

Development of Field Girth Welding Simulation and Test Procedure Development to Evaluate Pipe Properties at HAZ in Girth Welded Portion

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Abstract

It is important controlling properties in welded portion generated by field girth welding. Thus Nippon Steel & Sumitomo Metal Corporation is conducting two developments about the girth welding. The first one is simulation technique of the field girth welding, it is called "field girth welding simulation". The second one is a test procedure development to evaluate properties of weld heat affected zone generated in pipe body, it is called "weldability test". A field girth welding simulation on X80 UOE pipe and a weldability test on X65 seamless pipe are reported in this paper.

1. Introduction

Line pipes are usually joined together by girth welding. The weld zone consists of the weld metal and heat affected zone (HAZ). The weld metal differs in composition from the base metal because it is a mixture of the base metal and welding consumables. HAZ differs in microstructure and properties from the base metal because of the thermal history during welding. Therefore, every pipe manufacturer must have a store of knowledge about weld metals, the properties of weld zones (including HAZ), and pipe base metals. In particular, when constructing a natural gas or crude oil pipeline, field girth welding efficiency and appropriate weld zone properties are key to the success of the project. Therefore, there is a strong need to evaluate the girth weldability of line pipe.

When collecting data about weld zone properties, it is necessary to carry out girth welding and prepare girth-welded joints. In this case, there are mainly two types of welded joints the pipe manufacturer is required to prepare. One type is obtained under conditions as close as possible to actual field welding conditions. Welded joints of this type are often demanded by pipeline construction contractors. The welding of line pipes began in the United States. Around 1945, a combination of the spread method and efficient manual welding using a high cellulose-type welding rod was established as the welding method for onland pipelines.

Since then, in order to save labor through automated welding operations and to improve welding efficiency, efforts have been made to narrow the welding grooves. The current mainstream is high-efficiency welding that combines gas metal arc welding and a groove angle of 5° or less.¹⁾ For the welding material, a thin, solid wire 0.9 to 1.2 mm in diameter is used. In many cases, downward welding is applied. Welding heat input is as low as around 0.3 kJ/mm to 1.5 kJ/mm.^{2,3)} By applying downward welding, it is possible to increase welding speed and shorten welding time per pass, thereby enhancing welding efficiency. This allows for a low heat input. In addition, a relatively high interpass temperature is used to shorten wait time.

The other welded joint type is welded joints of HAZ used to evaluate performance. In this case, unlike in actual welding, a half K bevel-shaped groove, one side of which is vertical, is used, and the welding line is kept linear. In addition, the welding is required to be performed with maximum and minimum heat inputs that can be applied at the construction site. These demands often come from oil and gas companies who are the final users of line pipes.

In this report, the author presents the results of a simulative test of field girth welding on X80 UOE pipe using gas metal arc welding with a narrow groove, and the results of evaluations of the properties of girth-welded HAZ joints of X65 seamless pipe with a half K

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bevel-shaped groove.

2. Simulation of Field Girth Welding and Evaluation of Weld Zones, Using X80 UOE Pipe

2.1 Specimen and girth welding method

The test used an X80 UOE pipe 610 mm in outside diameter and 15.6 mm in wall thickness. The chemical composition of the pipe base metal is shown in Table 1. The pipe material was a low carbon steel added with Mn, Cu, Ni, Cr, Mo, Nb, V and Ti. The Pcm was 0.18 mass%.

To simulate field girth welding, gas-shielded metal arc welding with a narrow groove was applied. Figure 1 shows the groove shape used. In the present case of welding, in order to simulate root running from the inside, a groove shape with one stage on the inside and two stages on the outside was adopted. As shown in Fig. 1, the main bevel angle was 5°. Fig. 1 also shows the pass sequence. A one-layer, one-pass sequence — the most popular for field girth welding — was adopted.

