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Matching Ferritic Filler MIG Welding of 9%Ni Steel

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The body can be viewed from the next page.

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A technique for stabilizing pure argon shielded MIG arcs using rare earths-bearing electrode wires has been applied to the matching ferritic filler welding of 9%Ni steel. Investigations have been made on the hot crack susceptibility, mechanical properties and fracture toughness of weld metals. The results of the investigations summarized below have proved the practicability of the matching ferritic filler welding.

(1) Hot crack resistivity of ferritic weld metals is far better than that of high-Ni-based weld metals, with no crack occurring even in weld craters.

(2) Tensile properties of all-deposited metals and welded joints are equal to those of the base plates, with a rise in the allowable design stress value.

(3) Ferritic weld metals obtained with pure argon shielded MIG arcs have excellent low-temperature toughness based on the reduction in silicon and oxygen contents.

(4) Matching ferritic welds obtained with pure argon shielded MIG arcs have excellent fracture toughness.

1 Introduction

For welding 9%Ni steel plates for low-temperature liquefied gas tanks and others, high-Ni-based (austenitic) welding materials are primarily used. The weld metals show excellent low-temperature toughness even without post weld heat treatment (PWHT), but they have a disadvantage in that owing to their relatively low strength, allowable design stress of welded structures cannot be set up high (JIS B 8243: 16.7 kgf/mm^2). Moreover, they pose problems such as inferior deposition efficiency and poor welding operational efficiency, because the austenitic weld metals lack hot crack resistivity.

In order to solve the present situation involving the welding of 9%Ni steel, research has been carried out recently on the TIG welding using matching ferritic fillers having practically the same chemical composition as that of the steel plates[1,2]. For obtaining ferritic weld metals excellent in low-temperature toughness, it has been suggested that decreasing such impurities as oxygen and nitrogen is indispensable[3]. Therefore, TIG arcs stable in a pure argon shield may be considered a heat source suitable for the matching ferritic filler welding, but the difficulty lies in their very low welding efficiency.

Research and development of the matching ferritic filler MIG welding method which allows high-speed welding were once performed[4], but no practical advancements have been achieved, since MIG arcs are stabilized only in the oxidizing-gas-mixed atmosphere.

Kawasaki Steel Corporation has been working on the method of stabilizing pure argon shielded MIG arcs, and has achieved the purpose by adding minute quantities of rare earths to the welding wire[5,6]. Kawasaki Steel has also succeeded in applying the stabilization techniques to the matching ferritic filler MIG welding of 9%Ni steels. This report gives an outline of the MIG welding of 9%Ni steel using rare earths-bearing matching ferritic fillers and describes the mechanical properties of such welded joints.

2 Effects of Silicon and Oxygen Contents on the Toughness of Weld Metal

In order to give excellent low-temperature toughness to the ferritic weld metal, it is considered necessary to reduce the contents of oxygen and other impurity elements in the weld metal[3]. In this chapter, attention is focused on oxygen and silicon contents in the weld metal, and the relation between these elements and the low-temperature toughness of the weld metal is described.

2.1 Preparation of Weld Metals

Steel plates used were commercial 9%Ni steel plates

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** Research Laboratories

Table 1 Chemical compositions of materials used

Material		C	Si	Mn	P	S	Ni
Plate (14mm*t*)		0.042	0.26	0.58	0.005	0.005	8.84
Wire (1.2mmϕ)	No.161	0.047	0.12	0.52	0.002	0.001	11.47
	No.162	0.047	0.30	0.50	0.002	0.001	11.36
	No.163	0.048	0.52	0.52	0.002	0.001	11.51

Table 2 Chemical compositions of weld metals

%CO_2 in shielding gas	No.161		No.162		No.163	
	Si (%)	O (ppm)	Si (%)	O (ppm)	Si (%)	O (ppm)
1.5	0.12	135	0.26	149	0.47	95
3	0.099	240	0.26	221	0.45	206
5	0.094	407	0.28	235	0.44	239
10	0.073	528	0.27	328	0.43	321

* 0.04%C, 0.50%Mn, 0.002%P, 0.002%S, 11%Ni, 25ppmN

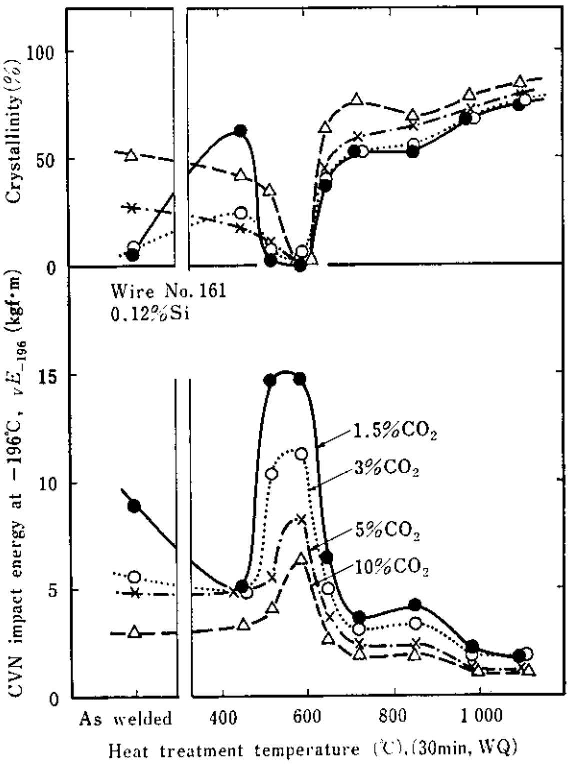


Fig. 1 Effects of %CO_2 in shielding gas and heat treatment temperature on the toughness of weld metal

of 14 mm in thickness, and welding wires were 1.2 mmϕ matching ferritic wires having different silicon contents. **Table 1** shows the chemical compositions of the materials used.

