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In a narrow gap arc welding process with a single-pass-per-layer technique, the toughness of weld metal greatly depends on that of as-dendrite structure. The increase in carbon content and V-addition have beneficial effects on improving the as-dendrite structure toughness by refining the bainitic lath sub-structure and increasing fine carbo-nitrides which have precipitated uniformly within the γ-grains after PWHT. Two types of narrow gap SAW consumables, i.e., the high C-V system for excellent-toughness Cr-Mo steels and high C-V-Ti system for enhanced-strength Cr-Mo steels have been developed on the basis of the above-mentioned metallurgical findings. The realization of a narrow-gap tandem SAW process was confirmed by a production scale mock-up test using the newly developed consumables.

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Development of High-Quality Narrow Gap Submerged Arc Welding Consumables for Cr-Mo Steel*



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The realization of a narrow-gap tandem SAW process was confirmed by a production scale mock-up test using the newly developed consumables.

1 Introduction

Cr-Mo steels are frequently used for reactor vessels operated under high-temperature and high-pressure conditions in the oil refining process. Since these vessels are operated over long periods in the temper embrittling region around 450°C, deterioration due to in-service temper embrittlement poses problems. As a result, strong demand has arisen recently for the development of steels and welding consumables which have excellent toughness, particularly improved temper embrittlement characteristics.

As temper embrittlement indexes, the following have been proposed, and compositional design has been made which minimizes the contents of embrittling elements, thereby achieving considerable improvements:

$$J \text{ factor}^{1)} = (\text{Si} + \text{Mn})(\text{P} + \text{Sn}) \times 10^4 (\%)$$

$$\bar{X}^{2)} = (10\text{P} + 5\text{Sb} + 4\text{Sn} + \text{As}) \times 10^{-2} (\text{ppm})$$

Further, aiming at economic advantage obtainable from a higher efficiency operation of the equipment designed larger and thinner using a material made stronger than the current ASME code levels, efforts are being made to lower the following temper parameters or to develop materials consisting of a new component series:

$$TP = T(20 + \log t) \times 10^{-3}$$

where

T: PWHT (Postweld heat treatment) temperature (K)

t: PWHT holding time (h)

As a method of reducing the manufacturing costs for heavy section pressure vessels, a narrow-gap single-pass-per-layer submerged arc welding process has been developed and entered the practical application stage.[3] This process, however, is inferior to the conventional multi-pass-per-layer process in the grain refining effect using

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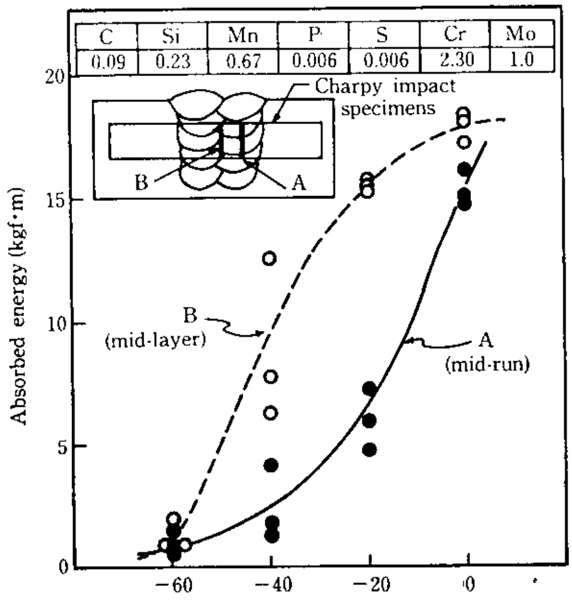


Fig. 1 Toughness variation for notch locations in two-pass-per-layer weld metal (PWHT: 690°C × 26 h)

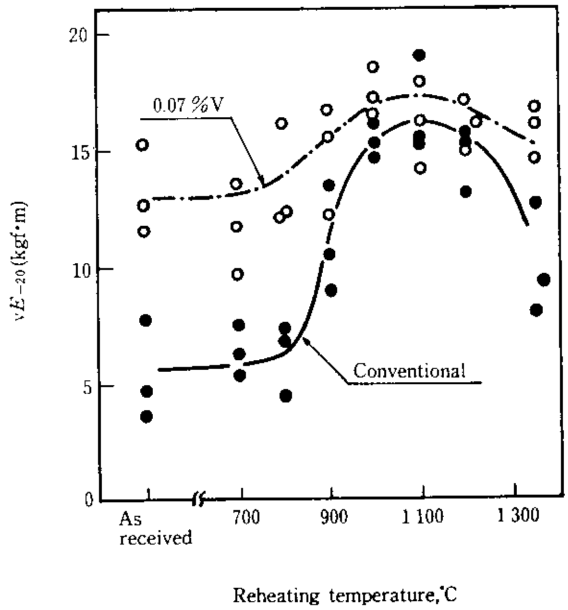


Fig. 2 Effect of reheating temperature on single-pass weld metal toughness

the succeeding welding heat; therefore, an improvement in toughness of the as-dendrite structure becomes the key point.[4,5]

In the present study, the authors made a metallurgical examination of toughness improvement of single-pass-per-layer weld metal of 2¼Cr-1Mo steel, particularly, of the as-dendrite structure, and determined the composition system best suited to obtaining homogeneous and high-toughness weld metal.