The girth welding conditions used are shown in Table 2. For root running, semiautomatic gas-shielded metal arc welding was performed from the inside. During root running, the pipe was held on a clamp from the outside and turned while it was welded. In the

second and succeeding passes, downward welding was applied from the outside with the pipe fixed. The welding process was pulsed gas metal arc welding. Welding conditions are shown in Table 2. In the second pass (hot pass), 100% CO₂ was used as the shielding gas in order to ensure sufficient penetration. In the first pass (root pass), argon-25%CO₂ was used as the shielding gas, whereas argon-30%CO₂ was used in the third (fill) and fourth (cap) passes. Mixed gases were used in order to inhibit an increase in oxygen content in the weld metal, and thereby secure sufficient weld metal toughness. The welding wire was a solid wire 1.0 mm in diameter, equivalent to AWS A5.18 ER70S-G. A Gr70-equivalent welding wire was applied to the X80 pipe in order to permit even-match welding, with consideration given to the increase in strength with low welding heat input. Table 3 shows the results of a chemical analysis of the girth weld metal. Pcm was 0.19 mass%, nearly the same as that of the base metal. Oxygen content was controlled at 0.03%.

2.2 Cross-section macrostructure of weld zone; hardness distribution in weld zone

Figure 2 shows the cross-section macrostructure of a prepared welded joint, and points of hardness measurements. The cross-section macrostructure is characteristic of field girth welding: a small welding width, and a small cross-sectional area of weld metal.

Weld metal hardness was measured at three points: through-thickness at the center, 1 mm from the pipe inner surface, and 1 mm from the pipe outer surface. The hardness of the weld metal center cyclically varied (see Fig. 3) under the influence of cyclic heating in multilayer welding. Maximum hardness was HV 274; minimum hardness, HV 219; and average hardness, HV 244. At the three measuring points shown in Fig. 4, the base metal did not demonstrate any significant difference in hardness, the average hardness being HV 251. The weld metal and base metal were nearly the same

Table 1 Chemical compositions of base metal of X80 UOE pipe

(mass%)				
C	Si	Mn	P	S
0.06	0.14	1.72	0.006	0.0012
Others			Ceq (IIW)	Pcm
Cu, Ni, Cr, Mo, Nb, V, Ti			0.43	0.18

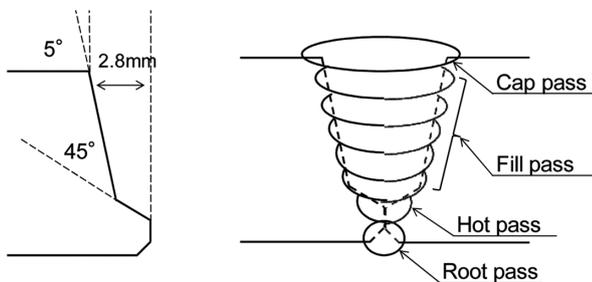


Fig. 1 Bevel preparation and pass sequence

Table 2 Welding procedures

Pass	Root (inside)	Hot	Fill - cap
Process	Semi-auto	GMAW	PGMAW
Position	1G	5G	5G
Equipment	DAIHEN DM-350	RMS	RMS
Welding wire	Nippon-Sumitomo YM-SCV (1.0 mm) (Eq. AWS 5.18 ER70S-G)		
Shielding gas	75%Ar-25%CO ₂	100%CO ₂	70%Ar-30%CO ₂
Heat input (kJ/mm)	—	0.3	0.4–0.7
Note	Preheating was not applied. Inter pass temp < 100 °C		

Table 3 Chemical compositions of girth weld metal

(mass%)				
C	Si	Mn	P	S
0.069	0.71	1.48	0.009	0.005
Cu	Ni	Cr	Mo	V
0.31	0.04	0.04	0.02	0.01
Ti	Nb	B	Sol-Al	Insol-Al
0.002	0.008	0.0006	0.008	< 0.001
O	N	Pcm		Ceq (IIW)
0.03	0.0033	0.19		0.35

