Joint Strength of Heavy Plates with Lower Strength Weld Metal

Tests demonstrate the applicability of undermatching welded joints in heavy plates of HT 80 steel from the standpoint of joint performance and ease of welding

BY K. SATOH AND M. TOYODA

ABSTRACT. Since the undermatching electrode which deposits weld metal of an appreciably lower yield and/or tensile strength than the base metal has been found effective for preventing weld cracking of low alloy high strength steels, a demand for using it has been increasing recently in fabricating welded structures of heavy plates. Investigation has been carried out on the mechanical behavior of the undermatching welded joint of HT 80 structural steels.

The present paper includes both fundamental and joint performance studies. The fundamental study is made theoretically and experimentally by using an idealized model joint including a "soft" interlayer. The joint strength is found to be increased toward the ultimate tensile strength of the base metal used as the interlayer decreases in thickness. Plate width also affects joint strength up to a certain value. Joint performance of HT 80 steel plates with undermatching weld metal is studied by static tension test, brittle fracture initiation test and fatigue test. A reasonable tensile strength level for the undermatching weld metal is found to be not less than 90% of the base metal strength. Burst tests of HT 80 steel pipe specimens including undermatching welded joints demonstrate that its fracture strength is as high as the tensile strength of the base metal.

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Introduction

It has been said from the standpoint of joint efficiency of weld connections that the strength of weld metal should not be lower than that of base metal. The strength of weld metal, however, changes with welding procedure details such as type of filler metal, number of passes, welding position, weld heat input, etc. In particular, in welding heavy plates of low alloy, high strength structural steels, the strength of weld metal exceeds sometimes by far the nominal value of the electrode used because of its hardenability.

For example, it is often experienced in the welded joint of HT 80 steel plate, of nominal tensile strength of 80 kg/mm^2, that tensile strength obtained by coupon test of the filler metal exceeds 90 kg/mm^2 under low heat input and that weld cracks occur under high restraint. Therefore, in welding heavy plates of HT 80 steel, determination of welding conditions is of importance for preventing weld cracking. Some experiments reveal (Ref. 1) that the use of electrodes having a nominal strength level lower than that of base metal is one effective way for preventing weld cracks. Such use would lead to easier welding of heavy plate construction, such as over-sea bridges and offshore structures. In this sense, a demand for using electrodes of lower nominal strength level is increasing.

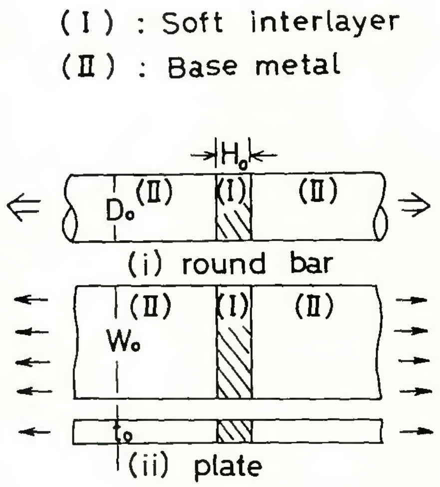


Fig. 1 — Round and flat bar models used in analytical study

The purpose of the present paper is to investigate the mechanical behavior of "undermatching welded joints," or welded joints in which strength of filler metal is appreciably lower than the base metal, and to find reasonable strength levels of the filler metal from the standpoint of both workmanship and joint performance.

Fundamental study using an idealized model joint was first undertaken at the authors' laboratory in Osaka University. For the past three years, the SJ-Committee of the Japan Welding Engineering Society, of which one of the authors is chairman, has collected more practical data on mechanical behavior of the undermatching welded joints of HT 80 structural steel plates.

Fundamentals

Theory

The undermatching welded joint is idealized as a bar model consisting of a soft interlayer (I) and base metals (II) having higher strength, as shown in Fig. 1. When tensile load is applied on the model joint, initial yield starts at the soft interlayer. The plastic deformation or the necking in the interlayer will be constrained by the base metals having higher strength. Thus, a multiaxial state of stress will result in the interlayer and the joint strength will be increased from the strength of the material (I). Plastic analysis for this state was made by assuming the material (II) a rigid body (Refs. 2,3).

According to the analysis for a round bar model joint of a given value of $H_0/D_0(\equiv X)$, the relationship of nominal axial stress σ_z vs. engineering strain ε_z in the section of the neck is represented as:

$$\sigma_z(\varepsilon_z) = \sigma(\varepsilon_z) \times (1 + Y) \qquad (1)$$

in which $\sigma(\varepsilon_z)$ is nominal stress-strain relation of the material (I) under simple tension and Y is a numerical value obtained from Eq. (2) for a given value of X and ε_z:

$$X = (1/3)\left\{(1-\varepsilon)[(\varepsilon/2Y) - 1 + \varepsilon]\right\}^{1/2}\left\{2\varepsilon + \varepsilon^2 - 4(1-\varepsilon)Y\right\}$$
$$\varepsilon = (1 + \varepsilon_z)^{-1/2} \qquad (2)$$

Ultimate tensile strength σ_u of the model joint can be calculated as the σ_z value when $d\sigma_z/d\varepsilon_z$ becomes zero. According to Eqs. (1), (2), the σ_z value depends upon the value of H_0/D_0 ($\equiv$ X) or relative thickness of the soft interlayer, and it is increased with decrease of the X value. The same analysis (Ref. 4) as the above for a wide plate model joint ($W_0 > t_0$) in Fig. 1 leads to the conclusion that the joint strength depends upon the relative thickness H_0/t_0 ($= X_t$).

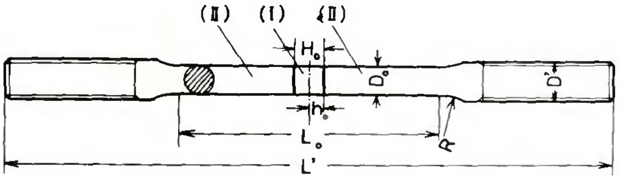
Table 1 — Series of Model Joint Specimen in Fundamental Study

Series		Material	Tensile properties				Welding method
			T.S. (kg/mm²)	Y.S. (kg/mm²)	n	$\varkappa$	
I	Soft interlayer	0.10%C steel	47.8	32.6	0.17	2.27	Flash butt welding
	Base metal	0.35%C steel	108.7	96.8	0.07		
II	Soft interlayer	0.10%C steel	47.8	32.6	0.17	1.74	
	Base metal	0.35%C steel	83.3	64.1	0.07		
III	Soft interlayer	0.10% C steel	49.0	37.6	0.18	1.50	
	Base metal	0.35%C steel	73.5	52.4	0.14		
IV	Soft interlayer	AWS E 7016	58.3	48.8	0.17	1.44	Narrow gap shield metal arc welding
	Base metal	HT 80	84.1	78.0	0.09		

NOTE: T.S.; Tensile strength , Y.S.; Yield strength
n ; Strain hardening exponent , $\varkappa = \sigma_u^B/\sigma_u^I$

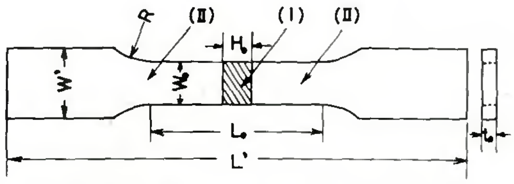
Experiment (Refs. 2-5)

Four series of the model joint specimen including a soft interlayer were prepared for fundamental study. In Series I, II, III, the specimens were made by flash welding round bars of a low carbon steel and a medium carbon steel. Applying a selected condition of postweld heat treatment in each series, tensile and yield strength of base metal and soft interlayer varied in a wide range, as shown in Table 1. In addition to this, an undermatching welded joint was made in Series IV by metal-arc narrow gap welding an HT 80 structural steel 25 mm thick with an electrode of 50 kg/mm² nominal tensile strength level. Figure 2 shows the design of the round bar and flat bar tension specimens which were machined after welding.