2 Metallugical Examination of Toughness of Weld Metal

Toughness variations due to notch locations of Charpy impact specimens taken from a commercial weld metal deposited by a two-pass-per-layer technique are shown in **Fig. 1**. Toughness of notch location A, which consists of many as-dendrite structures, is lower than that of the refined-grain structure B. Therefore, in order to put into practical application the single-pass-per-layer SAW process, improvement in toughness of the as-dendrite structures is extremely important.

2.1 Effects of Multi-Pass Welding Heat on Toughness

A single bead was deposited at a V-groove of 2¼Cr-1Mo steel with a heat input of 48 kJ/cm, and thermal simulation test specimens were sampled from the weld. These specimens were subjected to heat cycles at varying peak temperatures of 700 to 1 350°C with a 30-sec cooling time from 800°C to 500°C. After these specimens were stress-relieved at 690°C for 12 h, some were given additional step-cooling treatment and used in a Charpy impact test to determine their in-service embrittlement. Chemical compositions of the weld metals are shown in **Table 1**.

The effect of reheating temperature on the toughness of single-pass weld metal is shown in **Fig. 2**. Within the temperature range of 900°C to 1 200°C, conventional weld metal toughness is greatly improved. In the 0.12%C-0.07%V weld metal, however, the effect of the reheating temperature is not as marked as with the conventional weld metal, and high toughness is invariably

Table 1 Chemical compositions of weld metal (wt %)

Weld metal	C	Si	Mn	P	S	Cr	Mo	V	N	O	$\bar{X}$*
Conventional	0.09	0.22	0.78	0.008	0.004	2.39	0.96	—	0.0043	0.033	10
0.07%V addition	0.12	0.19	0.73	0.007	0.005	2.35	1.00	0.069	0.0047	0.031	9

* $\bar{X} = (10P + 5Sb + 4Sn + As) \times 10^{-2}$ (ppm)

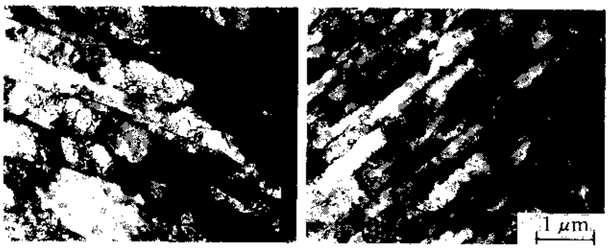


Photo 1 Transmission electron microstructures of single pass weld metal after PWHT 690°C × 12 h

obtained in the coarse- and refined-grain structures. In both composition systems, excellent toughness values are obtained in the vicinity of 1 100°C, because γ grains have been refined. However, it is difficult to explain the large difference in toughness between the as-dendrite structures of the two composition systems from their optical microstructures alone.

Transmission electron microstructures of the as-dendrite structures are shown in **Photo 1**. The conventional weld metal consists of an upper bainitic structure with significant lath width, but the 0.12%C-0.07%V weld metal consists of a lower bainitic or a tempered martensite structure, which is one of the reasons for the wide improvement in toughness of the as-dendrite structure.

When the fractured surfaces of the specimens tested at −60°C after step cooling treatment were observed, all the specimens reheated at 1 100°C showed only quasi-cleavage or ductile fractures, but the as-dendrite structure and 1 350°C-reheated specimen showed some intergranular facets. The portion where γ grain sizes became coarser was more susceptible to temper embrittlement,[5] and the same phenomenon was confirmed in the conventional system. Addition of C and V was effective in improving the toughness after PWHT of the as-dendrite structures, but had little effect in preventing in-service temper embrittlement.

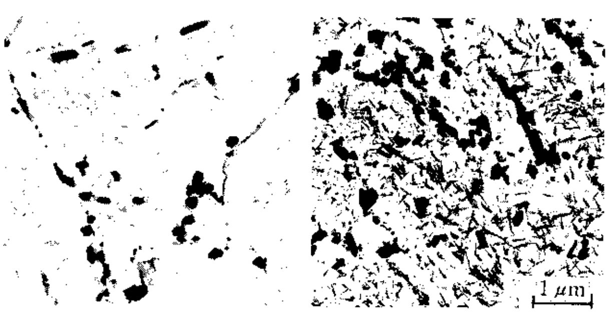


Photo 2 Extraction replica microstructures of single pass weld metal after PWHT of 690°C × 12 h

Carbide precipitates in the single-pass weld metal are shown in **Photo 2**. The 0.12%C-0.07%V weld metal shows a larger increase in the amounts of intergranular fine precipitates than the conventional weld metal and more uniform distribution. These carbides did not bring about precipitation hardening (described below), demonstrating that a large increase in these fine precipitates will improve 2¼Cr-1Mo weld metal toughness.

2.2 Carbide Precipitation Behavior and Toughness Change Due to PWHT

After a U-groove was welded in three passes with a heat input of 36 kJ/cm using three types of wires of varying C and V contents, PWHT (TP = 13.46 to 21.19) was performed under several conditions. Impact test specimens were taken from the second and third passes, and electron microstructure was observed at the final pass.