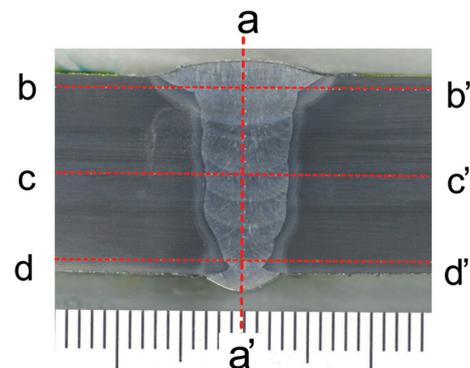


Fig. 2 Macro structure and measurement lines of hardness distribution

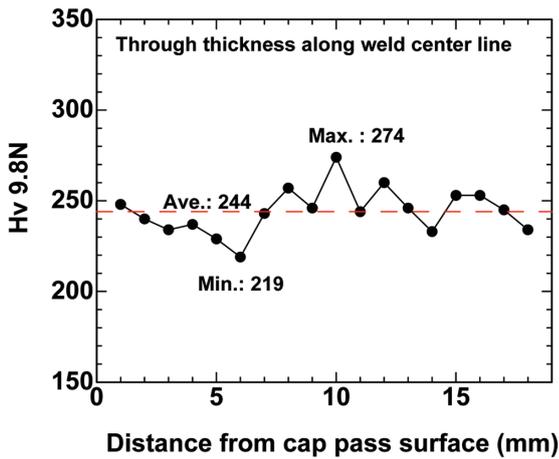


Fig. 3 Hardness distributions through thickness along weld center line

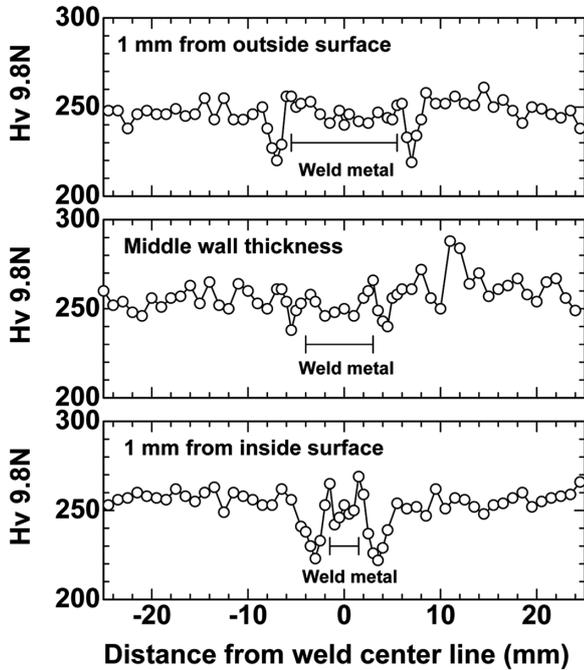


Fig. 4 Cross weld hardness distributions

in hardness. Thus, it was confirmed that the aimed-for even-match welded joint could be obtained. The increase in HAZ hardness was minimal, and a slight decrease in HAZ hardness was observed. Minimum HAZ hardness was HV 219, or 87% of the average base metal hardness.

2.3 Weld zone tensile properties

As shown in Fig. 3, the weld metal for girth welding underwent a cyclic change in hardness under the influence of the multi-pass heat cycle. Thus, it is evident that a local change in strength occurred within the weld metal. To verify this, round bar specimens and strip specimens were collected from the weld metal (see Fig. 5), and subjected to tensile tests. The round bar specimens were 3 mm in diameter, and were collected from three positions in the thickness direction. The strip specimens were 15 mm in width, and were collected so that their properties along the entire thickness could be measured.