Series	D_0 (mm)	H_0 (mm)	L_0 (mm)	X	Remarks (type)
I , III	10	0.25 ~ 19.0	90	0.03 - 1.90	
II	3	0.30 ~ 4.34	27	0.10 - 1.43	II A
	6	0.24 ~ 9.39	54	0.21 - 1.56	II B
	10	0.60 ~ 13.9	90	0.06 - 1.39	II C
	15	1.04 ~ 15.2	135	0.07 - 1.01	II D

(a) round bar



Series	t_0 (mm)	H_0 (mm)	W_0 (mm)	L_0 (mm)	X_t	Remarks
IV	20	7	20 ~ 120	200	0.33	IVS-A
	15	7	15 ~ 100	200	0.47	IVS-B

(b) rectangular bar

Fig. 2 — Specimen design in fundamental study

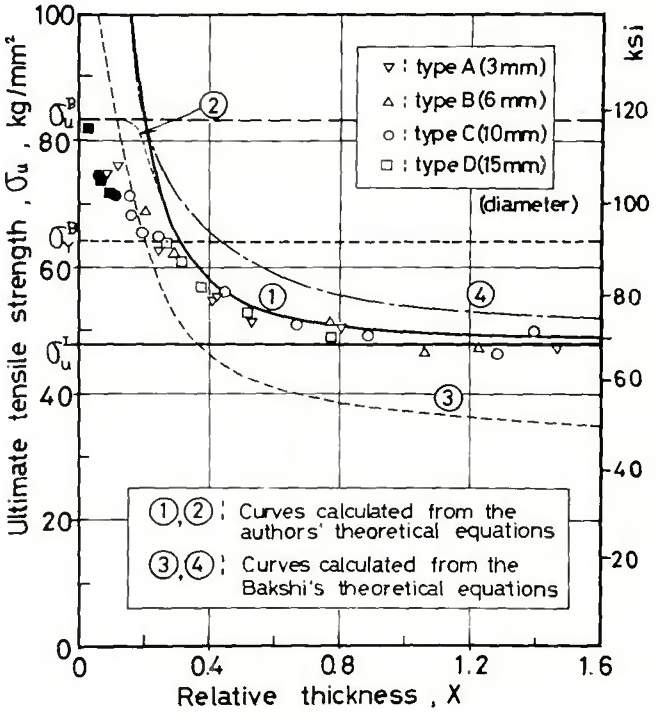


Fig. 3 — Effect of relative thickness of soft interlayer on the ultimate tensile strength of round bar specimen (Series II)

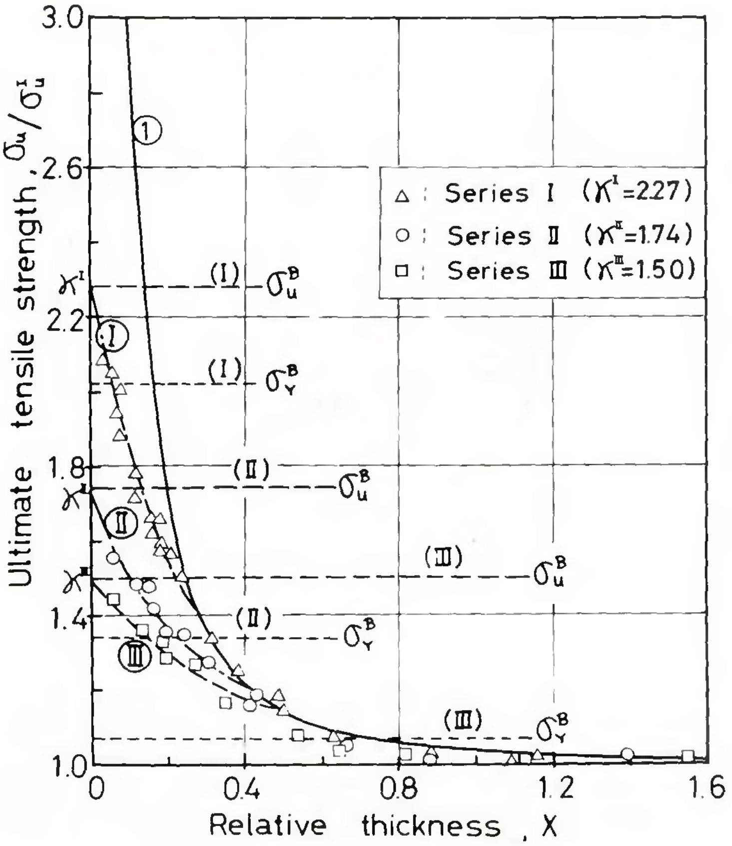


Fig. 4 — Ultimate tensile strength, σ_u/σ_u^I, as a function of relative thickness, X, (Series I, II, III)

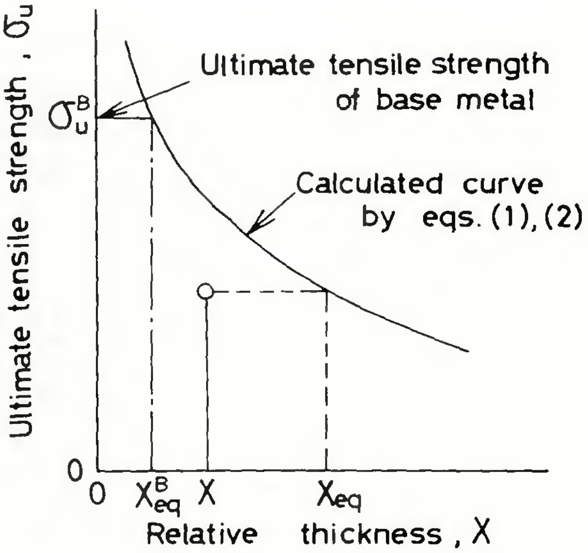


Fig. 5 — Determination of X_{eq}^B value

Results of Round Bar Tests

As mentioned, the ultimate tensile strength σ_u of the round bar joint specimen depends upon its relative thickness X. Therefore, the test results of the σ_u value were plotted for the X value of each specimen.

Figure 3 shows the test results of Series II in which specimen diameter ranges between 3 mm and 15 mm. The ultimate tensile strength is represented as a function of the relative thickness regardless of the specimen diameter, and it approaches the ultimate tensile strength of the base metal σ_u^B when the X value decreases. The curve 1 in Fig. 3 is calculated from Eqs. (1), (2) and the curves 3, 4 are obtained from the conventional formula given by Bakshi under more simple assumptions (Refs. 6,7). The experimental values can be estimated from the calculated curve 1 when the X value exceeds nearly 0.4.