Effects of PWHT on weld metal hardness and carbide morphology (X-ray diffraction analysis of precipitated residues) are shown in **Fig. 3**. Examples of the carbide precipitates in the 0.13%C-0.06%V weld metal are shown in **Photo 3**. After developing slight secondary precipitation hardening at 550°C, softening at the weld metal occurs abruptly under higher heating conditions ($TP \geqq 17.46$). Hardening effects of 0.06%V addition are not obvious, but the effect of increase in C content is significant. This difference in hardness decreases as TP becomes greater, but is also observed in 1∼100 h holding at 690°C. Slight hardening around 550°C is due to the precipitation of fine-grained M_3C. At a heating temperature of 600°C or above, the tempering effect accompanying the decrease in dislocation density surpasses

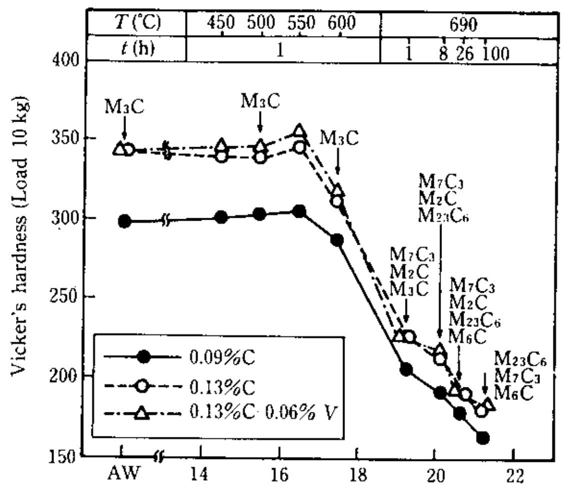


Fig. 3 Effect of PWHT on weld metal hardness and carbide morphology (X-ray diffraction analysis of precipitated residues)

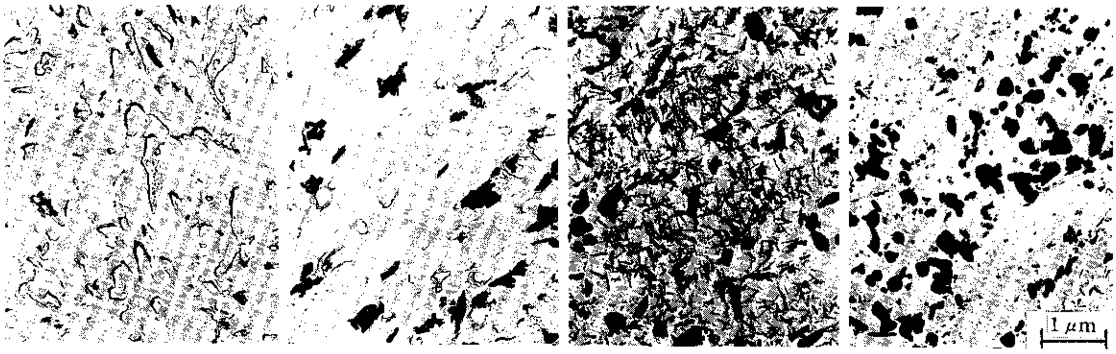


Photo 3 Extraction replica microstructures of 0.13%C-0.06%V weld metal after various PWHT conditions

precipitation hardening of carbides, and the hardness drops as the heating temperature rises.

In all weld metals, precipitates in PWHT at 600°C or below ($TP \leqq 17.46$) consist only of M_3C, but in PWHT at 690°C for 1 h ($TP = 19.26$), needlelike carbides (M_2C) are observed within the grains, and granular carbides (M_7C_3) are observed both in the grains and at grain boundaries. In PWHT at 690°C for 8 to 26 h ($TP = 20.13$ to 20.62), which is the ordinary working condition for pressure vessels, M_3C and M_2C precipitates decrease, and polygonal ones ($M_{23}C_6$, M_7C_3, and M_6C) tend to increase, so that they change into a more stabilized type of carbide with increased PWHT duration.[6] The difference in precipitate morphology due to the composition systems tends to show that granular carbides increase with increase in C and needlelike carbides increase with V-addition. Particularly in the high C-V system, the amount of precipitate is greatly increased and is uniformly distributed in the grains and at the grain boundaries as shown in Photo 2.

Toughness change in the weld metal arising from PWHT conditions is shown in **Fig. 4**. All composition systems show overall low toughness after PWHT at 600°C for 1 h or below ($TP \leqq 17.46$), but toughness is considerably improved after PWHT at 690°C for 1 h ($TP = 19.26$). By PWHT at 690°C for 26 h ($TP = 20.62$), all composition systems reach their respective highest toughness, and the 0.13%C-0.06%V weld metal shows the most excellent toughness value. This tendency remains the same even after step cooling treatment. Further, in longer-time PWHT at 690°C for 100 h ($TP = 21.19$), the conventional 0.09%C system shows a slight development of embrittlement, but 0.13%C and 0.13%C-0.06V systems maintain nearly the same high toughness.

These results reveal that 2¼Cr-1Mo weld metal toughness can be improved by making finer the bainitic and martensitic lath substructure and by precipitating a large amount of carbides uniformly within the grains and at the grain boundaries.

