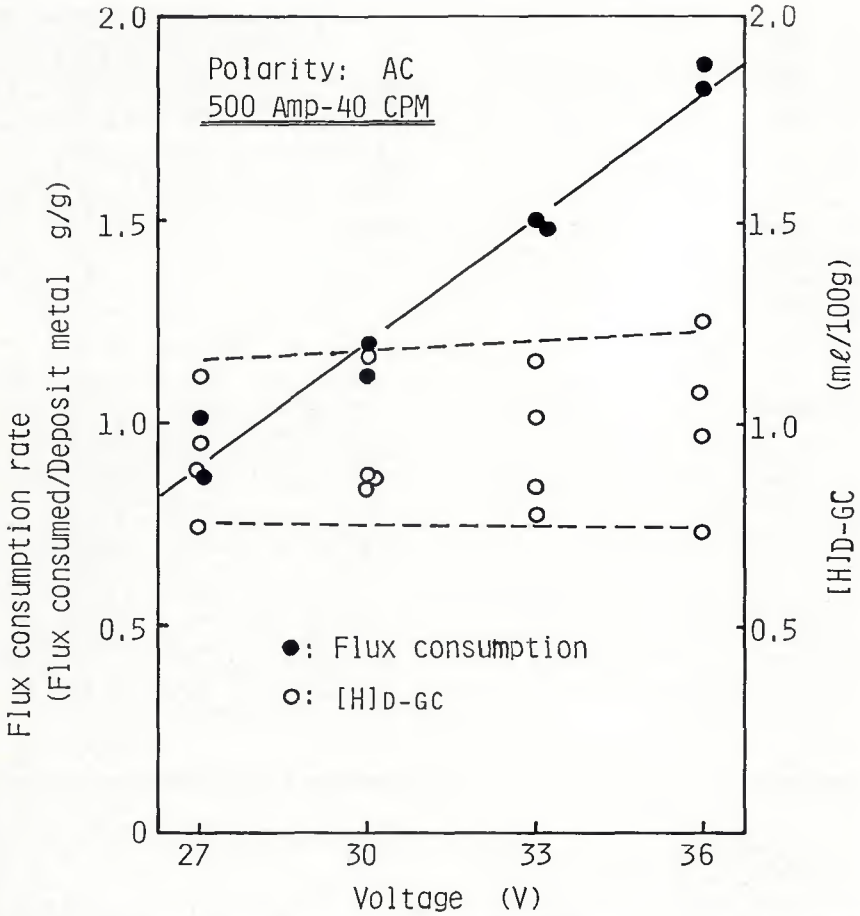


Fig. 5 — The influence of welding variables on flux consumption and the diffusible hydrogen content in the weld metal

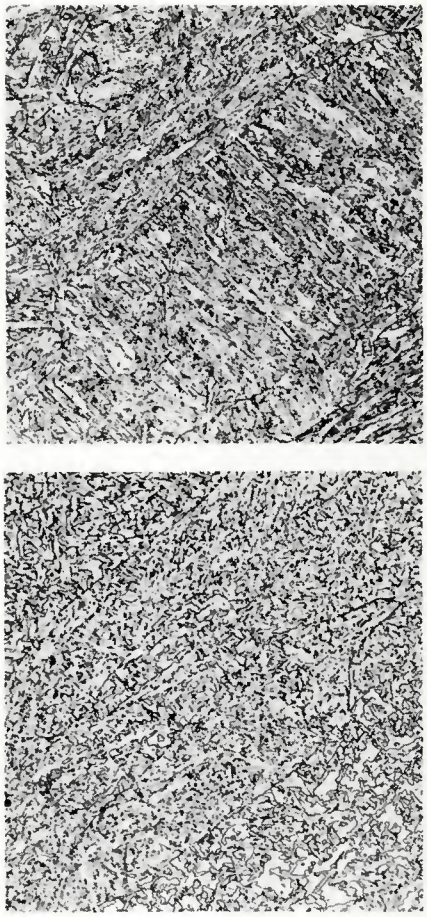


Fig. 8 — Microstructure of the weld metal (400 X)

critical temperature for preventing HIC was determined from diffusible hydrogen content, while the tensile strength was kept constant. Therefore, the critical temperature was estimated in accordance with the parameters of tensile strength and diffusible hydrogen, by the method of multiple regression analysis, under the assumption that the tensile strength and diffusible hydrogen content as measured by the gas chromatographic method ($[H]_{D\text{-}GC}$) are independent of each other in terms of their influence on cracking susceptibility. The critical temperature Tc was determined with the following formula:

$$Tc = 5.24\,\sigma B + 277 \log [H]_{D\text{-}GC} - 482$$

where

σB : 77 to 110 kgf/mm^2 (109 to 156 ksi)
$[H]_{D\text{-}GC}$: 1.0 to 5.1 mℓ/100 g

The maximum residual stress in the weld metal tends to level off to a constant value with plates not less than 50 mm (2 in.) in thickness. However, the cracking susceptibility increases as local hydrogen accumulates in accordance with the increase in weld thickness. Therefore, estimating cracking suscepti-

