Toughness and Creep Strength of Modified 2.25Cr-1Mo Steel Weld Metal

Weld metal compatible with modified 2.25Cr-1Mo was produced when the carbon, manganese, nitrogen and oxygen were kept low

BY K. ICHIKAWA, Y. HORII, A. SUEDA, AND J. KOBAYASHI

ABSTRACT. This paper reports the optimum chemical compositions for submerged arc (SA) weld metal of modified 2.25Cr-1Mo steel by investigating the influence of carbon, manganese, nitrogen and oxygen on the mechanical properties of the weld metal.

Submerged arc welding was conducted at a welding heat input of 3 kJ/mm (76.2 kJ/in.), and weld metal tests were performed to determine tensile strength, creep strength, toughness and hydrogen embrittlement characteristics. Metallographic investigations by optical microscopy, TEM and x-ray diffraction were also conducted.

A decrease of gas elements such as oxygen and nitrogen improves toughness. A decrease of nitrogen also improves the resistance to hydrogen embrittlement susceptibility through an increase of effective vanadium precipitates, which leads to a reduction in diffusible hydrogen.

A decrease in the manganese content is beneficial for the creep strength because more coarsened grains facilitate grain boundary sliding, and, to a lesser extent, microvoid nucleation at grain boundaries. However, a reduction of manganese lowered tensile strengths at room and high temperatures, as well as toughness at low temperatures due to coarsened grains.

In conclusion, the optimum composition for weld metal is a low-carbon, low-manganese, low-oxygen, low-nitrogen type with microalloyed vanadium and niobium.

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Introduction

The 2.25Cr-1Mo steel is widely used as a heat-resisting material for pressure vessels in power stations or in petroleum and chemical plants, because of its superior mechanical properties at elevated temperatures. Recently, there have been demands on those plants to operate at higher temperatures and pressures to improve the operating efficiency. This calls for increasing steel strengths, which also can reduce construction costs, because of decreased plate thicknesses. The demands for higher strength steel have led to the development of the modified 2.25Cr-1Mo steel (hereafter referred to as modified 2.25Cr-1Mo steel) in which conventional 2.25Cr-1Mo steel is microalloyed with niobium and vanadium to improve tensile strength and creep rupture strength. The modified steel was standardized as ASME CASE 2098-1 (Ref. 1). At present, many power plants built 20 or 30 years ago are reaching the end of their design lives. Therefore, most fabricators are trying to adopt modified 2.25Cr-1Mo steel for plants to be renewed.

KEY WORDS

Toughness
Creep Strength
Modified 2.25Cr-1Mo
Weld Metal
SAW
Mechanical Properties
Tensile Strength
Effect of Nitrogen
Effect of Oxygen
Effect of Mn

The modified steel must retain not only higher strength, but also greater toughness because some plants are located in frigid areas. For instance, the ASME CASE 2098-1 specifies a tensile strength of 586 to 758 MPa (85–110 ksi) and an average Charpy V-notch toughness of 54 J (40 ft-lb) at 255 K (0°F) (Ref. 1). The improvement of resistance to hydrogen embrittlement susceptibility is important because the steel is often used in hydrogen environments.

Welding consumables are needed to adapt this steel for actual construction so that the weld metal possesses the same level of mechanical properties as the base steel.

Several studies have been made on the influence of alloying elements on the mechanical properties of modified 2.25Cr-1Mo steel weld metal, including tensile strength, toughness, creep rupture strength and hydrogen embrittlement characteristics (Refs. 2–5). According to those studies, increases of niobium and vanadium effectively raises creep rupture strength, and it may be concluded that the optimum contents of niobium and vanadium are approximately 0.02 wt-% and 0.2 to 0.3 wt-%, respectively, in order to provide weld metal with satisfactory creep rupture strength and toughness. The influence of carbon and manganese on mechanical properties has also been discussed (Refs. 3, 4), and little is known about how carbon and manganese affect creep rupture strength. Moreover, gas elements, such as oxygen and nitrogen, are important to determine the chemical composition of the SA welding flux, because they exert considerable effects on the toughness of weld metal (Refs. 5–7). It was reported that nitrogen added (0.027 wt-%) to conventional 2.25Cr-1Mo steel weld metal displayed Charpy properties superior to a low-nitrogen (0.006 wt-%) type of weld metal (Ref. 7). However, few studies have been tried to increase nitrogen in modified 2.25Cr-1Mo steel weld metal as a way to improve toughness (Refs. 4, 5). The effect of nitrogen on the toughness of this weld metal is not yet obvious.

The purpose of this study is to determine submerged arc (SA) welding materials suited to modified 2.25Cr-1Mo steel through investigations of the effects of such alloying elements as carbon, manganese, nitrogen and oxygen on the mechanical properties of weld metal.