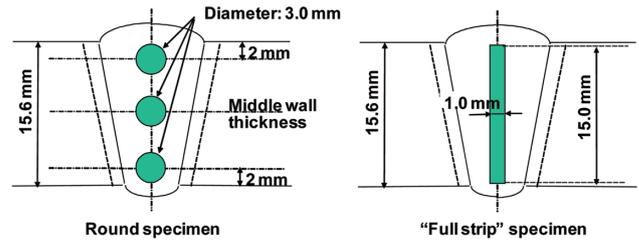


Fig. 5 Schematic illustration showing location of tensile specimen

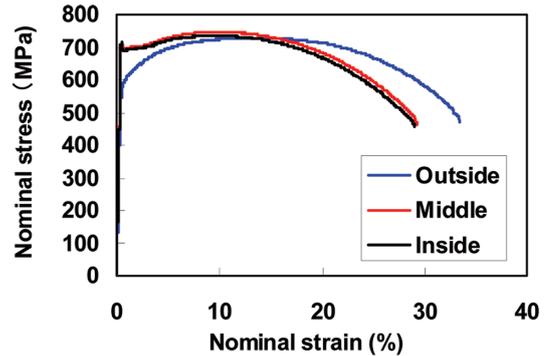


Fig. 6 Stress-strain curves of girth weld metal by using round bar specimen

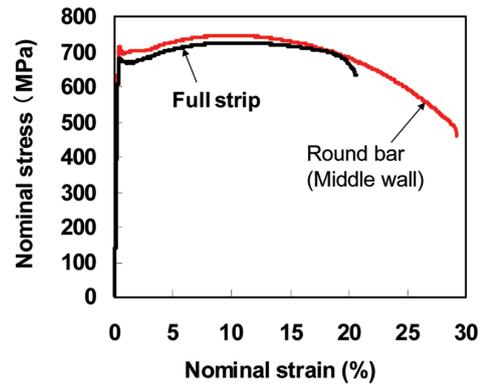


Fig. 7 Comparison of stress-strain curves of girth weld metal by using round bar and full strip specimen

Table 4 Results of tensile test on girth weld metal

Specimen type	Location	Yield strength (MPa)	Tensile strength (MPa)
Round bar	Outside	574	728
	Middle	708	745
	Inside	693	734
Strip	Full thickness	674	725
Base metal data		541–576	717–741

Test results are shown in Figs. 6 and 7, and Table 4. As can be seen from Fig. 6, the round bar specimens collected from the thickness center and from the position 2 mm from the inside of the pipe showed nearly the same stress-strain curves. Both curves were of Luder's elongation type having a yield elongation. Yield strength was 708 MPa for the specimen collected from the thickness center,

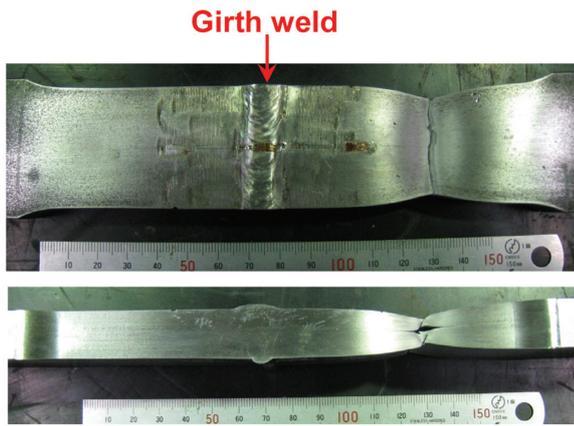


Fig. 8 Fracture appearance after the cross weld tensile tests

and 693 MPa for the specimen collected from a position 2 mm from the inside of the pipe. The round bar specimen collected from a position 2 mm from the outside of the pipe did not show any yield elongation, and its stress-strain curve was of the round house type. The yield strength of this specimen was 574 MPa, lower than that of the other two round bar specimens. The difference in S-S curves is probably due to the fact that in the last pass the weld metal maintained its microstructure as solidification-hardened, since it was not reheated by any succeeding welding pass. On the other hand, the strip specimen showed a stress-strain curve of Luder's elongation type, and had the yield elongation shown in Fig. 7. The yield strength of this specimen was 674 MPa. Thus, it was confirmed that a round bar specimen collected from the thickness center would produce nearly the same test results as other specimens collected from any other position.

As summarized in Table 4, the tensile test results revealed that the welded joints are an even match with the base metal in tensile strength, but exceed the base metal in yield strength by about 20%. There is a controversy over whether tensile strength or yield strength should be used to define strength matching between the base metal and the weld metal in a welded joint. In recent years, studies have been conducted to determine which of the two definitions is valid, and have included comparative studies using FEA.

Figure 8 shows the appearance of a strip specimen after it fractured in a tensile test. The fracture occurred at a base metal part way from the weld zone, indicating that the welded joint had no problems as far as fracture mode is concerned.