Figure 4 shows the test results of Series I, II, III in which tensile strength of the soft interlayer σ_u^I is about 47 kg/mm² and those of the base metal σ_u^B differ from each other. The experimental values of the tensile strength diverge from the curve 1 calculated from Eqs. (1), (2) as the X value decreases, and because of difference in the ultimate tensile strength of the base metal in each series, different values of the joint strength are obtained, even though the tensile strength of the soft interlayer is the same in each series.

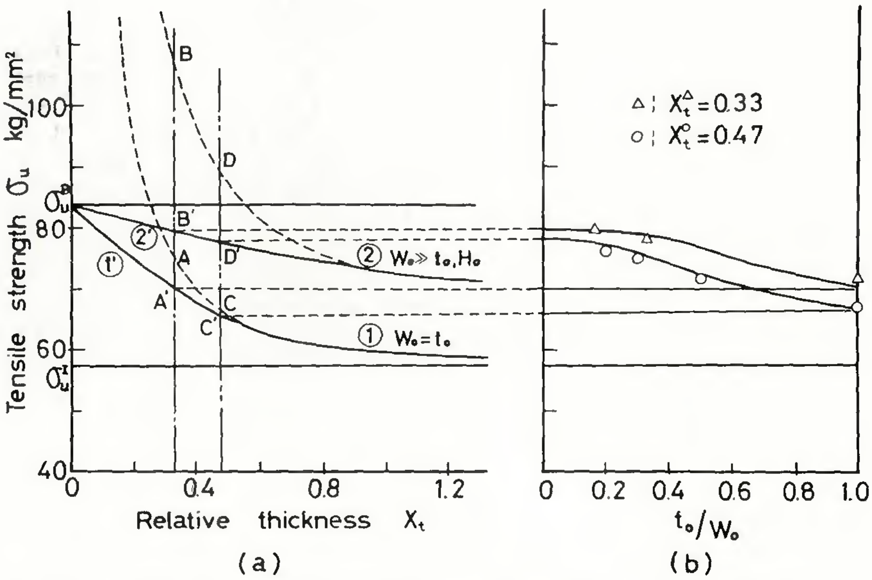


Fig. 6 — Effect of width of specimen on ultimate tensile strength, σ_u, (Series IV)

As illustrated in Fig. 5, let the X value at which the tensile strength calculated from Eqs. (1), (2) becomes σ_u^B be denoted by X_{eq}^B. When the X value is smaller than $2X_{eq}^B$, the X_{eq} value as given by Eq. (3) should be used in Eq. (2) in place of X;

$$X_{eq} = 0.5\,X + X_{eq}^B \qquad (3)$$

Using the X_{eq} value, the tensile strength σ_u can be calculated as the curves I, II, III in Fig. 4.

Results of Flat Bar Tests

The test results of tensile strength σ_u obtained in Series IV, in which the specimens consist of several combinations of width W_0 and plate thickness t_0 under a constant thickness of undermatching filler metal, are plotted in Fig. 6(b) as a function of t_0/W_0. The dotted curves 1, 2 in Fig. 6(a) represent the relationship of σ_u vs. X calculated for $W_0 = t_0$ and $W_0 \gg t_0$, H_0 respectively. They are modified as the solid curves 1′, 2′ by using the X_{eq} value given by Eq. (3). It has been found that the ultimate tensile strength of the square bar model joint specimens is nearly equal to the round bar test results when $X_t = X$ (Refs. 3,4). Therefore the curves 1,1′ can be calculated from Eqs. (1), (2), and the curves 2, 2′ are obtained in a manner analogous to the above, under the condition of plane strain along the cross section of weld.

It is known from Fig. 6(a) that the ultimate tensile strength σ_u increases from the curve 1′ in the square bar to the curve 2′ in the infinitely wide plate with increase of the plate width. The ratio of the σ_u value when $W_0 \gg t_0, H_0$ to that when $W_0 = t_0$ is given by

$$\frac{(\sigma_u)_{W_0 \gg t_0}}{(\sigma_u)_{W_0 = t_0}} = 0.8\ (\kappa - 1)X_t + 1.0,$$

for $X_t \geq (X_t)_D$

or $(0.1/X_t) + 1.1$, for $X_t < (X_t)_D$ (4)

in which $\kappa = \sigma_u^B/\sigma_u^I$, and

$$(X_t)_D = \frac{1 + \sqrt{1 - 32(\kappa - 1)}}{16(\kappa - 1)} \quad (5)$$

For example, the σ_u value increases with decrease of t_0/W_0 from the point A′ to B′ when $X_t = 0.33$ and from the point C′ to D′ when $X_t = 0.47$. The corresponding curves of σ_u vs. t_0/W_0 are represented by solid curves in Fig. 6(b), which agree with the experimental results.

The experimental results in Fig. 6(b) suggest that the tensile strength becomes almost the same as that of an infinitely wide plate when the plate width W_0 becomes larger than a certain finite value $W_{inf.}$ depending upon the relative thickness X_t. Several results obtained by the tension test of the undermatching welded joint are shown in Fig. 7, from which the $W_{inf.}$ value may be roughly estimated by the line 3 or $W_{inf.} \approx 5t_0$ when $X_t \leq 1$.

Performance of Undermatching Welded Joint

General

The fundamental study suggests that the ultimate tensile strength of the undermatching welded joint may become as high as the base metal if the average width in the cross section of weld metal is appreciably small compared to the plate thickness. In order to find out whether the undermatching electrode is applicable in practical welding of heavy plates of high strength steels or not, the SJ-committee of JWES has conducted a joint performance study for the past three years.

In the joint performance study three kinds of tests were undertaken, i.e., static tension test, brittle fracture test and fatigue test. The materials used were HT 80 structural steels of 12 mm, 25 mm and 70 mm thickness for the base metal and electrodes of 47 kg/mm² through 80 kg/mm² nominal tensile strength level for filler metal. The 12 mm thick plate was used only for the fatigue test because of the capacity of testing apparatus available.

Tension Test and Results (Ref. 8)

The undermatching welded joints were made from a HT 80 steel plate 70 mm thick by shielded metal-arc welding. The electrodes selected are of E11016 type and of undermatching E9016 and E7016 type. Welding was done under 150 to 250 C preheating and interpass temperature to avoid weld cracking. No harmful weld defects were found by nondestructive testing after welding. Design of the specimen is illustrated in Fig. 8, in which two types of specimens are shown, i.e., square bar (type M) and wide plate (type L). Differing from the model joint specimen in the previous paragraph, the shape of the weld metal in cross section is oblique (V groove) to the plate surfaces. Therefore, the average value of the relative thickness $(X_t)_{av}$, was calculated from a macro-etched photograph of each weld by the formula given in Fig. 8. Table 2 shows the coupon test results of the base metal and weld metal.

The tension test results are summarized in Fig. 9(a) and (b). In type M (square bar) specimens, the joint strength σ_u does not reach the tensile strength of the base metal used nor the value of 80 kg/mm² (minimum required tensile strength of HT 80 steel plate). In type L (wide plate) specimens, however, the σ_u value is increased as estimated by Eq. (4), and it becomes as high as the tensile strength of the base metal even when the undermatching electrode of E9016 type is used.