Experimental Procedure

Conventional 2.25Cr-1Mo (ASTM A387-87 Grade 22 Class 2) steel with a plate thickness of 50 mm (2 in.) was used as the base metal. The chemical composition of the steel is shown in Table 1. Four kinds of laboratory melted SA welding electrodes of 4.0 mm (0.16 in.) diameter were used. Their chemical compositions are shown in Table 2. Eleven kinds of laboratory manufactured agglomerated SA welding flux of a basic type were used. Their chemical compositions are listed in Table 3. Eleven welds were made with various combinations of the electrodes and fluxes. The combinations are listed in Table 4. All the welds contained approximately 0.02-wt-% Nb and 0.3-wt-% V, which were added from electrodes or fluxes to maintain certain levels of creep rupture strength and tensile strength at elevated temperatures.

Single-electrode SA welding was conducted in the welding conditions shown in Table 5. The postweld heat treatment (PWHT) for all the welds was carried out for the duration between 8 and 24 h at 963 K (1274° F). Some welds were subjected to step cooling SOCAL No. 1 type accelerated embrittling heat treatment to assess the embrittlement of the weld metal during service. This heat treatment is characterized by the thermal history after PWHT as shown in Fig. 1. After those heat treatments, joint weld metal tests were carried out with respect to tensile strength, creep rupture strength and Charpy V-notch absorbed energy. The locations of the specimens of those tests are described in Fig. 2.

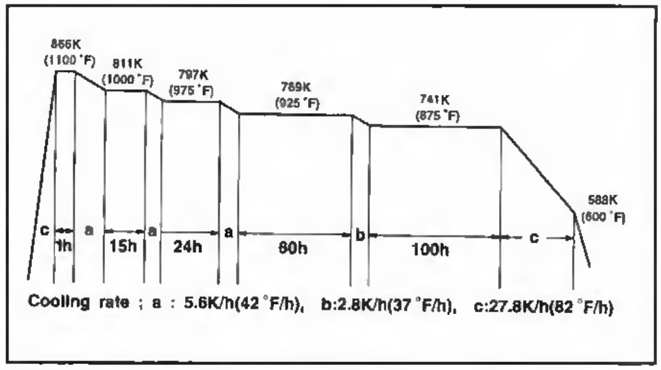


Fig. 1 — Step cooling heat treatment used.

Hydrogen embrittlement characteristics for the welds N1 and N2 were also investigated by constant load tests. Compact type (CT) specimens described in Fig. 3 were used to determine the stress intensity factor K_I. This factor is given by Srawley (Ref. 8) as the following equation.

$$\frac{K_I}{P}BW^{1/2} = \frac{2+a/w}{(1-a/w)^{3/2}} \left\{ 0.886 + 4.64\left(\frac{a}{w}\right) - 13.32\left(\frac{a}{w}\right)^2 + 14.72\left(\frac{a}{w}\right)^3 - 5.6\left(\frac{a}{w}\right)^4 \right\} \quad (1)$$

Where P = load. See Fig. 3 for dimensional parameters; B, W and a.

The location of this specimen from the test weld is also shown schematically in Fig. 4. Metal blocks (30 x 30 x 12.5 mm/1.2 x 1.2 x 0.5 in.) for the measurement of diffusible hydrogen were also taken from the place where the CT specimens were taken. Two different types of hydrogen charging conditions listed in Table 6 were applied here. First, both the CT specimens and the blocks were hydrogen charged in an autoclave at the same time under condition A shown in Table 6. In addition to this, some blocks were charged under condition B to confirm the influence of nitrogen contents on diffusible hydrogen contents. According to Japan Industrial Standard JIS Z 3118, two methods, namely the glycerin displacement method and the gas chromatography method are available to measure a diffusible hydrogen content in weld metal. It is reported that there is satisfactory correlation between two methods if the content is rather high (Ref. 13). In this study, hydrogen was charged under high pressure in the autoclave and the diffusible hydrogen content was high enough to be determined by the glycerin displacement method. The glycerin method is available for large specimens. For these reasons, diffusible hydrogen contents were measured by the glycerin displacement method at a temperature of 321 K (118°F).

The metallographic investigations with an optical microscope, as well as the characterization of precipitates in the weld metal with transmission electron microscope (TEM) and x-ray diffraction