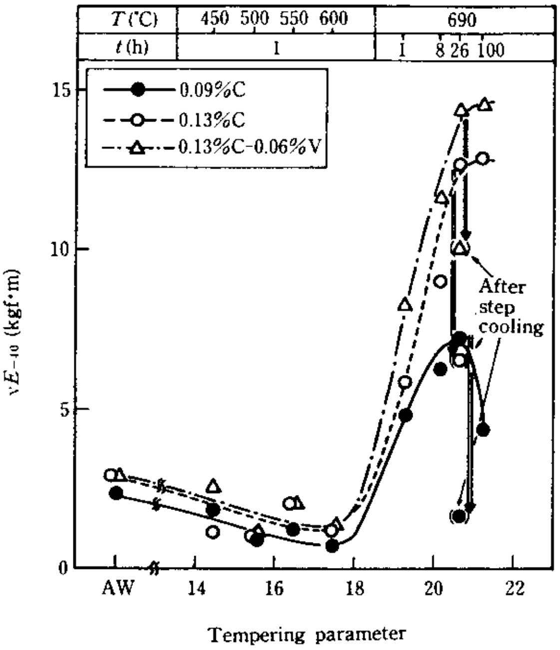


Fig. 4 Effect of PWHT on weld metal toughness

3 Determination of Optimum Chemical Composition for Single-Pass-per-Layer Narrow Gap SAW Weld Metal

A U-shaped groove of a 75-mm-thick 2¼Cr-1Mo steel plate (ASTM A387 Gr. 22 Cl. 2) was given single-pass-per-layer SAW with a heat input of 36 kJ/cm using a combination of an alloyed wire with varied contents of C, Si, P, V, Ti, and Nb and a high-basicity agglomerated flux. Optimum quantities of these micro-alloys were thus determined. PWHT was performed under the two

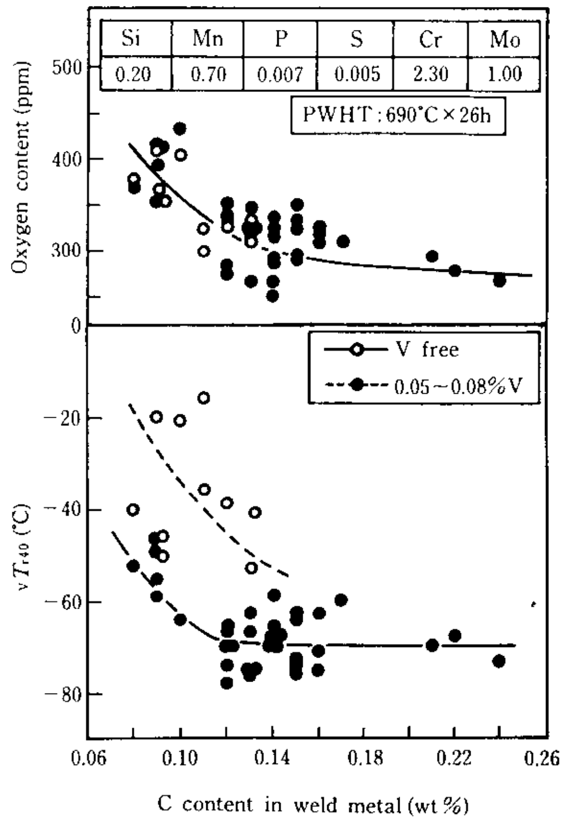


Fig. 5 Effect of carbon content on toughness and oxygen content of weld metal

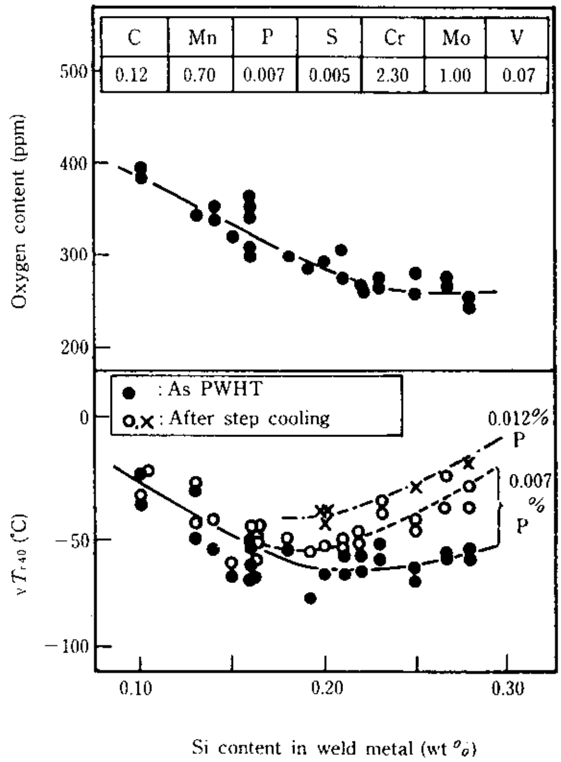


Fig. 6 Effect of Si content on weld metal toughness subjected to PWHT of 690°C × 26 h

conditions of 690°C × 8 h and 26 h, both within the range of ordinary working conditions.

3.1 Determination of Basic Composition System

The relationship of carbon content to oxygen content and weld metal toughness is shown in **Fig. 5**. As C content is increased, oxygen content tends to decrease and toughness improve; this trend becomes obvious at C $\leqq$ 0.12%. The optimum C content lies within the range of 0.10 to 0.15%, considering hot crack and cold crack sensitivities. The V-bearing weld metal gives higher toughness at the same oxygen content within the above-mentioned optimum C content range.

Effects of Si content on weld metal toughness are shown in **Fig. 6**. It is generally reported that reduced Si content in a steel plate and weld metal can improve toughness after PWHT and step cooling treatment.[1,2,4] However, in the high-basicity agglomerated flux in which temper embrittling impurities such as P, Sn, Sb, and As have been reduced, the optimum Si content becomes 0.15% $\leqq$ Si $\leqq$ 0.25%, as shown in Fig. 6.[7] Temper embrittlement after step-cooling is slight at an Si content below 0.15%, but the original toughness is deteriorated by high oxygen content after PWHT, since a decrease in Si content accompanies an increase in oxygen content. At an Si content above 0.25%, on the other hand, in-service temper embrittlement is liable to occur; a tendency is particularly obvious at P $\geqq$ 0.012%.