In all of the type L specimens, fracture occurred nearly along the weld fusion line accompanied by appreciable lateral contraction in the plate width direction. In some of the fracture surfaces of the specimens made with E11016 and E9016 type electrodes there was observed a brittle fracture appearance, of which crystallinity is less than 20 percent. However, in the specimens using E7016 type electrode, it exceeds 80 percent. Thus, the joint ductility becomes considerably small when using E7016 type undermatching electrode as shown in Fig. 9(b).

Figure 10 shows the tensile strength ratio to the base metal of undermatching welded joint versus undermatching weld metal. In the figure, open and black circles are test results shown in Fig. 9(a) and the curves represent the results calculated by the method described in the previous paragraph. The average relative

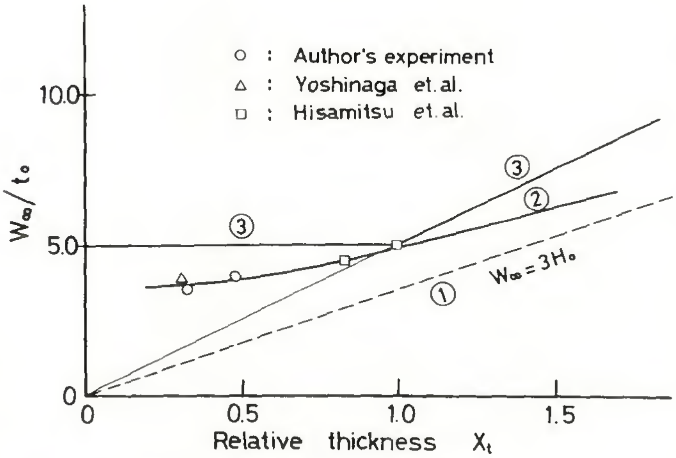
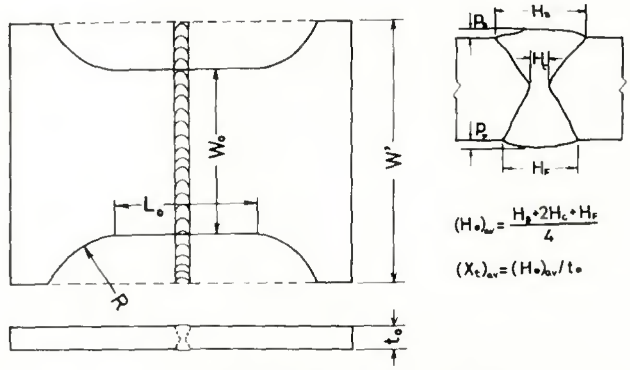


Fig. 7 — The ratio $W_{inf.}/t_0$ as a function of X_t



type	W_0	L_0	t_0	W'	R
L	500	400	70	800	200
M	70	400	70	140	200

Fig. 8 — Specimen design in static tension test

thickness, $(X_t)_{av}$, illustrated in Fig. 8 was between 0.2 and 0.3 in each specimen, and the calculation was made as $(X_t)_{av}$ = 0.25. The joint strength could be well estimated by the calculation. In type L specimen, it reaches the tensile strength of the base metal σ_u^B when the tensile strength of the weld metal is higher than nearly 90% of the base metal. It will be concluded from the results that the undermatching welded joint showing a strength ratio, Sr (Fig. 10), higher than 0.9, represents the same behavior as the usual overmatching welded joint from the standpoint of both joint strength and ductility (Ref. 9).

Brittle Fracture Test and Results (Refs. 10,11)

Two series of tests were conducted for investigating the behavior of brittle fracture initiation of the undermatching welded joint. Deep notched specimens as shown in Fig. 11 were made from the submerged arc welded joint of an HT 80 steel plate 25 mm thick. Nominal tensile strength (NTS) level of the electrodes used was 80 kg/mm² and 50 kg/mm². Weld reinforcement was machined off the deep notches 120 mm long were saw cut from both sides of the BI type specimen and 140 mm long at the center of the BII type specimen. Testing temperatures were selected between 0 C and −200 C. The BI type deep notch test of the HT 80 steel plate was also done as a reference test. Mechanical properties of the base metal and the filler metals are shown in Table 3.

Figures 12 and 13 show the relationships between fracture stress at the net section of each specimen and testing temperature in BI type and BII type tests respectively. The σ_y curves show the temperature dependence of 0.2% proof stress of each material.

In the BI-type test, the fracture stress curves of the welded joint move to the higher temperature side as compared to the base metal. Among the three kinds of filler metal selected, the welded joints using elec-

Table 2 — Coupon Test Results of Base Metal and Weld Metal in Static Tension Test

Base metal

Steel	Plate thickness (mm)	T S (kg/mm²)	Y S (kg/mm²)	Elongation (%)	Reduction in area (%)
HT80[a]	70	82.1	75.4	25.4	69.2

(JIS No 4)

Weld metal

Specimen No.	Electrode	Groove	T S (kg/mm²)	Y S (kg/mm²)	Elongation (%)	Reduction in area (%)
①-6U	E9016	U	67.8	–	(24.5)	67.5
①-6X	E9016	X	65.1	–	(25.0)	70.6
①-5U	E7016	U	59.6	51.4	–	75.2
①-5X	E7016	X	54.0	47.8	–	79.8
①-8	E11016	–	88.3	83.7	–	71.0

(a) Chemical composition C 0.10%, Si 0.31%, Mn 0.84%, P 0.009%, S 0.009%, Ni 1.08%, Cr 0.53%, Mo 0.40%

Table 3 — Mechanical Properties of Base Metal and Filler Metal in Brittle Fracture Test

Series	Material (Weld metal)		Mechanical properties T S (kg/mm²)	Y S (kg/mm²)	vTs (°C)	thickness (mm)
B I	Base metal (HT80)[a]		82.1	75.3	−88	25
	Weld metal	NTS : 80	81.3	59.0	−43	
		NTS : 60	70.8	56.3	−75	
		NTS : 50	64.4	49.4	−53	
B II	Base metal (HT80)		82.6	76.8	−78	25
	Weld metal	NTS : 80	80.5	66.0	82	
		NTS : 50	63.4	50.0	−20	

vTs : Fracture transition temperature in V-Charpy test

(a): Chemical composition : C 0.14%, Si 0.23%, Mn 0.90%, P 0.012%, S 0.008%, Mo 0.44%, Cr 0.73%, V 0.03%