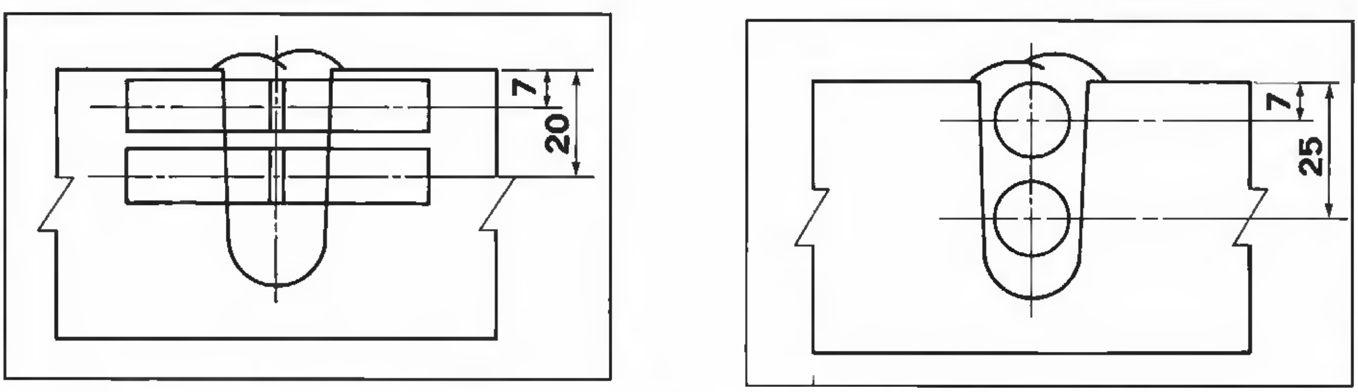


Fig. 2 — Location of test specimens (in mm). A — Charpy impact test specimen; B — tensile and creep rupture specimen.

Table 1 — Chemical Compositions of Base Metal (wt-%)

	C	Si	Mn	P	S	Cr	Mo	Nb	V
ASTM A387-87 Grade 22 Class 2	0.13 ~ 0.14	0.14 ~ 0.17	0.50 ~ 0.57	0.007 ~ 0.011	0.002 ~ 0.004	2.36 ~ 2.40	0.97 ~ 1.01	—	—

Table 2 — Chemical Compositions of SAW Electrode (wt-%)

Electrode	C	Si	Mn	P	S	Cr	Mo	Nb	V
W1	0.11	0.05	0.44	0.004	0.004	2.38	1.00	0.02	0.31
W2	0.13	0.03	0.92	0.003	0.003	2.36	1.01	—	0.40
W3	0.13	0.03	0.91	0.003	0.003	2.35	1.00	0.03	0.29
W4	0.13	0.03	1.00	0.002	0.004	2.32	1.00	0.03	0.14

Table 3 — Chemical Compositions of SAW Flux (wt-%)

Flux	ΣCaO	Al_2O_3	MgO	SiO_2	Metallic Elements
F1	48.8	17.9	23.0	6.2	4.1
F2	48.1	17.6	22.7	6.2	5.4
F3	45.3	17.7	22.3	6.6	8.1
F4	45.3	17.7	22.3	6.6	8.1
F5	45.3	17.7	22.3	6.6	8.1
F6	45.3	17.7	22.3	6.6	8.1
F7	39.7	21.6	26.2	9.5	3.0
F8	38.8	21.2	26.0	9.0	5.0
F9	39.6	21.6	26.2	9.4	3.2
F10	46.3	18.1	22.9	6.7	6.0
F11	46.3	18.1	22.9	6.7	6.0

Table 4 — Combinations of SAW Flux and Electrode

Weld	OX1	OX2	N1	N2	N3	N4	CM1	CM2	CM3	HN1	HN2
Electrode	W1		W2					W3		W4	
Flux	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11

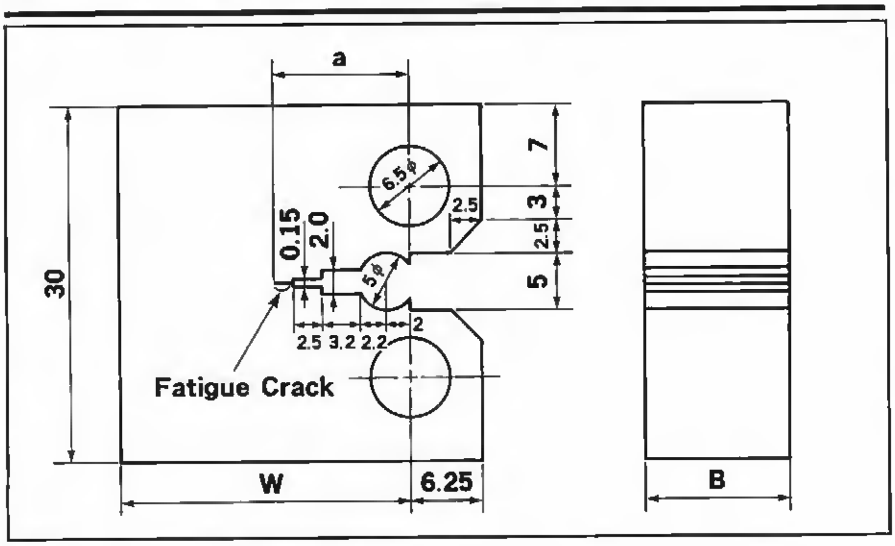


Fig. 3 — Geometry of CT specimen. W = 25 mm; B = 12.5 mm.

on electrolytically extracted residues, were also conducted to clarify the mechanism of mechanical property improvements in the weld metal. The etching used for the optical microscopy was prepared in a following manner: 2 mL of 10-g solution dodecylbenzenesulfonic acid sodium salt + 5-g picric acid + 5-g oxalic acid + 100 mL distilled water was solved into 100 mL distilled water. This solution was selected because it was effective in revealing bainite in this weld metal. Carbon-extracted replicas were prepared for the observation on precipitates. An analytical electron microscope (AEM) (JEM-4000FX) was used for the TEM observation. Electrolysis for the x-ray diffraction on extracted residues was done in a bath of methanol solution of 5g/100 mL maleic anhydride by potentiostatic electrolysis.