3.2 Effects of Micro-Alloying Elements on Toughness and Strength

Toughness of V-bearing weld metal after PWHT is shown in **Fig. 7**. Toughness is significantly improved at V $\geqq$ 0.04%, and the optimum range of V is from 0.04 to 0.12%. Within this range, the rise in strength is slight; stable high toughness can be confirmed from Figs. 2 and 5. At V > 0.12%, precipitation hardening becomes obvious and toughness tends to drop gradually, but since 0.25%V weld metal brings about TS = 65 to 70 kgf/mm^2, it is promising as an enhanced material which will be necessary for high-temperature, high-pressure operation at future oil refining facilities.

The relationship between tensile strength and toughness, when a composite addition of micro-alloying elements of V, Ti, and Nb is made to the basic composition, is shown in **Fig. 8**. Toughness tends to drop linearly as tensile strength increases, but the V system and Ti system do not show the same level of toughness drop. V systems such as the V-single addition system, V-Ti system or V-Nb system show practically no difference in toughness at the same strength level, and gives about 20°C improvement in $_vT_{r40}$ compared with the Ti-single

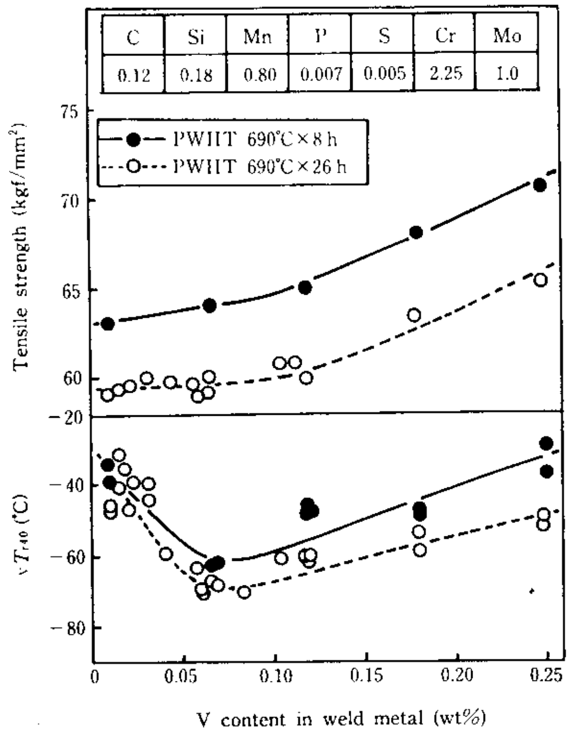


Fig. 7 Effect of V content on tensile strength and toughness in weld metal

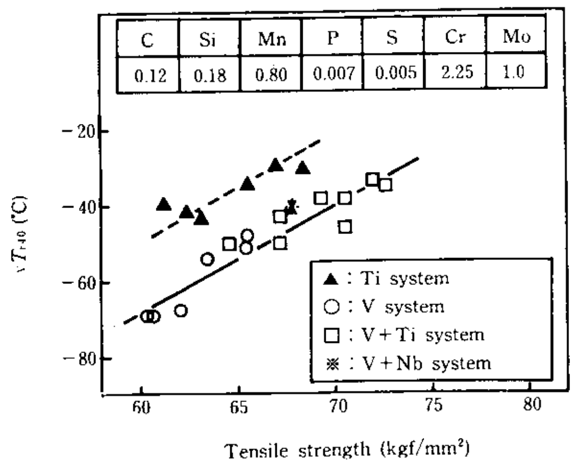


Fig. 8 Effect of micro-alloying elements on tensile strength and toughness in weld metal (PWHT: 690°C × 26 h)

addition system.

Alloy elements such as Ti and Nb essentially precipitate very fine carbon-nitrides and harden the matrix. Thus they are thought to be undesirable, because they sometimes develop embrittlement under the PWHT conditions which are used for the ASTM A387 Gr. 22 Cl. 2 steel pressure vessels. However, Ti and Nb demonstrate their effectiveness when small amounts of