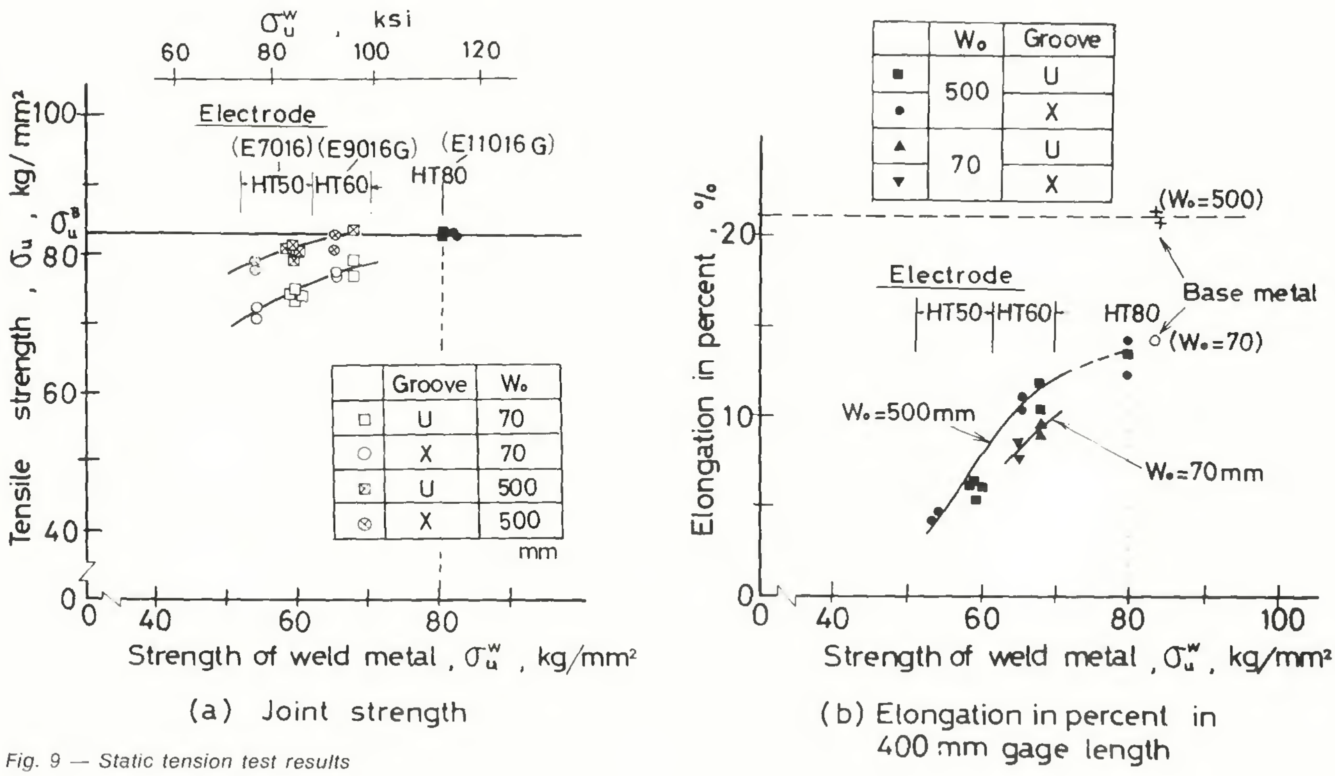


Fig. 9 — Static tension test results

trodes of 60 kg/mm² NTS level seem to have rather higher strength, but the others have almost the same fracture strength in each temperature tested despite the considerable difference in yield and tensile strength of their filler metals. The reason will be due to the difference in fracture toughness of each material. As shown in Table 3, fracture transition temperature vTs obtained from V-notch Charpy test is lowest for the filler metal of 60 kg/mm² NTS level and is highest for the filler metal of 80 kg/mm² NTS level. It will be recognized that the stress at the initiation of brittle fracture is influenced by both strength and fracture toughness of the materials near the notch; the lower strength will decrease the fracture stress at the temperature tested and the higher fracture toughness will move the fracture intiation temperature at the stress level tested to the lower temperature side.

In the BII-type test, two steps of fracture were observed in the higher temperature range tested; complete fracture of the specimen was accompanied by primary fracture of considerably shorter crack length at a lower stress level. This will be due to residual stresses from welding. Because of much higher vTs values in the filler metal of 80 kg/mm² NTS level as shown in Table 3, the primary fracture stress is lower in this welded joint than in the undermatching welded joint.

It will be understood from the above test results that higher fracture toughness or lower transition temperature should be required for the undermatching filler metal than for the overmatching filler metal from the standpoint of brittle fracture initiation. Fracture mechanics approach will give quantitatively the fracture toughness required in the undermatching welded joint for obtaining the same fracture initiation temperature T_i as in the overmatching welded joint, at which the fracture stress of the notched plate becomes equal to half of the yield stress of the base metal at room temperature. This paper uses the criterion that brittle fracture should initiate when the size of tensile yield zone ρ formed ahead of a pre-existing crack attains a crit-

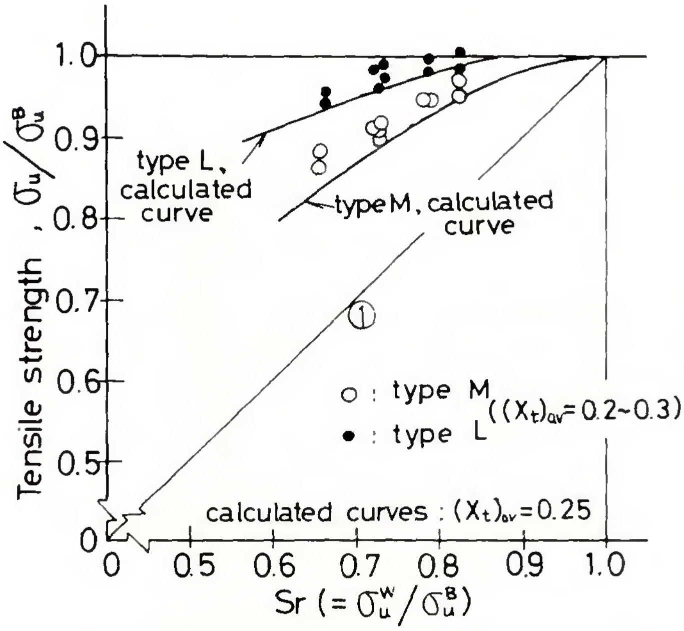


Fig. 10 — Tensile strength ratio of undermatching welded joint vs. undermatching weld metal