Welding conditions are 320 A, 25 V, and 25 cm/min (19.2 kJ/cm), and 5-pass welding was performed in the V-groove with an argon shield having different CO_2 gas mixing ratios. **Table 2** shows the chemical compositions of weld metals.

After welding was completed, part of the samples was subjected to the tests in the as-welded condition, and the remainder was subjected to heat treatments of 450 to 1 100°C × 30 min (water cooled), in order to examine the proper tempering conditions for the weld metals.

2.2 Test Results and Discussion

Fig. 1 shows the relation between heat treatment temperatures and CVN properties of the weld metal obtained with an ultra-low silicon wire (No. 161). As CO_2 content in the shielding gas is decreased, namely, as oxygen content in the weld metal drops, toughness tends to be improved, thereby indicating that decreasing oxygen content is an effective measure

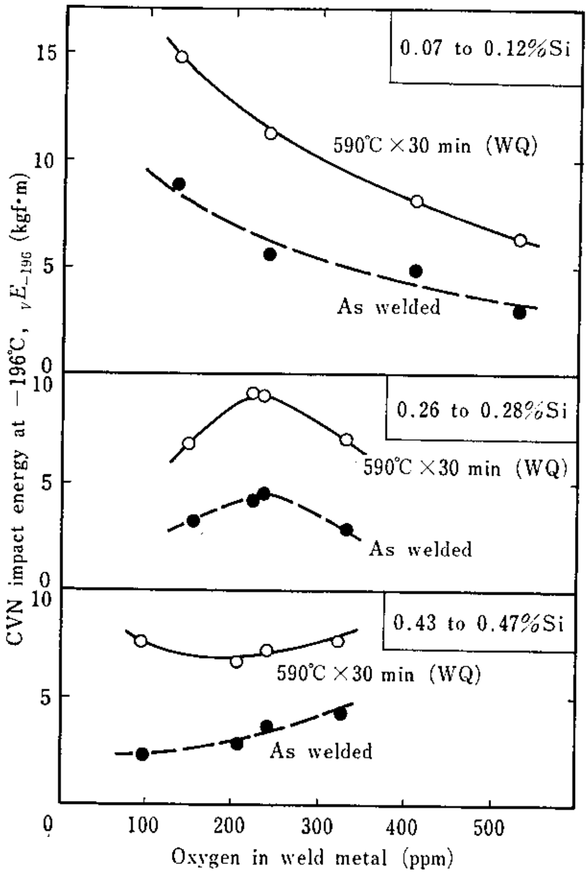


Fig. 2 Effects of silicon and oxygen on the toughness of weld metal

for improving toughness. The variation in toughness with respect to heat treatment temperatures indicates that the highest toughness value is obtained within the tempering temperature range of 550 to 600°C regardless of the magnitude of oxygen content. This temperature range is slightly lower than that for the steel plates (565 to 635°C: ASTM A553).

When medium- and high-silicon wires (Nos. 162 and 163) were used, toughness also showed the maximum value within the temperature range of 550 to 600°C, but the toughness value no longer indicated a straight correlation to oxygen content in the weld metal, thereby proving that when silicon content is high, decreasing oxygen content could not be a measure for improving toughness. **Fig. 2** shows the effects of oxygen content on ${}_{V}E_{-196}$ of weld metals in both the as-welded and tempered condition. The figure clearly shows that as silicon content in the weld metal changed, so did the proper oxygen content, but the absolute value of absorbed energy was the largest for the low-silicon and low-oxygen weld metal. Therefore, conditions required of the matching ferritic filler MIG welding are ① to use low-silicon wires, and ② to use pure argon for the shielding gas.

Photo 1 shows the effects of heat treatment temperatures on the optical microstructure of the weld metal. The weld metal in the as-welded condition shows a structure primarily consisting of martensite, and this structure shows no conspicuous changes even after tempering at 450°C. After 520°C tempering, precipitation of carbides is found at the solidification grain boundary, and this trend becomes conspicuous in 590°C tempering when absorbed energy reaches a peak value. Reproducing this structure by means of heat treatment is important next to the reduction in silicon and oxygen contents. The factor which exercises the most significant effect on the microstructure is the heat treatment temperature, while the effect of silicon and oxygen contents in the weld metal was insignificant.

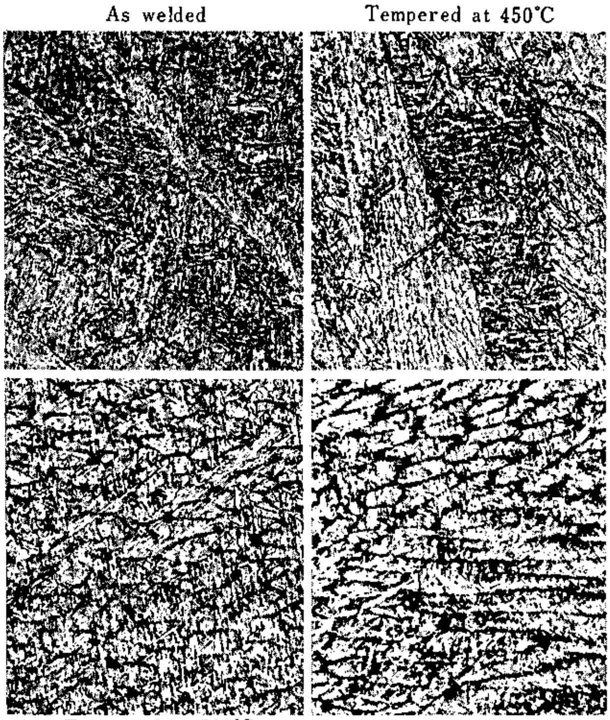


Photo 1 Effect of tempering temperature on microstructure of weld metal (× 100)