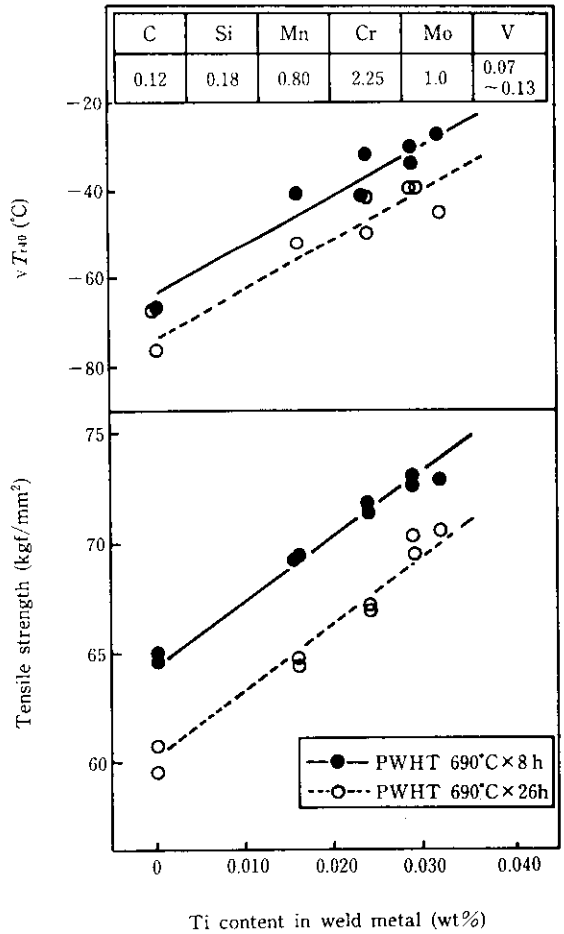


Fig. 9 Effect of Ti content on tensile strength and toughness in weld metal

the elements are added together with V for high-strength specifications. The effect of Ti addition on tensile strength and toughness of the 0.07~0.13% V weld metal is shown in **Fig. 9**. Tensile strength is enhanced linearly with the increase of Ti content, and with 0.015% Ti addition to the 0.07~0.13%V weld metal, $TS \geqq 65$ kgf/mm² can be achieved after PWHT at 690°C for 26 h, while the $_vT_{r40}$ temperature remains around −50°C.

From the above results, optimum chemistry of weld metal has been determined for high toughness use and high strength use, as shown in **Table 2**.

4 Characteristics of High-Quality SAW Consumables for Cr-Mo Steel

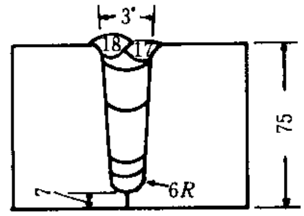
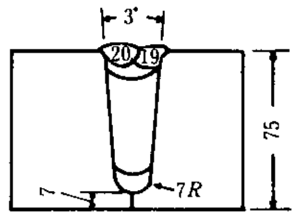
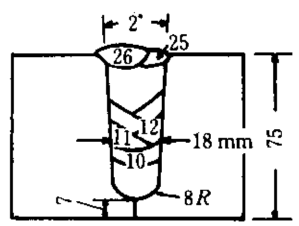
4.1 High-Toughness Welding Consumables for 2¼Cr-1Mo Steel (Flux KB120CM and Wire KWT 210)

Welded joints were prepared out of a 75-mm-thick

Table 2 Optimum chemistry of high-quality weld metal

Application	Welding consumables		Chemical compositions (wt %)						
	Flux	Wire	C	Si	Mn	Cr	Mo	V	Ti
High-toughness use	KB 120 CM	KWT 210	0.12	0.20	0.70	2.25	1.0	0.07	—
High-strength use		KWT 210 (M)	0.13	0.20	0.70	2.25	1.0	0.10	0.015
		KWT 310 (M)	0.13	0.20	0.70	3.00	1.0	0.10	0.015

Table 3 Welding conditions for narrow gap submerged arc welding

Welding process	Pass No.	Current (A)	Voltage (V)	Travel speed (cm/min)	Heat input (kJ/cm)	Groove shape and weld sequence
Single-electrode welding 1 run-1 layer (6 mm$R$)	1	450	27	20	36	
	2~5	500	28,	25	34	
	6~16	550	29	28	34	
	17, 18	550	29	30	32	
Two-electrode welding 1 run-1 layer (7 mm$R$)	1	450	27	20	36	
	2~6	L 450 T 400	27 27	40	34	
	7~10	L 450 T 450	27 28	42	35	
	11~12	L 500 T 450	28 28	46	35	
	13~18	L 500 T 500	28 29	48	36	
	19, 20	500	28	30	28	
Two-electrode welding 2 run-1 layer (8 mm$R$)	1	500	30	25	36	
	2~4	L 450 T 450	27 29	38	40	
	5~10	L 500 T 500	29 31	46	39	
	11~24	L 500 T 500	27 29	60	28	
	25, 26	L 500	28	28	30	

Preheat and interpass temperature: 175~200°C

ASTM A387 Gr. 22 Cl. 2 steel plate under the conditions shown in **Table 3**, and subjected to PWHT at 690°C for 8 h (TP = 20.13) and for 26 h (TP = 20.62), and to additional step-cooling treatment.

Typical examples of chemical composition of weld metal are shown in **Table 4**. All the weld metals showed uniform chemical composition irrespective of welding processes and plate thickness locations.

Results of the Charpy impact test performed on the weld metals are shown in **Table 5**. In the single-electrode process, the weld metal toughness showed ${}_{V}T_{r40} < -60$°C and ${}_{V}T'_{r40} < -50$°C after PWHT and step-cooling treatment, respectively, and the shift of transition temperature $\Delta_{V}T_{r40}$ was also minimal, less than 10°C. In the two-electrode process, high toughness, ${}_{V}T_{r40} \leqq -46$°C, was also obtained after both

Table 4 Chemical compositions of weld metal

Welding process	Sample location	C	Si	Mn	P	S	Cr	Mo	V	O	N	$\bar{X}$	J factor
Single electrode	$t/4$	0.13	0.15	0.76	0.005	0.003	2.21	0.97	0.064	0.032	0.0055	7	73
Two-electrode (7 mm*R*)	Subsurface	0.12	0.15	0.71	0.005	0.003	2.12	0.97	0.063	0.036	0.0053	7	76
	$t/4$	0.12	0.15	0.71	0.005	0.003	2.11	0.96	0.063	0.036	0.0056	7	69
	$t/2$	0.13	0.15	0.74	0.005	0.004	2.18	0.99	0.067	0.038	0.0052	7	71