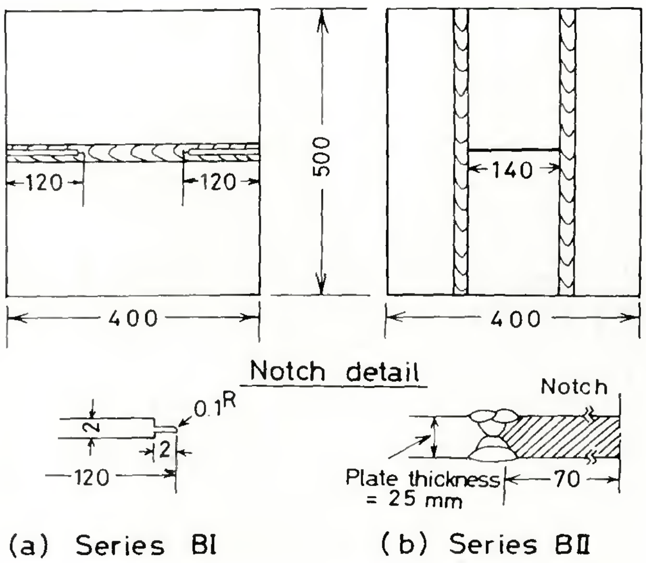


Fig. 11 — Brittle fracture test specimens

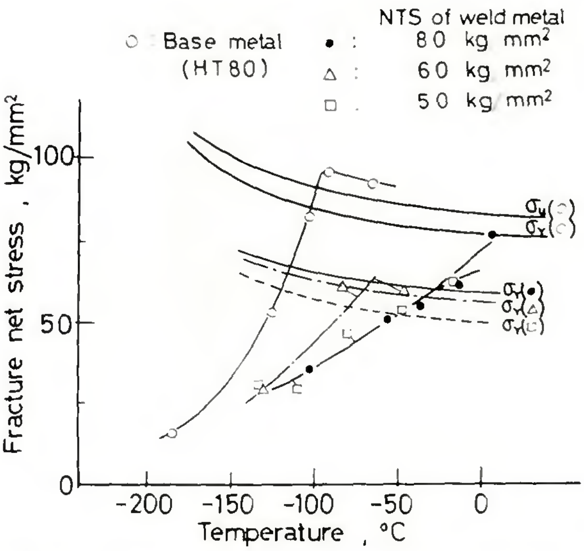


Fig. 12 — Fracture stress vs. temperature relations in BI-type test

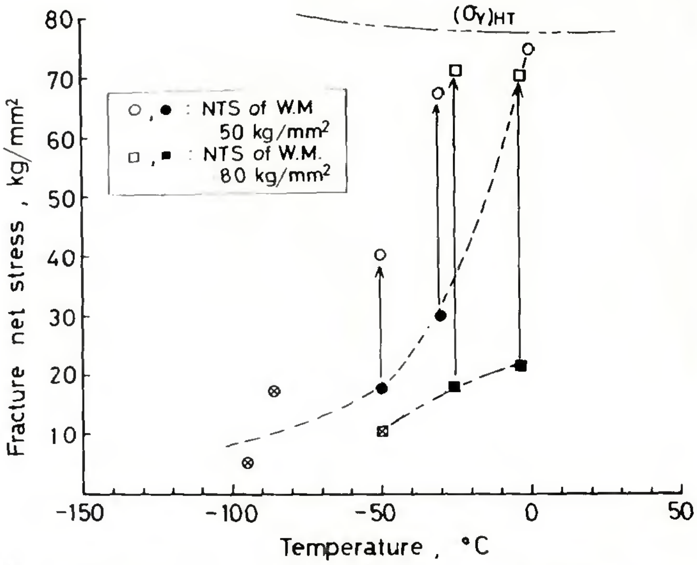


Fig. 13 — Fracture stress vs. temperature relations in BII-type test

ical value ρ_c. Applying the criterion and using the temperature dependency of the ρ_c value as a function of the V-Charpy fracture transition temperature vTs obtained by Koshiga et al (Ref. 12), the difference ΔvTs of the vTs value between overmatching filler metal and undermatching filler metal required for obtaining the same values of T_i in the notched wide welded plate is given by (Refs. 9,13):

$$\Delta_v T_s = 80 \ln (S_r)_Y \quad [1 - 65\,(1/T_i - 1/273)] \qquad (6)$$

in which $(Sr)_Y$ is the yield stress ratio of undermatching filler metal vs. overmatching filler metal and T_i is in deg K. It is seen from Eq. (6) that when $(Sr)_Y$ = 0.8 and T_i = about −50 C to −150 C, the required ΔvTs value is about 15 C to 20 C, or the vTs value required in the undermatching filler metal is 15 C to 20 C less than that of the overmatching filler metal.

Fatigue Test and Results

Fatigue strength of the undermatching welded joints under pulsating load was investigated by using groove weld specimens of a HT 80 steel plate 12 mm thick. Shielded metal-arc welding was done with E11016 and E7016 type electrode under 150 C preheating and interpass temperatures. Two types of the specimen, as shown in Fig. 14, were machined for applying the pulsating load transverse and parallel to the weld. The weld reinforcement was not removed. Table 4 shows the mechanical properties of the base metal and weld metals used.

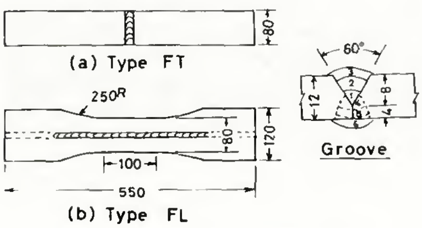


Fig. 14 — Fatigue test specimen design

The fatigue test was done under pulsating load between nearly zero minimum stress and maximum stresses of 35 kg/mm² and 55 kg/mm². The test results are summarized in Table 5. In the FT-type specimens, in which tensile stresses are applied transverse to the weld, fatigue cracking occurs at the toe of the reinforcement and propagates in the thickness direction. Therefore, appreciable difference in the number of cycles to fracture does not appear between overmatching and undermatching welded joints. In the FL-type specimens, in which tensile stresses are applied parallel to the weld, on the other hand, fatigue life of the overmatching welded joint is rather longer than the undermatching welded joint because fatigue crack initiation starts on the surface of weld metal. However, the difference may be very small, particularly at the lower maximum stress level.

Further Study

Since the fundamental study and the performance study have made it clear that the undermatching electrode may be applicable to practical welding of heavy plates of high strength steels, the SJ-Committee has attempted further study to gather and summarize experimental and practical data in structural welded joints.

One of the examples of experimental study on structural welded joint performance is a burst test of welded pipes of HT 80 steel plate. The test was carried out as cooperative study of Osaka University, Sakai Iron Works and Nippon Kokan.

The test specimen consisted of welded pipes 4100 mm, long, 950 mm diam, made from HT 80 steel plate 12 mm thick, as shown in Fig. 15. The axial joints were made by submerged arc welding with electrodes of 80 kg/mm² nominal tensile strength (NTS) level. However, a mis-selected welding procedure resulted in the ultimate tensile strength of its filler metal to be only about 77 kg/mm², or 12 kg/mm² less than the base metal. The circumferential joints were made by gas metal-arc welding with electrodes of 60 kg/mm² and/or 80 kg/mm² NTS level in each weld, for which ultimate tensile strength by coupon test was 77 kg/mm² and 82 kg/mm² respectively.

The burst test was carried out by applying hydraulic internal pressure. At 235 kg/cm² internal pressure, fracture started at a location in the base plate just outside of the heat-affected zone of an axial weld, about 700 mm from the end of the specimen, and ran nearly parallel to the axial weld (See Fig. 16). The circumferential stress calculated from 235 kg/cm² internal pressure at fracture is 90 kg/mm² which agrees well with the ultimate tensile strength 89 kg/mm² of the base plate used. In this case, the undermatching filler metal apparently did not have any harmful influence on the fracture.