3 Pure Argon Shielded MIG Welding Process Matching Ferritic Fillers

In order to give excellent low-temperature toughness to the matching filler weld, it is necessary to weld in the pure argon shield as mentioned above. However, if pure argon shielded MIG arcs are generated by using welding wires of normal chemical composition, a cleaning action of cathode spots is generated on the surface of the base plate, and this cleaning action results in welding defects such as undercut. In the past, such defects were avoided by mixing an active gas into argon to stabilize arcs, but as mentioned in the previous chapter, it is not desirable to mix an active gas into argon in matching ferritic filler welding of 9 %Ni steels.

After examining the method of stabilizing pure argon shielded MIG arcs, it was found that addition of rare earths to welding wires was effective. The arc stabilizing effect of the addition of rare earths is described below.

3.1 Materials and Experimental Procedures

Table 3 shows the chemical compositions of materials used. In order to compare arc stabilizing properties, rare earths were added only to wire No. 543.

Table 3 Chemical compositions of materials used

Material		C	Si	Mn	P	S	Ni	RE	O (ppm)
Plate (12mm*t*)		0.05	0.29	0.54	0.003	0.004	9.04	—	13
Wire (1.6mm*ϕ*)	No.541	0.012	0.044	0.47	0.001	0.004	11.24	—	30
	No.543	0.010	0.044	0.48	0.001	0.003	11.45	0.049	35

Pure argon was used as the shielding gas, and bead-on-plate welding was performed at a constant speed of 60 cm/min. A comparison was made between two types of wire in respect of changes in the arc voltage waveform and in the droplet transfer mode when wire feeding speed was changed.

3.2 Arc Stabilizing Effects by Rare Earths

Fig. 3 shows arc voltage waveforms when wire feeding speed was changed under a constant arc voltage. For the wire of ordinary chemical composition (No. 541), the wire tip irregularly forms short circuits on the surface of the molten pool without being sharply pointed. As a result, the frequency of short circuiting was 120 times/sec at the most, and the duration was 2.5 msec. This transfer mode causes severe spattering and overlapping, and the surface of the base metal adjacent to the weld toe showed a trace of the cleaning action of cathode spots. On the other hand, when the rare earths-bearing wire (No. 543) is used, the wire tip becomes sharply pointed as shown in **Photo 2**, and the pointed tip contacts the surface of the molten pool and causes short circuiting. Thus the short circuit frequency increases to about 250 times/sec and the duration decreases to 1 msec and under. When rare earths are added to the wire, the instantaneous short circuit transfer is stabilized and cathode spots do not wander to the outside of the molten pool, thereby minimizing spattering and suppressing undercut.

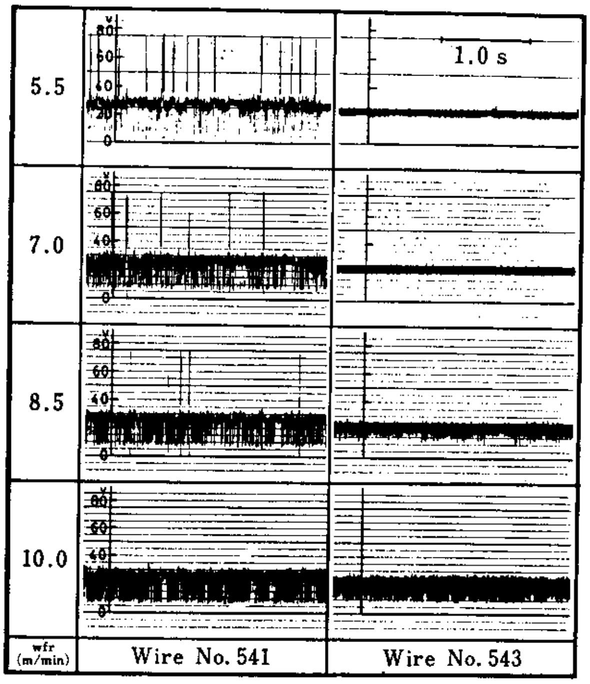


Fig. 3 Effect of rare earth addition on short circuit transfer

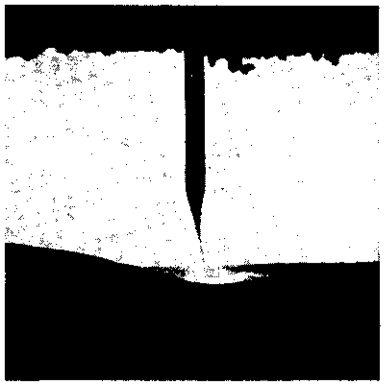


Photo 2 Typical wire tip shape of rare earths-bearing wire during stable instantaneous short circuit transfer

Arc stabilizing conditions were investigated by changing arc voltage and welding current over wide ranges, but the stabilizing conditions for wires of ordinary chemical composition were not found, owing to the above-mentioned irregular short circuits, wandering of cathode spots and resultant variation in arc length. For rare earths-bearing wires, on the other hand, stable instantaneous short circuits were formed within the current range of about 220 A or above as shown with white circles in **Fig. 4**. The lower current limit of the stabilized area spread to about 110 A (for 1.2 mmϕ wire) by using pulsating current, resulting in still further stabilized welding.