2.4 Charpy and CTOD test results

Two notches in the weld metal centerline and fusion line (FL: HAZ = 50:50) were subjected to a Charpy impact test. Test results are shown in Fig. 9. At the FL, a high energy value over 100J was obtained at a temperature as low as -60°C . The ductility-brittleness transition temperature was -53°C . At the notch in the weld metal centerline, energy values were generally smaller than those at the notch in the FL. This is due to the fact that the oxygen content of the weld metal (0.03 mass%) was one digit higher than that of the base metal. Oxygen in steel forms oxides which induce ductile fractures and cause the energy value in 100% ductile fractures to decrease. However, it was confirmed that the ductility-brittleness transition temperature at the notch in the weld metal centerline was lower than -60°C , indicating that the weld metal has sufficient toughness.

A CTOD test was carried out at -10°C . The notch positions were on the weld metal centerline and FL, as in the Charpy impact test.

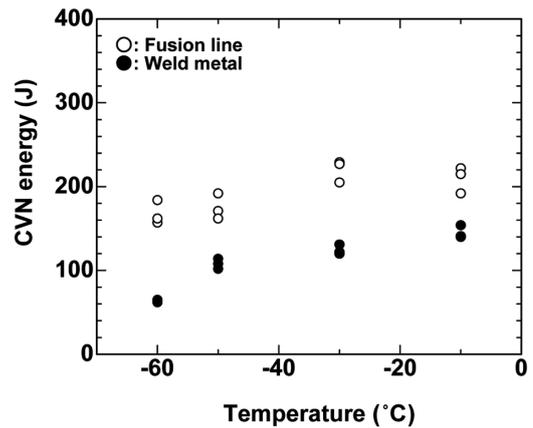


Fig. 9 Charpy impact test results at welded portion

Table 5 CTOD test results

Notch location	Temp. (°C)	CTOD value (mm)
Weld center line	-10	0.32, 0.35, 0.33
Fusion line	-10	0.40, 0.61, 0.34

The CTOD test results are shown in Table 5. CTOD values for the weld metal centerline notch were 0.32 mm, 0.35 mm and 0.33 mm, and those for the FL notch were 0.40 mm, 0.61 mm and 0.34 mm. All specimens fractured at 100% ductility, proving that the weld zones had excellent crack resistance.

3. Evaluation of HAZ Properties in Girth Welding with Half K bevel-Shaped Groove

3.1 Purpose for performing welding with half K bevel-shaped groove

When performing girth welding or any other type of welding, it is common practice to prepare a groove and fill it with fused welding wire or the like. Therefore, in order to evaluate the Charpy and CTOD characteristics of a coarse-grain HAZ (CGHAZ) formed along the fusion line using ordinary welded joints, for example, the notches for Charpy and CTOD tests are prepared so that the ratio of weld metal to HAZ in each of the notches becomes 50:50, as described in Section 2.4. In this case, the notch may contain not only a CGHAZ but also a fine-grain HAZ (FGHAZ) and weld metal. If so, it is not always possible to evaluate the actual CGHAZ properties.

It is generally thought that in multi-pass welded joints, the parts whose toughness declines most are the CGHAZ and the intercritical reheated CGHAZ (ICCGHAZ), which is the CGHAZ reheated to the midpoint between Ac3 and Ac1 during the subsequent welding heat cycle. Therefore, as a means of accurately evaluating the CTOD characteristics of HAZ, in particular, API-RP2Z recommends preparing welded joints with a half K bevel-shaped groove to increase the proportion of CGHAZ and ICCGHAZ at the notch. In the present study, with reference to RP2Z, the author and collaborators evaluated the HAZ characteristics of joints which met the following requirements:

- (1) Irregularities in the fusion line: within 1.0 mm
- (2) Average distance between notch and fusion line: 0.5 mm or less
- (3) Proportion of HAZ in notch: 80% or more

(4) Proportion of CGHAZ and ICCGHAZ adjoining fusion line: 25% or more

(All of the above requirements apply to the central 60% of the wall thickness or specimen thickness.)