In addition to the experimental studies, some examples of the undermatching welded joints in actual weld-

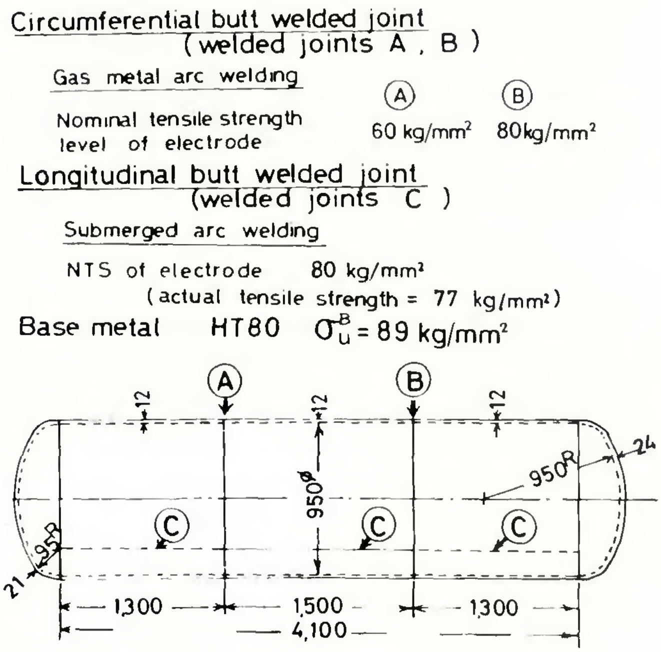


Fig. 15 — Specimen design for burst test

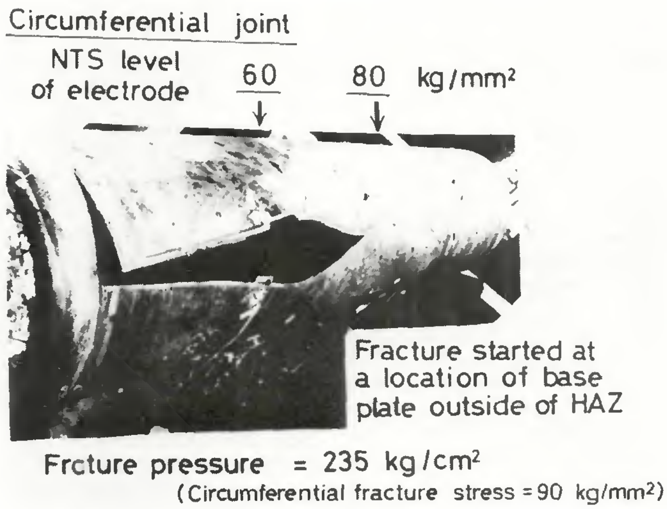


Fig. 16 — Fracture specimen by burst test

Table 4 — Mechanical Properties of the Materials used for Fatigue Test

Material		Tensile strength (kg / mm²)	Yield strength (kg / mm²)
Base metal HT80[a]		8 4	7 9
Electrode	E 11016	8 6	7 4
	E 7016	5 5	-

(a): Chemical composition : C 0.10%, Mn 0.79%, Si 0 26%
P 0.004%, S 0.007%, Ni 0 83%, Cr 0 52%
Mo 0.34%

Table 5 — Fatigue Test Results

Maximum stress applied (kg / mm²)	Electrode used	No of cycle at fracture: Type FT ($\times 10^4$)	Type FL ($\times 10^4$)
3 5	E 11016 - G	1 5 2 1 3 2	2 0 8 2 3 1
	E 7016	1 3 8 1 4 1	1 6 2 2 2 3
5 5	E 11016 - G	3 72 1 38 3 17	2 62 2 45
	E 7016	8 65 6 63	4 63 5 34

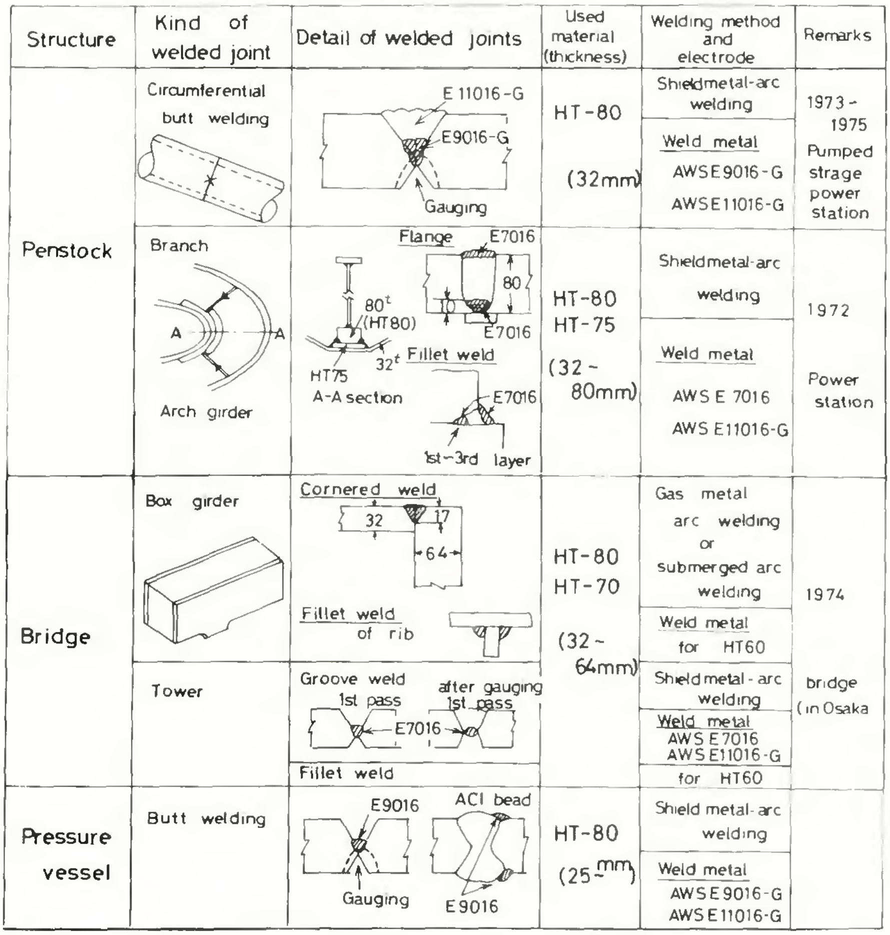


Fig. 17 — Some examples of the undermatching welded joints in actual welded structures

ed structures have been collected. They are summarized in Fig. 17. At present in Japan, undermatching electrodes are often used for several layers at the root and/or finishing layers on the surface of multipass groove welds and fillet welds in order to make it easy to prevent weld cracking.

Summary

1. Mechanical properties under static tension of the idealized model joint including a soft interlayer are influenced by the value of relative thickness of the interlayer. As the relative thickness decreases, the joint tensile strength increases from the tensile strength of the soft interlayer to the base metal strength. The joint strength is also changed with the plate width of the model joint; it is increased with increase in the width until the width becomes larger than about five times the plate thickness. Ultimate tensile strength of the model joint can be well estimated by formula including variables such as the relative thickness and the strength ratio of soft interlayer vs. base metal.

2. The results obtained from the fundamental study mentioned above can be also applied to the undermatching welded joint of heavy plates of HT 80 structural steel. In a sufficiently wide welded joint, the joint strength equal to the tensile strength of base plate could be guaranteed when tensile strength of the undermatching filler metal is not less than 90 percent of the base plate strength. In this case, joint ductility is also as high as the overmatching welded joint of the E11016 type electrode.

3. Initiation of brittle fracture at low stress level is influenced by both yield strength and fracture toughness of the undermatching filler metal. The lower yield strength reduces the stress leading to fracture in a notched wide welded joint at a given testing temperature and the higher fracture toughness lowers the fracture initiation temperature at a given stress level. As the result, if the fracture toughness of the undermatching filler metal is higher than the overmatching filler metal, the same temperature T_i as the overmatching welded joint (at which brittle fracture of a notched wide welded joint initiates under the stress level of half the yield strength of base metal at room temperature), can be obtained even in the undermatching welded joint. Yield strength of the undermatching filler metal being selected as 80 percent of the overmatching filler metal, this is realized when the Charpy-V fracture transition temperature vTs of the undermatching filler metals is about 15 C to 20 C lower than vTs of the overmatching filler metal.