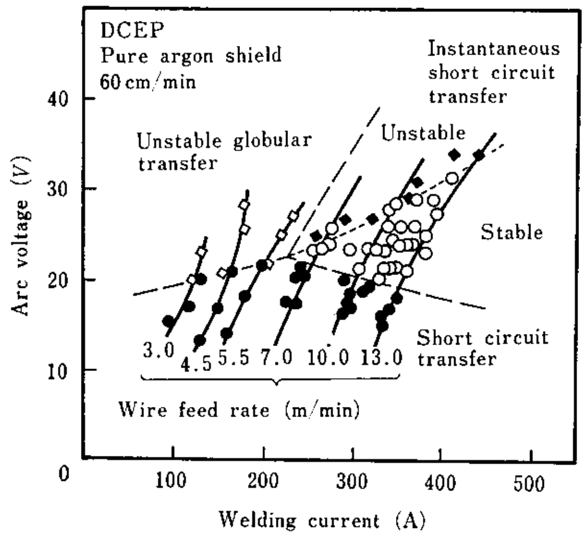


Fig. 4 Relationship of metal transfer modes to voltage/current conditions

Table 4 Chemical compositions of materials used

Material		C	Si	Mn	P	S	Ni	Cr	Mo	RE
Plate (14mm$t$)		0.057	0.24	0.59	0.004	0.002	9.12	—	—	—
Wire (1.2mmϕ)	A	0.028	0.02	0.52	0.001	0.001	11.88	—	—	0.043
	B	0.02	0.29	0.07	0.011	0.003	61.32	22.18	9.18	—

Table 5 Welding conditions for Trans-Varestraint test

Process	Electrode or wire	Current (A)	Voltage (V)	Speed (cm/min)	Shielding gas
TIG	Thoriated tungsten	250	18	15	100%Ar
MIG	A	320	27	90	100%Ar
	B	320	27	90	7%CO_2+Ar

4 Hot Crack Susceptibility of the Matching Filler Welds

This chapter describes the hot crack susceptibility of the matching filler welds investigated by the Trans-Varestraint test and the FISCO crack test.

4.1 Materials and Test Procedures

The chemical compositions of materials used are shown in **Table 4**. For comparison's sake, high-Ni-based wires were also used. In the Trans-Varestraint test, the normal method of remelting the overlaid test bead surface with TIG arcs[7] (hereafter called the "TIG method") was used, and the MIG weld bead itself was also tested (hereafter called the "MIG method"). In the MIG method, a 90° V-groove of 3.8 mm in depth was cut on the test plate, and welding was performed so that the bead surface came to have the same height as that of the steel plate surface. **Table 5** shows the testing conditions for both TIG and MIG methods.

The FISCO crack test was performed according to the procedure set forth in JIS Z 3155. For groove shapes, 70° V-grooves having depths of 3 and 5 mm were used for steel plates of 6 and 9 mm thickness, respectively. Test conditions were a constant current and voltage of 280 A and 26 V, welding speeds within the range of 40 to 83 cm/min, root gaps within the range of 0 to 2.5 mm, and welding of a single bead per test piece.

4.2 Test Results and Discussion

Fig. 5 shows the relation between the augmented strain and the maximum crack length in the Trans-Varestraint test. The maximum crack length developed in matching filler welds for both the TIG and MIG methods became $\frac{1}{3}$ to $\frac{1}{4}$ of that in high-Ni-based weld metals, thereby indicating the excellence of hot crack resistivity of the matching filler weld. The reasons for

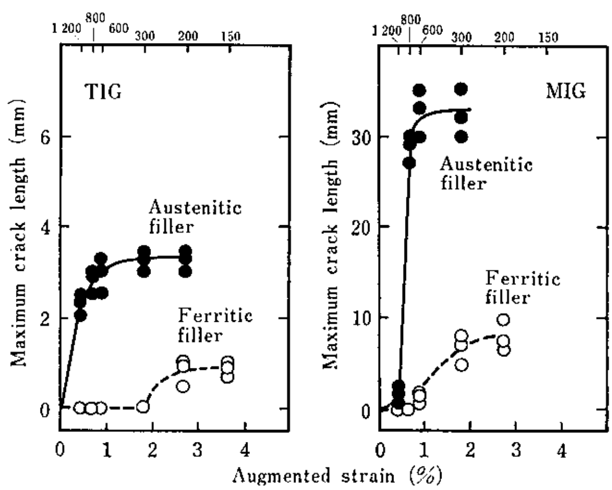


Fig. 5 Relation between maximum crack length and augmented strain in Trans-Varestraint test

Table 6 Summary of indicies[7] for solidification crack susceptibility (MIG process)

Wire	ε_{min}* (%)	BTR** (°C)	CST*** (°C^{-1})	CSS**** (s^{-1})	Remarks
A	0.69-0.92	435-510	4.44×10^{-5}	41.7×10^{-3}	Ferritic
B	<0.46	800	0.95×10^{-5}	3.6×10^{-3}	Austenitic

* Minimum ductility
** Solidification brittle temperature range
*** Critical strain rate for temperature drop
**** Critical strain rate to time

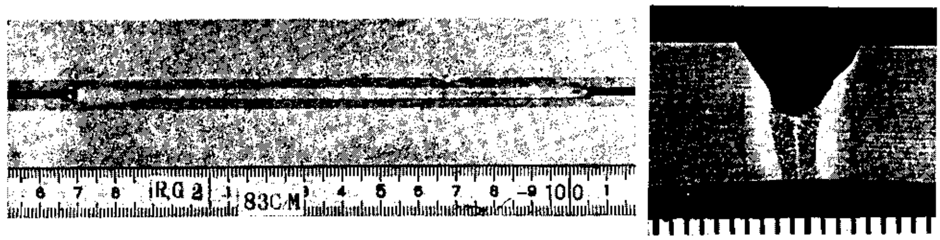


Photo 3 Bead surface and crater section after penetrant test showing no crack occurred during the FISCO crack test (9 mm*t*, 83 cm/min, 2 mm root gap)