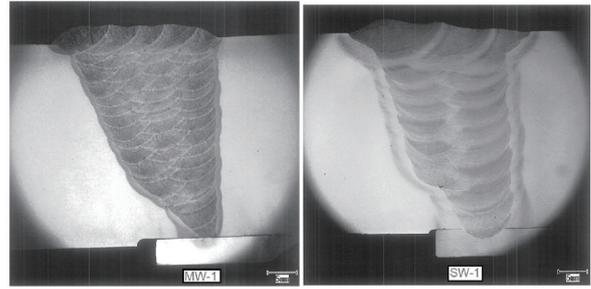
3.2 Specimens and girth welding method

The material welded was an X65 seamless pipe 219.1 mm in outside diameter and 33.45 mm in wall thickness. Welding conditions are shown in Table 6. Two levels of welding heat input were tested: 0.5kJ/mm (low heat input), and 1.6kJ/mm (high heat input). At both levels of heat input, the pipe was rotated while being welded. For welding with the low heat input, pulsed gas metal arc welding was used, with the preheating and interpass temperatures kept below 50°C. For welding with the high heat input, submerged arc welding was used, with the preheating and interpass temperatures controlled within a range of 125°C to 150°C. As mentioned in the Introduction, a low heat input (0.3kJ/mm ~ 1.5kJ/mm) is often used for the girth welding of line pipes. The author considers that the welding conditions selected in the present study almost entirely cover the conditions used in field girth welding operations. The welding groove was a deformed half K bevel-shaped groove, one side being vertical and the other side two-staged, as shown in Fig. 10.

3.3 Microstructures of weld zone cross sections

Figure 11 shows sample microstructures of the prepared welded joint cross sections. Table 7 shows the results of the measurements of irregularities in the fusion line (HAZ straightness) and the proportions of CGHAZ and ICCGHAZ adjoining the fusion line. It was confirmed that the joints obtained by gas metal arc welding with low heat input and the joints obtained by submerged arc welding with high heat input both attained the aimed-for HAZ straightness and microstructure.

Next, the author and collaborators studied the relationship between average notch-FL distance and the proportion of HAZ in the



(a) 0.5 kJ/mm GMAW joint HAZ straightness: 0.76 mm CGHAZ+ICCGHAZ: 64.9 %
 (b) 1.6 kJ/mm SAW joint HAZ straightness: 0.98 mm CGHAZ+ICCGHAZ: 52.5 %

Fig. 11 Macrographic examination results

Table 7 HAZ straightness and CGHAZ+ICCGHAZ ratio

WPS	Joint ID	Specimen ID	HAZ straightness (mm)	CGHAZ +ICCGHAZ (%)
PGMAW 0.5 kJ/mm	M-2	MW-1	0.76	64.9%
		MW-2	0.88	66.9%
	M-3	MW-3	0.68	58.9%
		MW-4	0.73	62.8%
SAW 1.6 kJ/mm	S-2	SW-1	0.98	52.5%
		SW-2	0.85	57.3%
	S-3	SW-3	0.95	67.1%
		SW-4	0.56	63.8%

Table 6 Welding procedures

	Low heat input	High heat input
Process	Pulsed GMAW	SAW
Position	Pipe rotated	Pipe rotated
Aimed heat input	0.5 kJ/mm	1.6 kJ/mm
Preheat/interpass temp.	Max. 50°C	125–150°C