Results and Discussion

Chemical Compositions of the Weld Metals

The chemical compositions of the weld metal are given in Table 7. The weld metals marked OX1 and OX2 were made to clarify the effect of oxygen on the mechanical properties. The welds from N1 to N4 were for the investigation on the effect of nitrogen. The welds, CM1, CM2 and CM3, were provided to investigate the effects of carbon and manganese on creep rupture strength and toughness. In this series, CM1 is of a standard type, CM2 is of a high-manganese type, and CM3 is of a high-carbon type. In the set of HN1 and HN2, the effect of nitrogen on hydrogen embrittlement characteristics is investigated.

Effect of Oxygen

Transition curves shown in Fig. 5 were obtained from the Charpy impact test results of the welds OX1 and OX2. This figure shows the effect of oxygen on toughness after PWHT: 963 K (1274°F) for 8 h. As this figure indicates, a decrease of

Table 5 — Welding Conditions of SAW

Pass	Polarity	Current (A)	Voltage (V)	Welding Speed (mm/min)	Heat Input (kJ/mm)	Ext. (mm)	Groove Geometry (unit in mm)	Preheat and Interpass Temperature
1st	AC	450	28	250 (9.8 in./min)	3.0 (76.2 kJ/in.)	30		423 K (302°F) ~ 473 K (392°F)
2nd ~ 17 or 19		500	29	300 (13.8 in./min)	2.9 (73.7 kJ/in.)			

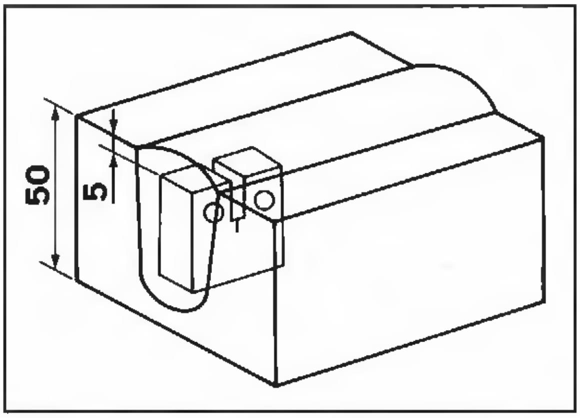


Fig. 4 — Location of CT specimen (in mm).

oxygen improves toughness of the weld metal. It might be supposed that an increase of oxygen raises the number of oxides that act as the initiation sites of brittle fracture in weld metal. Therefore, oxygen in weld metal should be decreased to improve toughness.

Effect of Nitrogen

Figure 6 was obtained from the test results of the welds from N1 to N4. It shows the effect of nitrogen on toughness. In this figure, the ordinate represents vTr_{40}, that is, a transition temperature at which the absorbed energy of 54 J (40 ft-lb) is obtained. It could be understood that toughness of the welds subjected to PWHT of 24 h is better than the welds after the PWHT of 8 h. Step cooling heat treatment embrittles the weld metal by approximately 10 or 20 K (50° or 70°F) in vTr40 for the welds after two kinds of PWHT. It should be emphasized, in this figure, that an increase of nitrogen raises vTr40 of the weld metal subjected to two kinds of PWHT and the step cooling heat treatment. Therefore, nitrogen degrades toughness of modified 2.25Cr-1Mo steel weld metal. Table 8 shows the tensile test results of weld metal from N1 to N4 with different PWHT conditions. Figure 7 shows the effect of nitrogen on tensile strength and 0.2% yield strength at room temperature. Both tensile strength and yield strength decrease by about 98 MPa (14 ksi) with long PWHT of 24 h as compared with 8 h. They slightly decrease with a reducing nitrogen content. The reduction is about 30 MPa (4.4 ksi) with a nitrogen reduction of 300 ppm. It is generally said that the toughness of weld metal consisting of tempered martensite or bainite increases with decreasing strength. Therefore, the toughness improvement by the long PWHT in Fig. 6 may be caused by the reduction of strength. But the change in strength by