Table 5 Summary of weld metal toughness after PWHT and step cooling treatment for welding process using KB 120 CM flux and KWT 210 wire

Welding process	PWHT	Location	As PWHT		After S. C.		Δ_vT_{r40} (°C)	$_vT_{r40}+2.5\Delta_vT_{r40}$ (°C)
			$_vT_{r40}$ (°C)	$_vT_{rs}$ (°C)	$_vT'_{r40}$ (°C)	$_vT'_{rs}$ (°C)		
Single electrode	690°C × 8 h	$t/4$	−65	−61	−59	−54	6	−50
	690°C × 26 h	$t/4$	−67	−55	−63	−51	4	−57
Two electrode (7 mm*R*)	690°C × 8 h	Subsurface	−63	−52	−46	−46	17	−20.5
		$t/4$	−53	−45	−49	−40	4	−43
		$t/2$	−52	−45	−50	−40	2	−47
	690°C × 26 h	Subsurface	−69	−61	−48	−40	21	−16.5
		$t/4$	−58	−50	−50	−40	8	−38
		$t/2$	−55	−48	−53	−44	2	−50
Two electrode (8 mm*R*)	690°C × 8 h	$t/4$	−67	−66	−51	−49	16	−27
	690°C × 26 h	$t/4$	−76	−68	−69	−56	7	−58.5

PWHT and step-cooling treatment, but compared with the single-electrode process, toughness dropped slightly in the two-electrode process. This is considered attributable to 50 ppm higher oxygen content for the two-electrode process, as shown in Table 4.

It was also found that there was virtually no difference in toughness between single-pass-per-layer and two-pass-per-layer weld metals, and both had excellent toughness. This can be explained by the fact that there is only a minor difference in toughness between the as-dendrite structure and the refined-grain structure of the present composition system, as shown in Fig. 2.

Reflecting the demands for assured safety during operation in arctic fields and extended service life, the following equation is required as an index of in-service temper embrittleness characteristics:

$$_VT_{r40} + \alpha \times \Delta_V T_{r40} \leqq 10°C$$
$$\alpha = 1.5\sim2.5$$

It can easily be understood that the newly developed weld metal can satisfy the more strict requirement of $\alpha = 2.5$ under any type of welding process. Tensile properties of these weld metals are shown in **Table 6.**

Table 6 Summary of tensile properties of weld metal for two-electrode welding process using KB 120 CM flux and KWT 210 wire

PWHT	Test temp. (°C)	0.2% proof stress (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)	Reduction of area (%)
690°C × 8 h	24	52.9	64.9	21	71
	454	43.0	50.4	19	71
690°C × 26 h	24	46.9	59.6	24	74
	454	38.2	45.8	19	74

From the above-mentioned results, the newly developed welding consumables can be seen to have the feature of excellent toughness irrespective of build-up method and notch location, and are advantageous in homogeneity of material quality, which is indispensable to oil refinery reactor vessels.

Table 7 Mechanical properties at $t/4$ location of 3Cr-1Mo modified steel welded joint

PWHT	Notch locations	Tensile strength (kgf/mm^2) 24°C	Tensile strength (kgf/mm^2) 454°C	Toughness (°C) $_vT_{r40}$	Toughness (°C) $_vT'_{r40}$	$_vT_{r40}+2.5\Delta _vT_{r40}$ (°C)
690°C ×8 h	WM	73	57	−35	−30	−22.5
	FL	—	—	−69	−64	−56.5
	HAZ 2 mm	—	—	−97	−95	−92
690°C ×26 h	WM	68	52	−46	−40	−31
	FL	—	—	−86	−72	−51
	HAZ 2 mm	—	—	−84	−74	−59

4.2 High-Strength Welding Consumables for 3Cr-1Mo Steel (Flux KB 120CM and Wire KWT 310)

Recently, in the Metal Properties Council, which is the Cr-Mo steel research committee in which oil companies, fabricators, and mill makers participate, a concept has been proposed for promoting enhanced strength of steels (TS = 85 to 110 ksi) and for seeking economic benefits through high-temperature and high-pressure operation of facilities and enhancement of design stress.

Narrow gap welding was carried out using a 350 mm thick 3Cr-1Mo-V-Nb modified forged steel by the two-electrode process with a heat input of 31 kJ/cm. The joint performance at the $\frac{1}{4}t$ location is shown in **Table 7**, which indicates that the joint has satisfactory strength and toughness.

4.3 Mock-up Test

To confirm the practical applicability of high-toughness welding consumables to the narrow-gap two-electrode SAW process, a mock-up test was conducted, although the single-electrode narrow gap SAW process had been successfully applied to the fabrication of 2¼Cr-1 Mo steel heat exchangers.[8]

In the mock-up test, a 90-mm-thick 2¼Cr-1Mo forged ring with an inside diameter of 2 500 mm was given a U-groove having a root radius of 8 mm, groove angle of 2° and depth of 75 mm. Welding conditions are shown in **Table 8**.