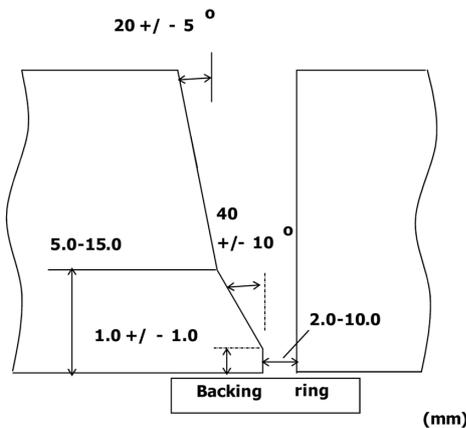


Fig. 10 Example of half K bevel

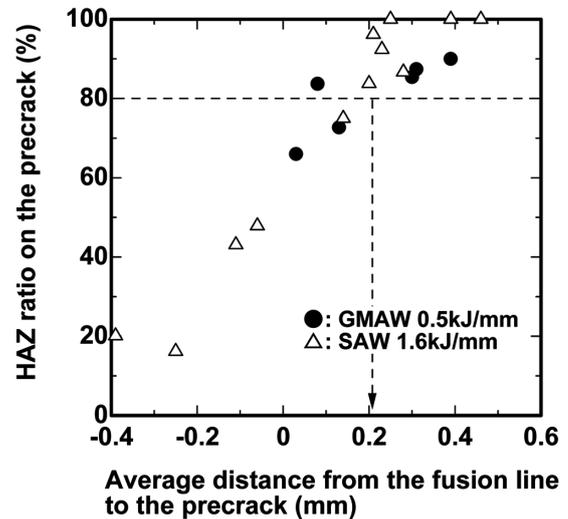


Fig. 12 Effect of the average distance from the fusion line and precrack on the HAZ ratio on the precrack

notch. Results are shown in Fig. 12. To accurately evaluate the CTOD characteristics of CGHAZ/ICCGHAZ, it is desirable that the notch should be as close to the fusion line as possible. However, if the notch is too close to the fusion line, the proportion of weld metal in the notch becomes too large to permit evaluation of the CTOD characteristics of the HAZ. As is evident from Fig. 12, when the average distance between notch and fusion line was smaller than 0.2

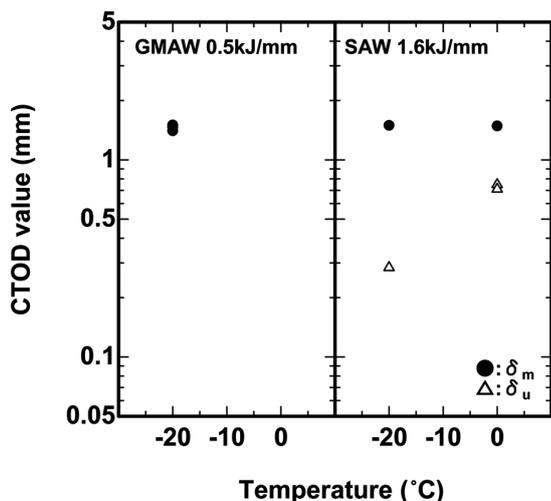


Fig. 13 CTOD test results at coarse grain HAZ

mm, the proportion of HAZ in the notch did not always attain the aimed-for 80%. From this it can be seen that, in order to attain the aimed-for values at all times, it is necessary to control the average notch-FL distance within an extremely narrow range of 0.2 mm to 0.5 mm.

3.4 CTOD test results

Figure 13 shows the results of a CTOD test in which a notch was introduced near to the fusion line using a half K bevel-shaped groove. In the case of joints obtained by gas metal arc welding with low heat input (0.5kJ/mm), all three specimens tested at -20°C completely underwent a ductile fracture after the maximum test load was reached, and showed a large CTOD value of 1.0 mm or more. With respect to joints obtained by submerged arc welding with high heat input (1.6kJ/mm), some specimens broke down at test temperatures of -20°C and 0°C before the maximum test load was reached.

However, these breakdowns were due to ductile fractures, and even the smallest CTOD value was 0.25 mm. It was considered, therefore, that X65 seamless pipe has sufficient crack arrestability as a line pipe.

4. Conclusion

While discussing the company’s R&D for line pipe girth welding technology, the author has described the development of techniques for simulating, as accurately as possible, girth welding operations performed at pipeline construction sites, and the development of techniques for accurately evaluating the properties (specifically the CTOD properties) of a HAZ produced in a pipe body as a result of welding heat hysteresis. Ever since the crude oil spillage in the Gulf of Mexico in 2010, customer awareness of the need for pipeline safety is stronger than ever before. In particular, interest in ensuring the properties required of pipeline weld zones is extremely strong.

We consider that it is the responsibility of every pipe manufacturer who develops, makes and sells pipe bodies to provide customers with pipe application technologies, including new and advanced welding techniques. Paying due attention to customer needs at all times, we are continuing to develop systems for evaluating pipe application technology, while accumulating relevant knowledge.

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