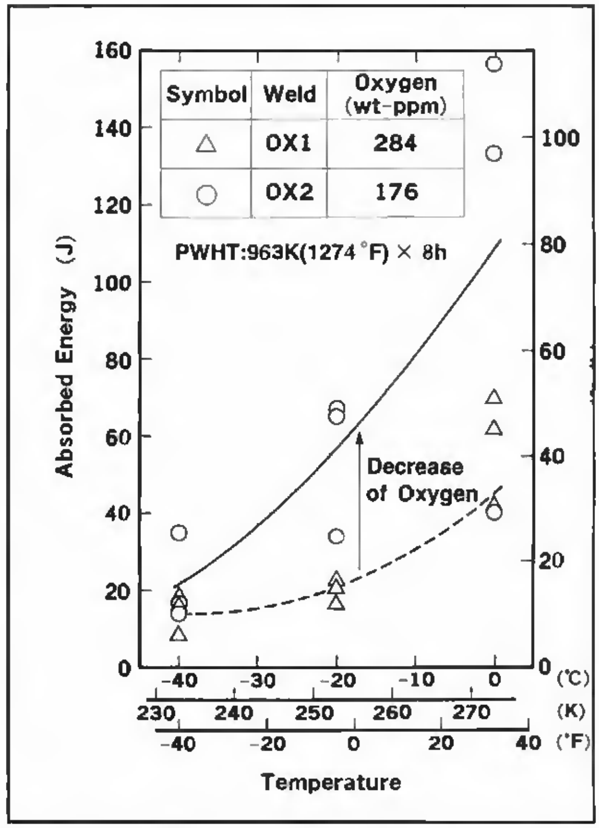


Fig. 5 — Influence of oxygen on Charpy absorbed energy of modified 2.25Cr-1Mo steel weld metal.

Table 6 — Hydrogen Charging Condition

	Temperature K (°F)	Pressure MPa (ksi)
Condition A	755 (900)	21 (3.05)
Condition 8	873 (1112)	30 (4.35)

Table 7 — Chemical Compositions of Weld Metals (wt-%, *:wt-ppm)

Weld	C	Si	Mn	P	S	Cr	Mo	Nb	V	N*	O*	PWHT
OX1	0.11	0.20	0.57	0.006	0.003	2.28	0.99	0.01	0.25	73	284	963 K (1274° F) × 8 h
OX2	0.13	0.19	0.58	0.007	0.002	2.30	0.99	0.02	0.25	69	176	
N1	0.12	0.14	1.34	0.008	0.002	2.23	1.00	0.02	0.31	37	292	963 K (1274° F) × 8 h
	0.12	0.13	1.29	0.009	0.002	2.26	0.99	0.02	0.30	35	344	963 K (1274° F) × 24 h
N2	0.12	0.15	1.36	0.008	0.002	2.26	0.99	0.02	0.32	101	243	963 K (1274° F) × 8 h
	0.11	0.14	1.32	0.008	0.002	2.27	1.00	0.02	0.32	127	334	963 K (1274° F) × 24 h
N3	0.12	0.13	1.23	0.008	0.002	2.29	1.01	0.02	0.32	166	303	963 K (1274° F) × 8 h
	0.11	0.13	1.20	0.008	0.002	2.26	1.00	0.02	0.31	156	283	963 K (1274° F) × 24 h
N4	0.12	0.15	1.28	0.008	0.002	2.27	1.00	0.02	0.31	245	237	963 K (1274° F) × 8 h
	0.12	0.13	1.18	0.007	0.002	2.26	1.00	0.02	0.31	312	286	963 K (1274° F) × 24 h
CM1	0.11	0.14	0.73	0.005	0.002	2.30	1.03	0.02	0.27	26	254	
CM2	0.12	0.14	1.03	0.006	0.002	2.30	1.03	0.02	0.27	22	166	963 K (1274° F) × 8 h
CM3	0.14	0.18	0.75	0.005	0.002	2.30	1.01	0.02	0.27	21	256	
HN1	0.10	0.10	0.90	0.007	0.002	2.33	1.03	0.02	0.29	54	246	963 K (1274° F) × 8 h
	0.10	0.10	0.88	0.006	0.002	2.30	1.02	0.02	0.30	57	277	963 K (1274° F) × 24 h
HN2	0.10	0.08	0.89	0.006	0.002	2.34	1.04	0.02	0.27	135	277	963 K (1274° F) × 8 h
	0.10	0.09	0.87	0.005	0.002	2.32	1.02	0.02	0.27	134	283	963 K (1274° F) × 24 h

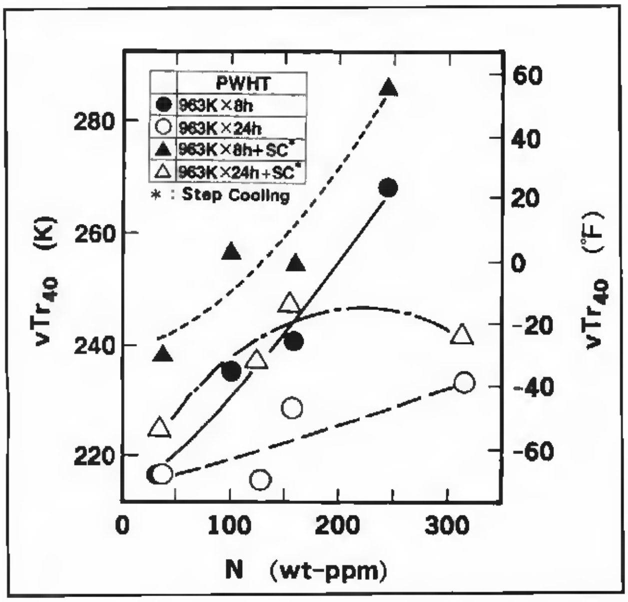


Fig. 6 — Influence of nitrogen content on toughness of modified 2.25Cr-1Mo steel weld metal.