4. Fatigue life under pulsating load applied across the weld is not changed appreciably between the undermatching and overmatching welded joint of HT 80 steel plate, because the fatigue crack starting at a toe of the reinforcement runs through the heat affected zone. When a pulsating load is applied parallel to the weld, fatigue life of the undermatching welded joint is rather small as compared to the overmatching welded joint.

5. A pipe specimen of HT 80 steel plate welded with the undermatching

electrode produced the same burst stress as the tensile strength of the base plate under hydraulic internal pressure. At present in Japan, an undermatching electrode is often used for one or more passes in multipass groove and fillet welds in HT 80 steel structures.

Acknowledgments

Part of the experiments presented here were conducted under the financial support from the Iron and Steel Technical Committee of the Japan Welding Engineering Society. The experiments and discussions have been made mainly at the SJ-Committee of the JWES. The authors would like to thank Professor H. Kihara, President of the JWES, for his help and support to this study. The authors also acknowledge the technical cooperation from, and many helpful discussions with, each member of the SJ-Committee.

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WRC Bulletin 203
February 1975

"Niobium and Vanadium-Containing Steels for Pressure Vessel Service"

by J. N. Cordea, Armco Steel Corp.

The effects of niobium (Nb) and vanadium (V) additions on the properties of plain carbon (C) steel have been well known for some years now. Recently, through refinements and processing technology, very effective use has been made of relatively small amounts of Nb or V (up to 0.2 wt-%) to significantly increase yield strength and improve notch toughness. These improvements have resulted through optimization of Nb and V carbonitride precipitation hardening, ferrite grain size refinement, and a reduction in C content. The latter item also significantly improves weldability.

Nearly all of the industrialized countries of the world have taken advantage of the economy of producing higher strength steels with a minimum of extra alloying cost. This is especially true for structural applications where weight saving is so important. Many countries have also made effective use of these steels for pressure vessel applications. Although the United States is very active in high-pressure line-pipe development, very little activity has been directed toward using Nb and V steels for pressure vessels and other containers. The principal reason is that allowable-stress calculation as specified by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code is usually governed by tensile strength. While yield strength is increased significantly by Nb and V additions, there is a relatively small effect on tensile strength. Consequently, no direct advantage can be gained in pressure vessel design by an increase in yield strength.

It is the purpose of this report to summarize the state of the art of Nb- and V-containing C-Mn steels for pressure vessel applications and to identify areas needing further research. Specifically, this report covers low-alloy steels with an upper yield-strength range of about 75 ksi (53 kg/mm^2). A brief summary of the pressure vessel codes around the world is presented in order to provide a basis for important material properties in the design of pressure vessels. Available steels, their mechanical properties and the technology for producing them are covered in detail. Although a few structural grades and pipeline steels from the United States are discussed, the main emphasis is directed toward foreign steels produced for pressure vessel applications. Where appropriate, comparisons are made to similar composition structural grades produced in the United States. Weldability and other important properties necessary for satisfactory fabrication and service are evaluated. This work was initiated and sponsored by the Pressure Vessel Research Committee of the Welding Research Council, Fabrication Division, Subcommittee on Thermal and Mechanical Effects.

The price of WRC Bulletin 203 is $6.50 per copy. Orders should be sent with payment to the Welding Research Council, United Engineering Center, 345 East 47th Street, New York, N.Y. 10017.

WRC Bulletin 201 December 1974

1. "The Submerged Arc Weld in HSLA Line Pipe — A State-of-the-Art Review"
by P. A. Tichauer

The submerged arc weld in HSLA line pipe is examined by briefly reviewing the metallurgy of high-strength low-alloy steels and then considering how the welding process affects this metallurgy. Particular emphasis is given to the influence of thermo-mechanical processing and to the role of micro-alloy additions as they relate to strength, grain size and toughness. The metallurgy of the weld is contrasted to that of the base plate, and some recent investigations are reviewed. The influence of consumable selection is considered, and some recommendations for further study are made.

2. "Experience in the Development and Welding of Large-Diameter Pipes"
by M. Civallero, C. Parrini and G. Salmoni

The production of X70 pipes up to 30 mm wall thickness with high base-material toughness has become necessary and possible today. In the choice of the most suitable type of steel, the mill and field weldability problems have been considered, as well as the weld-joint toughness requirements.

Of the experimental solutions, the best appears to be a control-rolled dispersoid steel, with extra-fine structure (mostly acicular type) with reduced pearlite and controlled inclusions. This steel, welded with the normal double-pass submerged arc techniques, allows one to achieve good toughness in the heat-affected zone, and to improve weldability compared to conventional steels. By further improving the type of flux on the basis of the theories developed, and by widening the knowledge of the effects of chemical composition (correlation between chemical composition, liquid-and-solid, austenite-to-ferrite transformation and final structures), it is believed possible to improve the low-temperature toughness up to the 10 kg/cm^2 level at temperatures down to -40 C, in wall thicknesses up to 30 mm.

3. "New Development in Weldability and Welding Technique for Arctic-Grade Line Pipe"
by E. Miyoshi, Y. Ito, H. Iwanaga and T. Yamura

In this study, low-temperature burst tests were performed on 48-in. diameter × 1-in. thick × 8-ft long line-pipe specimens of a 1% Ni steel recently developed and produced by controlled rolling. Notches twice the size of the largest allowable defect in API Std. 1104 were incorporated in the longitudinal weld seam. Test data were assessed by a COD approach. Two heat inputs were used in welding the specimens. A special GMA welding technique was developed for the lower heat input. It was found that the lower heat input was the best method of improving the fracture toughness of the weld.

4. "Technology of Wires and Electrodes for Welding High-Strength Pipe"
by J. Grosse-Wordemann

During the past few years, developments have led to steel grades with improved mechanical properties and reduced carbon content, compared to the previously known carbon-manganese grades. The new steels have improved weldability and API grades X60, X65 and X70 are already in use. The development of X80 is close to completion. This paper reviews the latest technology in developing suitable filler metals for welding these high-strength line-pipe steels.

5. "Preliminary Evaluation of Laser Welding of X-80 Arctic Pipeline Steel"
by E. M. Breinan and C. M. Banas

Single- and dual-pass laser welds were made in an alloy steel currently being evaluated for potential Arctic gas pipeline applications. The laser welds exhibited excellent overall mechanical properties and a Charpy shelf energy greater than 264 ft-lb, which is substantially above that of the base material. Dual-pass welds exhibited a ductile-to-brittle transition temperature below -60 F. Increased shelf energy was attributed to a reduction in the visible inclusion content of the fusion zone while transition temperature was shown to be strongly dependent upon fusion-zone grain size.

Paper (1) was prepared for the Subcommittee on Line-Pipe Steels of the Weldability (Metallurgical) Committee of the Welding Research Council. The other four papers were presented at a session sponsored by this subcommittee during the 1974 AWS Annual Meeting.

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