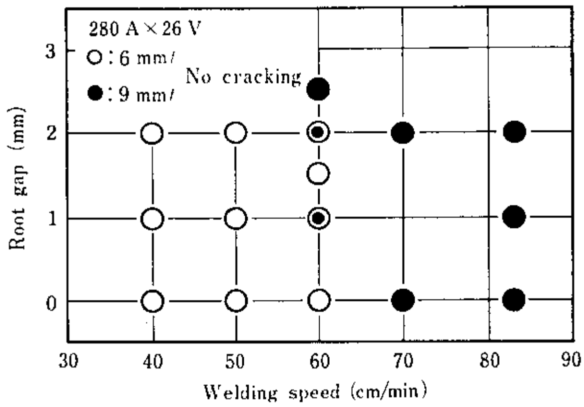


Fig. 6 Results of FISCO crack test

the crack length in the MIG method being about 10 times as long as that in the TIG method may be attributable to the differences in the welding conditions as well as solidification modes. **Table 6** shows the solidification crack susceptibility indices[7] obtained by the MIG method. It can be easily seen that the matching filler weld is superior in all respects.

Fig. 6 shows the results of the FISCO crack test of matching filler welds. When the root gap was 2.5 mm, a reverse side bead was formed and a partial burn-through occurred, but absolutely no crack was observed either on the bead surface or in the interior including the crater as shown by the examples in **Photo 3**.

5 Properties of Weld Metals and Welded Joints

This chapter describes the properties of all-deposited metals and welded joints made with rare earths-bearing wires in a pure argon shield.

5.1 Properties of All-deposited Metals

All-deposited metals were made by using steel plates of 30 mm thickness under the welding conditions of 280 A, 27 V, and 40 cm/min, and chemical analysis as well as tensile and impact tests were conducted. The effects of the PWHT temperature were also examined.

Table 7 shows the chemical composition of all-deposited metal; **Table 8** shows the results of the tensile test in the as-welded condition. The tensile properties satisfy the specified values of the steel plates (JIS G 3127 Class 9B), and the yield ratio shows a value as high as about 95%. **Fig. 7** shows the relation between tensile properties and PWHT temperature. Within a temperature range of 560 to 580°C (in the vicinity of the conventional A_{c1} point of the matching filler weld), 0.2% proof stress becomes lower than the specified value, and thus PWHT at a comparatively lower temperature (about 550°C) is desirable.

Fig. 8 shows the results of Charpy impact test on the all-deposited metal. The difference in absorbed energy with or without PWHT or based on the difference between PWHT temperatures is insignificant, thereby indicating excellent toughness in every case. This means that the tempering effect due to the multiplied

Table 8 Tensile properties of all-deposited metal

Code	0.2% proof stress (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)	Reduction of area (%)
M1	79.7	83.4	21.2	71.4
M2	79.3	82.8	21.6	71.1
M3	78.7	83.8	21.8	71.4
JIS G 3127	≧60	≧70	–	–

Table 7 Chemical compositions of all-deposited metal

C	Si	Mn	P	S	Ni	RE	N	O
0.025	0.02	0.51	0.002	0.001	12.20	0.034	0.0051	0.0053

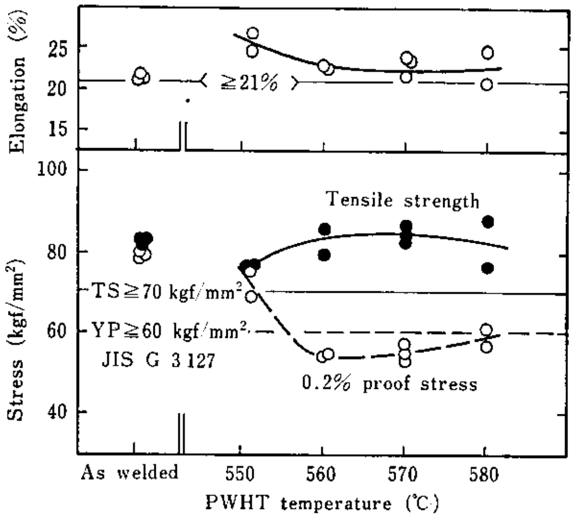


Fig. 7 Relation between PWHT temperature (3 hr., AC) and tensile properties of all-deposited metal

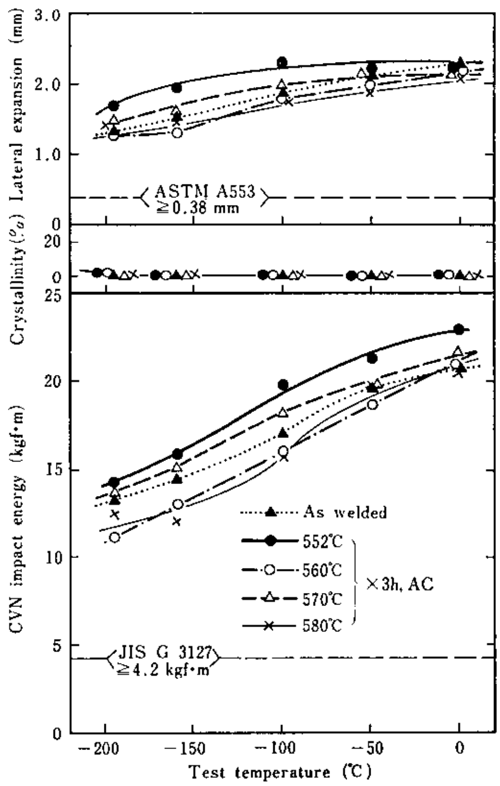


Fig. 8 CVN test results of all-deposited metal

thermal cycles has demonstrated its full action even in the as-welded condition.