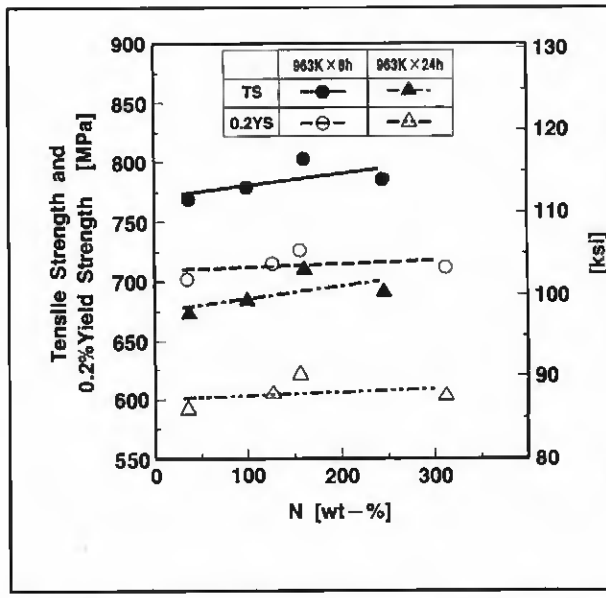


Fig. 7 — Influence of nitrogen content on strength of weld metal at room temperature.

nitrogen is negligibly small compared with the effect of PWHT duration. Then the toughness improvement by the nitrogen reduction cannot be satisfactorily explained by the reduction of strength. Hojo, *et al.*, has reported that a nitrogen-added (0.027 wt-%) conventional-type 2.25Cr-1Mo steel weld metal displays superior Charpy characteristics to a low-nitrogen (0.006%) type of weld metal (Ref. 7). The effect of nitrogen in the modified steel weld metal was absolutely opposite to that of the conventional steel weld metal. Then, it should be clarified how the difference in nitrogen behavior influences toughness of these welds.

Figure 8 shows the effect of a nitrogen content on the ductility of modified 2.25Cr-1Mo steel weld metal. The ductility, represented by reduction of area and elongation, decreases with an increase in nitrogen content. This ductility reduction seems to degrade toughness. Some metallographic investigations were carried out to obtain the following results in order to know the reason why the reduction of nitrogen improves toughness in the modified 2.25Cr-1Mo steel weld metal. Figure 9 shows the contents (%) of each alloyed element in precipitates in the weld metal of A) as-welded, B) after PWHT 963 K (1274°F) for 8 h, and C) 24 h. Numbers of percentage in the figure represent the weight ratio of each element in the weld metal. As Fig. 9 indicates, the content of vanadium precipitates gradually increases with increasing nitrogen contents in the weld metal for both PWHT conditions. Figure 10 is an example of the AEM observations of the weld metal, including TEM bright field image, electron beam diffraction and energy dispersive spectrometer (EDS). These observations and x-ray diffractions reveal the existence of fine vanadium precipitates (V, Mo)(C, N) and large precipitates M_7C_3 and $M_{23}C_6$. According to Hojo, one reason for the toughness improvement of the nitrogen-added conventional 2.25Cr-1Mo steel weld metal is that softening by PWHT was promoted by precipitation of CrN in the nitrogen- added weld metal (Ref. 7). However, CrN could not be identified by x-ray diffractions and AEM analysis in the modified 2.25Cr-1Mo steel weld metal in this study. Of course, the softening of the weld metal with increasing nitrogen was never found as shown in Fig. 7 and Table 8.

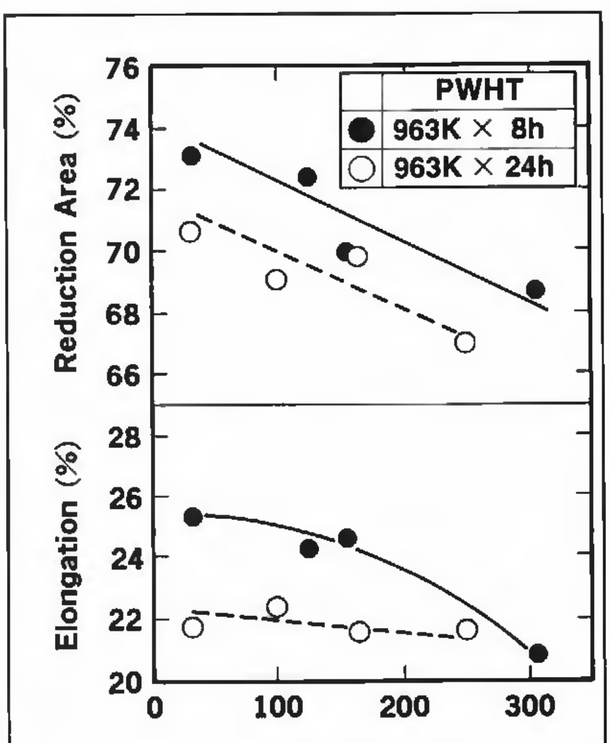


Fig. 8 — Influence of nitrogen content on ductility of modified 2.25Cr-1Mo steel weld metal.