Table 8 Welding conditions for mock-up test

Welding consumable	Welding process	Preheat and interpass temperature (°C)	Welding parameters (AC-AC) Current* (A)	Voltage (V)	Travel speed (cm/min)	Heat input (kJ/cm)
KB 120 CM and KWT 210	1 run-1 layer	180 ~ 200	530~540	29~31	45	36.8
	2 run-1 layer		520~530	28~30	62	29.5

* Welding current of leading electrode and trailing electrode

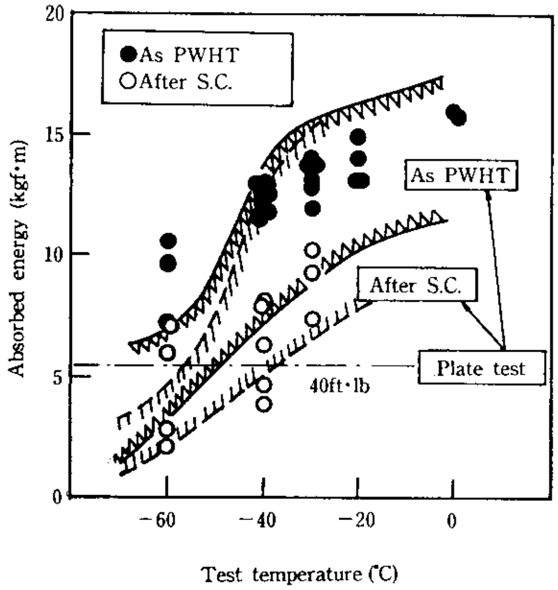


Fig. 10 Weld metal toughness deposited with one-pass-per-layer technique in mock-up test

4.3.1 Welding workability

Excellent bead wettability was exhibited by the new welding consumables on the side walls of the groove. Even if wire working position deviated slightly, occurrence of such defects as undercut was hardly observed, and no weld defects were detected by ultrasonic or radiographic inspection. Good slag detachability was also proved even in the single-pass-per-layer welding operation.

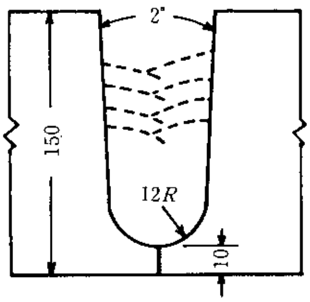
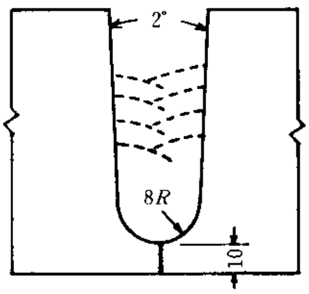
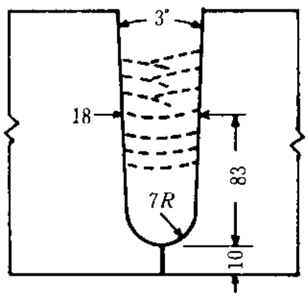
4.3.2 Impact test on weld metal

Toughness after PWHT at 690°C for 8 h and additional step-cooling treatment is shown in **Fig. 10**. The figure indicates that the test results for the ring reproduced well those of the plate test in the preceding section, given as a range for purposes of comparison. The figure also reconfirms that the $_vE_{-30}$ value after step cooling easily satisfied the target value of 5.5 kgf·m (40 ft·lb).

4.3.3 Comparison of welding efficiency

With the premise of two-electrode welding, a comparison of welding efficiency was made between the conventional welding process and the single-pass-per-layer and two-pass-per-layer narrow gap welding process. The results are shown in **Table 9**. The adoption of the narrow gap welding process permitted reductions of about 30% in welding consumable cost and 26% in arc

Table 9 Comparison of welding efficiency between conventional and narrow gap SAW process

Welding process	Conventional SAW (A)	Narrow gap SAW 2 run per layer (B)	Narrow gap SAW 1 run per layer & 2 run per layer (C)
Groove preparation			
Cross-sectional area for 150 mm thick steel	35.8 cm²	25.2 cm² (B/A=0.70)	24.0 cm² (C/A=0.67)
Welding condition (2 electrode)	500~600 A, 45~55 cm/min	500~550 A, 60 cm/min	450~550 A, 40~60 cm/min
Total arc time for 1 m long weld joint	127 min	94 min (B/A=0.74)	94 min (C/A=0.74)

time. Simultaneously with this cost saving, it has also become clear that the narrow gap welding is effective in shortening delivery period, considered another important point in recent fabrication of pressure vessels.

5 Conclusions

After metallurgical examination of the toughness and strength of 2¼Cr-1Mo weld metal, the authors have developed high-quality narrow-gap SAW consumables for Cr-Mo steel. Further, a production scale mock-up test of these welding consumables was performed. The results obtained are as follows:

(1) As a result of an increase in C content and an addition of V, finer bainitic substructure and uniformly dispersed carbides are obtained, thereby improving the toughness of the as-dendrite structure. Thus homogeneous weld metal with reduced variation in toughness can be obtained.

(2) A single addition of Ti enhances tensile strength, but lowers toughness. Composite small addition of Ti and V, however, improves toughness while maintaining high strength.

(3) On the basis of the above findings, the authors have developed high-quality narrow-gap SAW consumables for Cr-Mo steel, providing high toughness and high strength.

(4) High-toughness welding consumables, Flux KB 120 CM and Wire KWT 210, give high toughness irrespective of the build-up methods and easily satisfy the most stringent requirements.

(5) A mock-up test confirmed the practical applicability of the two-electrode narrow-gap SAW process. Through the application of this new process, arc time can be reduced by about 26%, and shortening of the delivery period can also be achieved.

Finally, the authors wish to express their deep appreciation to the staff concerned of the Muroran Works of The Japan Steel Works, Ltd., who rendered valuable advice and cooperation in the course of the mock-up test.

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