5.2 Mechanical Properties of Welded Joints

5.2.1 Tensile properties

Table 9 shows the results of the tensile test on the flat-position butt welded joints of steel plates of 6, 9, 12, and 30 mm thickness. When the effect of shapes of test pieces was observed in respect of the steel plate of 6 mm thickness, the longer gage specimen showed a value about 5 kgf/mm² lower both in yield and tensile strength. When the effect of PWHT was observed on the sample having a plate thickness of 9 mm, the yield strength of the welded joint satisfied the specified value of the steel plate even at a temperature of 570°C where the all-deposited metals exhibited less yield strength. Even for the welded joint of 30 mm thickness which was subjected to a greater softening effect of the multiplied thermal cycles, both yield and tensile strength fully satisfied the specified values of the steel plate.

Since the matching filler welded joints have strength corresponding to the steel plates concerned, it has become possible to employ the value of 22.3 kgf/mm² as the allowable design stress for welded structures, if

Table 9 Tensile properties of welded joint

Plate thickness (mm)	PWHT	Specimen	0.2% proof stress (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)	Location of fracture
6	—	*	75.3	85.0	—	Base plate
		**	70.6	80.6	19.5	〃
9	—	*	69.2	80.8	—	〃
	570°C× 2 h,AC	*	63.4	75.8	—	〃
12	—	*	70.6	81.7	—	〃
30	—	*	66.4	77.5	—	〃
JIS G 3127		—	≧60	≧70	—	—

* JIS Z 3121 No.1 (short gage length)
** JIS Z 2201 No.1 (long gage length)

JIS B 8243 is complied with, and an increase of 34% in the allowable design stress can be expected over the value of 16.7 kgf/mm² for the high-Ni-based steel.

5.2.2 Bending properties

The results of bending test on butt welded joints were all excellent as shown by the examples for the plate having a thickness of 9 mm in **Photo 4**. For the high Ni-based welded joint, it is difficult to bend it in the transverse direction to the weld line, because the difference in ductility between the base plate and weld metals is too large, whereas for the matching filler welds, satisfactory elongation was demonstrated in the ordinary bending test.

5.2.3 Charpy impact properties

Fig. 9 shows the relation between CVN impact energy and temperatures. The figure indicates satisfactory values corresponding to the values for the high-Ni-based weld[8,9], and satisfies all specified values of the steel plates concerned. The lateral expansion also satisfies the specified values of ASTM A553 (≧ 0.38 mm).

5.3 Fracture Toughness

5.3.1 Crack initiation properties

Crack Opening Displacement tests were conducted according to BS5762 using test pieces having a fatigue notch. **Fig. 10** shows the relation between the critical COD value and the test temperature. The rising trend of the critical COD value of the weld metal in keeping pace with the increase in the plate thickness is considered attributable to the facts that the thicker the plate, the more conspicuous will be the tempering effect due to the welding thermal cycles and that the thicker the plate, the larger will be the plastic constraint at the notch tip and the more difficult it will be for plastic collapse to occur. Assuming that the lower limit of the critical COD value is 0.1 mm and the total stress acting on the welded joint is a sum of design stress (22.3 kgf/mm²) and residual stress (30 kgf/mm²), an allowable penetrating defect length of 50 mm can be obtained from Dugdale's equation. This value can be considered a dimension which can be easily detected