The differences in the nitrogen behavior concerning toughness between the conventional 2.25Cr-1Mo steel weld metal and the modified 2.25Cr-1Mo steel, therefore, can be explained by the difference of precipitates, as mentioned above. The differences might be affected by the difference in vanadium contents. Consequently, for the vanadium-added 2.25Cr-1Mo steel weld metal, a decrease of nitrogen improves toughness, though an increase of nitrogen in the conventional 2.25Cr-1Mo steel weld metal improves toughness.

It may be expected that the reduction of nitrogen effectively improves hydrogen embrittlement susceptibility of weld metal. Then the effect of nitrogen on hy-

Table 8 — Tensile Test Results of Weld Metal Made with Different Nitrogen Contents

	PWHT at 963 K (1247°F)	Test at Room Temperature				Test at 755K (900° F)			
Mark	Duration (h)	0.2%YS MPa (ksi)	T.S. MPa (ksi)	El (%)	RA (%)	T.S. MPa (ksi)	El (%)	RA (%)	Hv (10kg)
N1	8	673 (97.6)	769 (112)	22	70	580 (84.1)	22	70	238
	24	592 (85.9)	702 (102)	25	73	515 (74.7)	23	71	221
N2	8	684 (99.2)	779 (113)	22	70	586 (85.0)	21	70	241
	24	605 (87.7)	715 (104)	25	70	521 (75.6)	23	71	225
N3	8	710 (103)	803 (116)	22	67	590 (85.6)	20	66	251
	24	621 (90)	726 (105)	21	69	529 (76.7)	21	68	228
N4	8	691 (100)	786 (114)	22	69	594 (86.2)	23	71	244
	24	603 (87.5)	712 (103)	24	72	528 (76.6)	26	75	223

drogen embrittlement characteristics was investigated by the constant load tests for the welds HN1 and HN2. Chemical compositions of the welds are included in Table 7.

Figure 11 shows the effect of nitrogen on hydrogen embrittlement characteristics. It indicates the rupture time under two levels of heat input after two kinds of PWHT. For two different kinds of PWHT, the weld of a low-nitrogen type did not break. Therefore, the reduction of nitrogen is effective in improving hydrogen embrittlement characteristics. In addition, hydrogen embrittlement characteristics depend on the PWHT condition. Figure 11 shows that the duration until rupture after PWHT of 8 h is longer than that of after 24 h. These phenomena can be explained by the difference in the quantity of diffusible hydrogen. Table 9 shows the results of the measurement of diffusible hydrogen in these welds. For every PWHT condition and hydrogen charging condition, the reduction of nitrogen lowered the hydrogen concentration. And it can be seen that an increase in PWHT duration for two charging conditions raises the hydrogen concentrations.

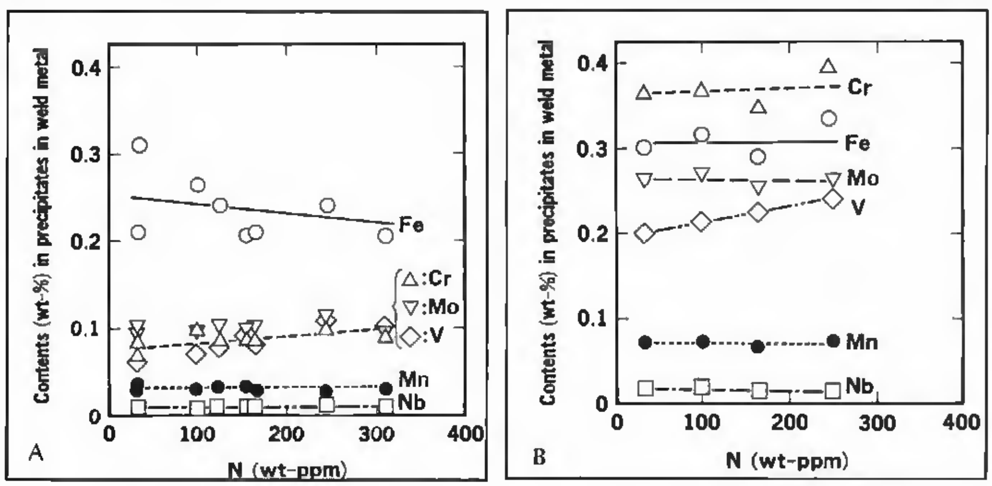
The mechanism of the improvement of the hydrogen embrittlement characteristics by the reduction in a nitrogen content can be presumed as follows:

It is well known that the addition of vanadium above 0.2 wt-% in 2.25Cr-1Mo steel suppresses the ductility reduction induced by hydrogen (Ref. 9). It might be thought in this study, therefore, that the reduction of nitrogen increases the effective vanadium for the reduction of the diffusible hydrogen in the weld metal and improves the embrittlement property.