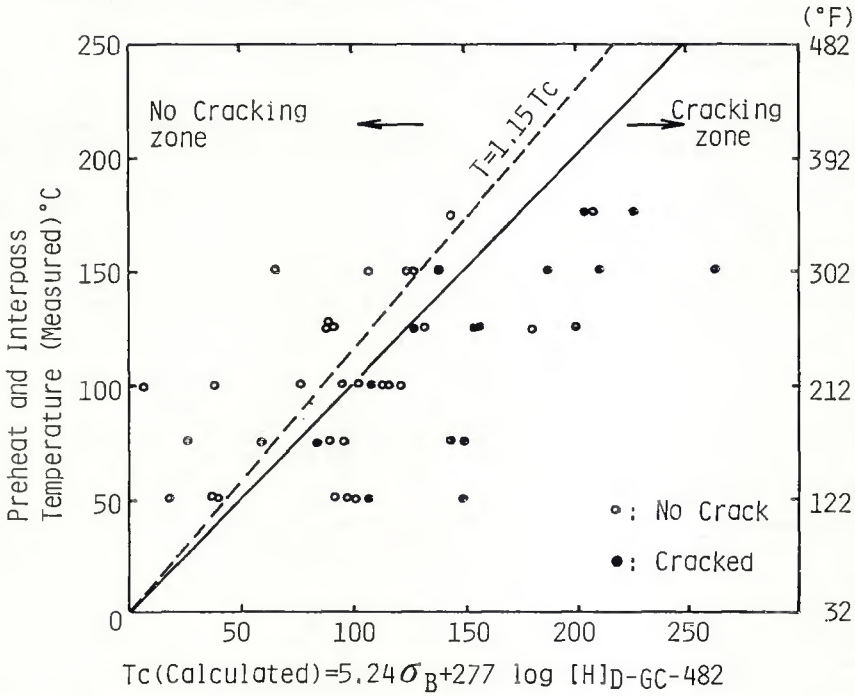


Fig. 9 — Comparison of cracking susceptibility variable, Tc (calculated), and preheat and interpass temperatures (measured)

bility by the above formula is practical for plates of 40 mm (1.6 in.) in build-up thickness, and in the case of double-groove joints, this formula can safely be used for base plates of 80 mm (3.1 in.) or less in thickness.

Figure 9 shows a comparison of the cracking susceptibility between the critical temperature (Tc), as calculated from all experimental plots in Fig. 5, and the actual preheat and interpass temperatures. The critical temperature is equivalent to Tc, and a very close estimate of the cracking susceptibility is possible from the Tc. In Fig. 9, one plot was out of the estimated range. The reason was presumed to be that the mean values of each level of tensile strength were used for the multiple regression analysis. Thus, it is safe to estimate the practical minimum temperature as 1.15 times the Tc (dashed line in Fig. 9). As a result, the practical minimum temperature T (°C) estimated within the above range is as follows:

$$T(°C) = 1.5\ Tc$$
$$Tc = 5.24\ \sigma B + 277 \log [H]_{D\text{-}GC} - 482$$

In addition, the influence on cracking susceptibility of weld thicknesses ranging from 20 to 80 mm (0.78 to 3.1 in.) was investigated. In the light of the very low diffusible hydrogen obtained for this experiment, as far as the no cracking zone in Fig. 9 is concerned, it was concluded that the influence of weld thickness on cracking susceptibility was sufficiently minimal, in that no cracking was recognized in weld metals ranging from 20 to 80 mm in thickness.

Conclusion

Multipass SAW cracking tests were conducted to investigate the hydrogen-induced cracking susceptibility of high-tensile strength steel weld metals. In the case of a weld thickness of 40 mm (1.6 in.) on a 50-mm (2-in.) plate, the practical minimum preheating and interpass temperature (T) was related to the tensile strength (σB) of the weld metal (77 to 110 kgf/mm^2), and to the diffusible hydrogen content in the weld metal, as measured by the gas chromatograph method (1.0 to 5.1 mℓ/100 g). The relationships are: $T = 1.15\ Tc$ and $Tc = 5.24\ \sigma B + 277 \log [H]_{D\text{-}GC} - 482$. In order to apply the above formula widely in industry, it will be necessary to conduct a detailed investigation of the influence of plate thickness or weld metal thickness on cracking susceptibility.

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WRC Bulletin 318
September 1986

The primary objective of this Bulletin, which contains two papers, is to present a comprehensive picture of the research work conducted to establish the current techniques and procedures for specifying the ferrite content of austenitic stainless steel weld metal and measuring its level.

Factors Influencing the Measurement of Ferrite Content in Austenitic Stainless Steel Weld Metal Using Magnetic Instruments

By E. W. Pickering, E. S. Robitz and D. M. Vandergriff

This report describes a program conducted under the auspices of the Welding Research Council (WRC) Subcommittee on Welding Stainless Steel to identify the optimum procedure for the preparation of austenitic stainless steel weld samples for Ferrite Number (FN) determination.

Measurement of Ferrite Content in Austenitic Stainless Steel Weld Metal Giving Internationally Reproducible Results

By E. Stalmasek

This report is a summary of the results of 14 years' work by the IIW Commission 2 in the field of ferrite content measurement, done prior to 1978.

The publication of these reports was sponsored by the Subcommittee on Welding Stainless Steel of the High Alloys Committee of the Welding Research Council. The price of WRC Bulletin 318 is $24.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.