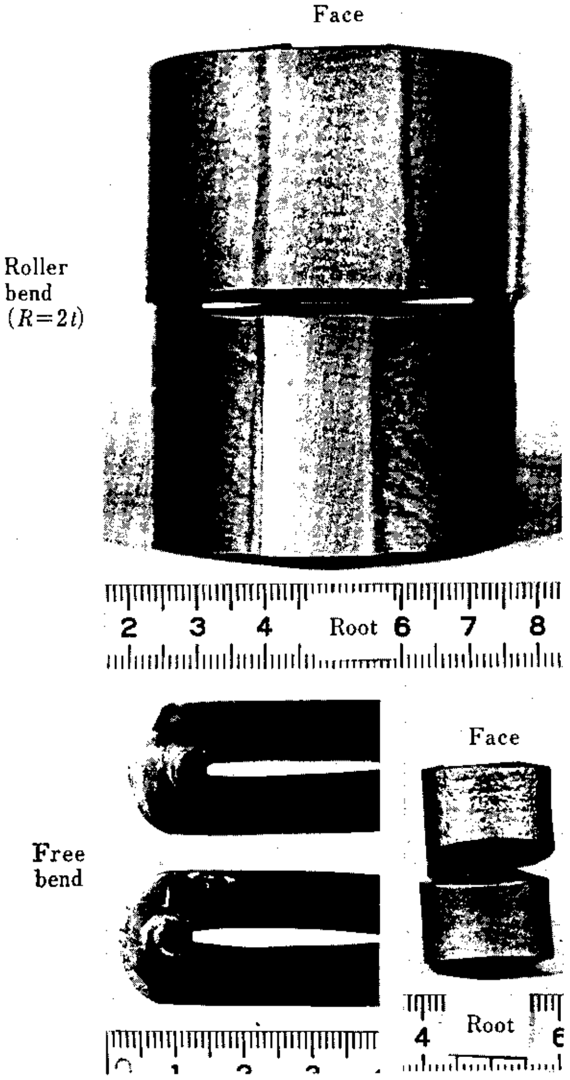


Photo 4 Bend test results of 9 mm thick welded joint

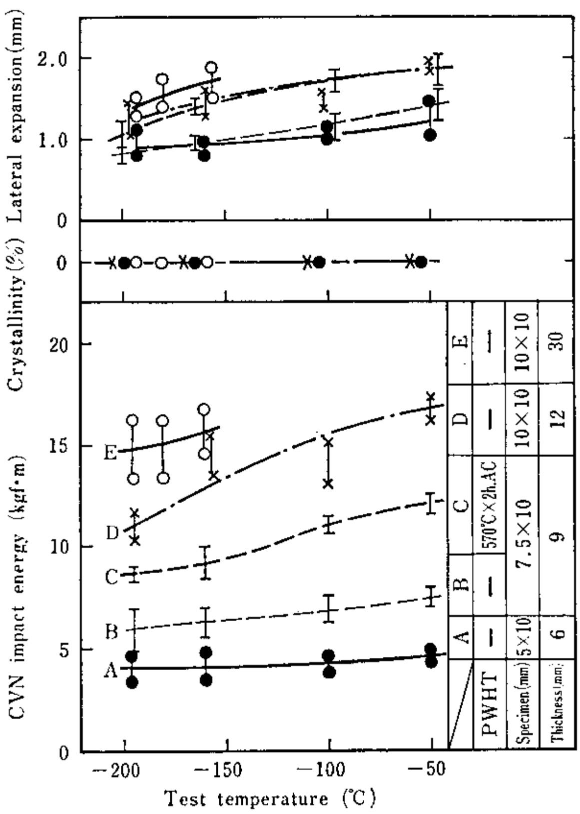


Fig. 9 CVN test results of weld metal

by nondestructive inspection.

Fig. 11 shows the shape of the test piece which was used in the deep notch test. The results are shown in **Fig. 12**. The net stress (σ_{net}) at the time of fracture exceeded the maximum stress (design stress + residual stress = 52.3 kgf/mm²) which was considered to act on the welded structure while it was used, and also showed a much higher value than the specified lower limit of the yielding point (60 kgf/mm²) of the steel plate.

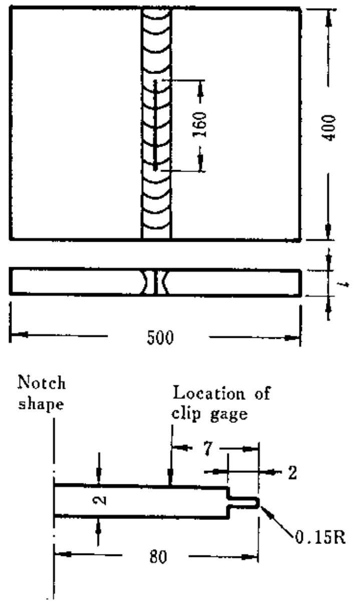


Fig. 11 Specimen configuration for deep notch test

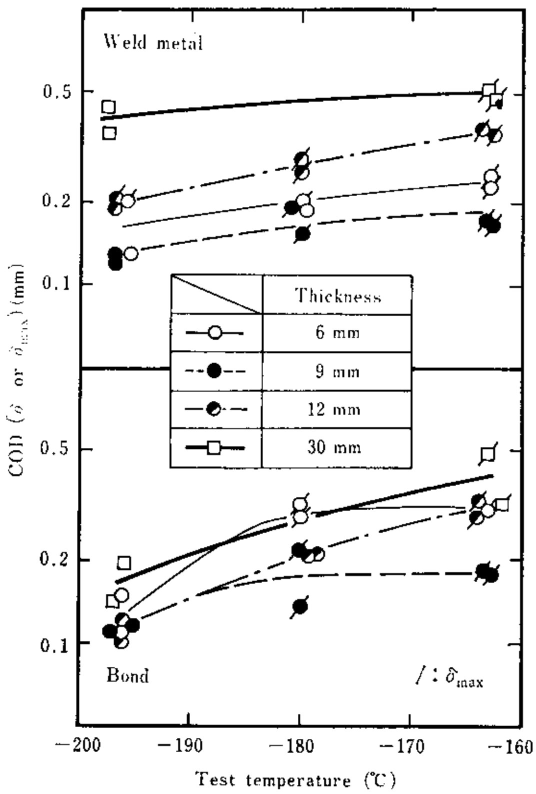


Fig. 10 COD test results of weld metal and weld bond

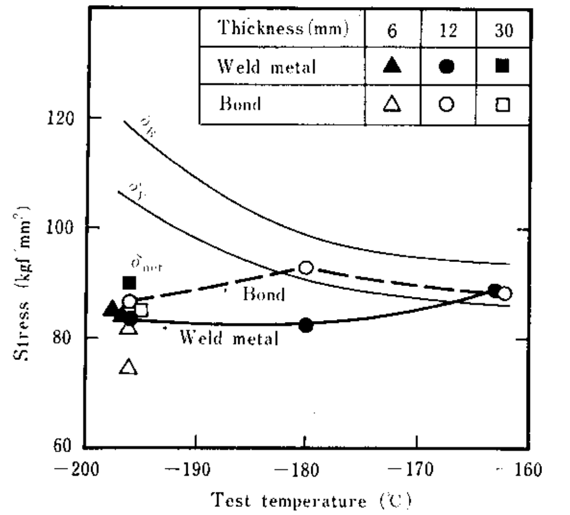


Fig. 12 Deep notch test results of weld metal and weld bond

Table 10 Results of hybrid ESSO test

Plate thickness (mm)	Test temperature (℃)	Specimen type	Notch location	Stress applied (kgf/mm²)	Go/No go
7.5	−191	A	—	36.8	No go
		A	—	40.0	No go
9	−196	B	WM	40.0	No go
		B	Bond	38.0	No go
12	−170	A	—	50.0	No go
		A	—	50.0	No go

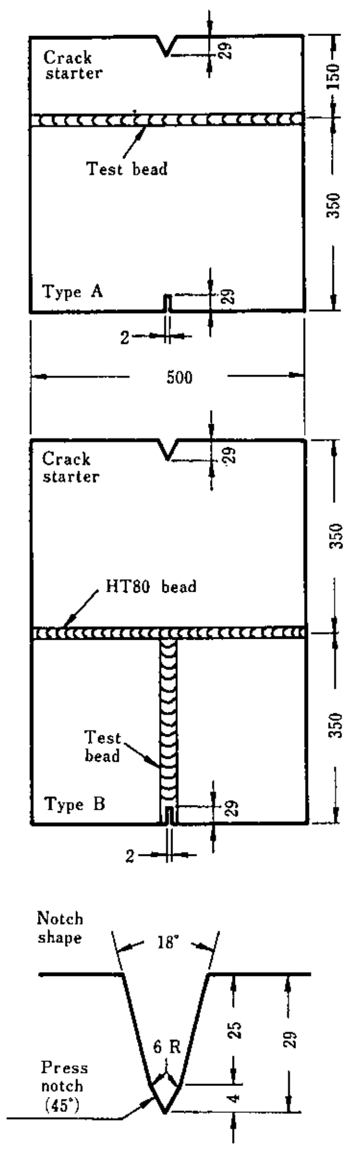


Fig. 13 Specimen configuration for hybrid ESSO test

5.3.2 Crack arrest properties

In order to determine crack arrest properties of matching filler welds, hybrid ESSO tests were conducted by using test specimens, with their shapes shown in **Fig. 13**. The results are given in **Table 10**. For test specimen A, brittle crack was arrested at the weld bond of a matching filler weld, as shown in **Photo 5** (a), and continuously propagated, in the form of a ductile crack, to a part of the weld metal. For test specimen B, brittle crack spread to the HT80 bead and its heat affected zone, and from then on it became a ductile crack and was arrested after straying toward the base metal.

From the results shown above, it is evident that the matching filler welds have an excellent crack arrest property.

6 Conclusion

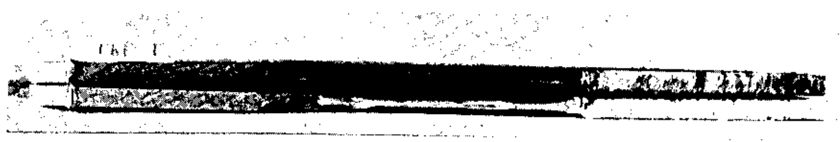
Matching ferritic filler MIG welding of 9%Ni steel has been studied for its practical application, and the following results obtained:

(1) In order to obtain matching filler welds excellent in low-temperature toughness, it is necessary to balance silicon content with a proper amount of oxygen. The absorbed energy in the Charpy impact test becomes highest when silicon and oxygen contents are both lowest.

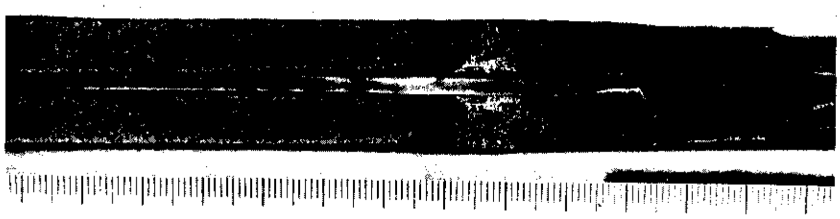
(2) Reduction in silicon and oxygen contents in weld metals can be achieved by using an ultra-low silicon wire and by welding in a pure argon shield.

(3) Pure argon shielded MIG arcs which are unstable when ordinary wires are used, become stabilized if about 0.05% rare earths are added to the welding wire.

(4) The hot crack susceptibility of the matching filler



(a) 12 mm*t*, Specimen A



(b) 9 mm*t*, Specimen B, Notch: Weld metal

Photo 5 Fracture surface of hybrid ESSO test specimens weld is far lower than that of the high-Ni-based weld metal, with no crack occurring even in weld craters.

(5) Tensile properties of all-deposited metals and welded joints satisfy the specified values of the steel plates (JIS G3127 Class 9B), thereby permitting the allowable design stress to be raised (16.7 → 22.3 kgf/mm^2: JIS B8243).

(6) The Charpy impact properties of all-deposited metals and welded joints are equal to those obtained by high-Ni-based welding materials, satisfying the specified values of the steel plates (JIS G3127).

(7) The critical COD value becomes larger as the plate thickness increases. Representative critical COD values of weld metals of 6, 9, 12, and 30 mm plate thickness at a temperature of −196°C are 0.13, 0.13, 0.21 and 0.43 mm, respectively, thereby eliminating the possibility of fracture caused by such minor defects beyond the detection by non-destructive inspection.

(8) Net fracture stresses in the deep notch test show much higher values than the specified yield stress of the steel plates.

(9) The hybrid ESSO tests have demonstrated that the matching filler welds have sufficient crack arrest properties.

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