The above results revealed that a decrease in nitrogen content improved both toughness and hydrogen embrittlement characteristics, although a further study may be needed to understand why a decrease in nitrogen content results in the reduction of the diffusible hydrogen in the steel.

Effects of C and Mn

Results of creep rupture tests for CM1, CM2 and CM3 weld metal are shown in Fig. 12. A decrease of manganese (CM1, Mn 0.73 wt-%) improves the creep rupture strength compared with higher manganese (1.03 wt-% of CM2). The improvement is more remarkable as the temper parameter increases. This suggests that the effect of manganese on creep rupture strength does not depend on the strengthening factor that governs the tensile strength at room temperature, but depends on the other factor governing the creep phenomenon. Carbon (C = 0.11 and 0.14 wt-%) has no significant ef-



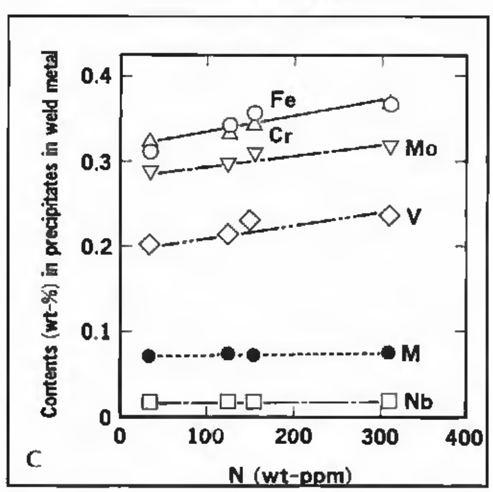


Fig. 9 — A — Influence of nitrogen on contents of alloyed elements in precipitates in as-welded weld metal; B — influence of nitrogen on contents of alloyed elements in precipitates in weld metal that was PWHT at 963 K for 8 h; C — influence of nitrogen on contents of alloyed elements in precipitates in weld metal that was PWHT at 963 K for 24 h.

Table 9 — Results of the Measurement of Diffusible Hydrogen in Weld HN1 and HN2

Weld	Nitrogen (wt-ppm)	PWHT (at 963 K) Duration (h)	Diffusible Hydrogen (wt-ppm) 755 K × 21 MPa (900° F × 3.05 ksi)	Diffusible Hydrogen (wt-ppm) 873 K × 30 MPa (1112° F × 4.35 ksi)
HN1	54	8	0.30	5.95
	57	24	0.75	6.95
HN2	135	8	1.89	7.84
	134	24	2.09	8.26

Table 10 — Tensile Strength of Weld CM1, CM2 and CM3

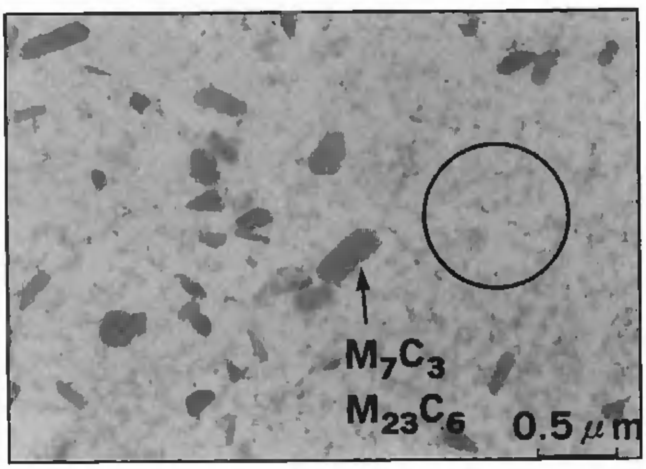
Weld	Test Temperature K (°F)	Tensile Strength MPa (ksi) PWHT:963 K (1274°F) × 8h	Tensile Strength MPa (ksi) PWHT:963 K (1274°F) × 24 h
CM1 C = 0.11 wt-% Mn = 0.73 wt-%	Room Temperature	739 (107)	685 (99.4)
	755 (900)	—	524 (76.0)
CM2 C = 0.12 wt-% Mn = 1.03 wt-%	Room temperature	745 (108)	696 (101)
	755 (900)	—	530 (76.9)
CM3 C = 0.14 wt-% Mn = 0.75 wt-%	Room Temperature	770 (112)	714 (104)
	755 (900)	—	542 (78.6)

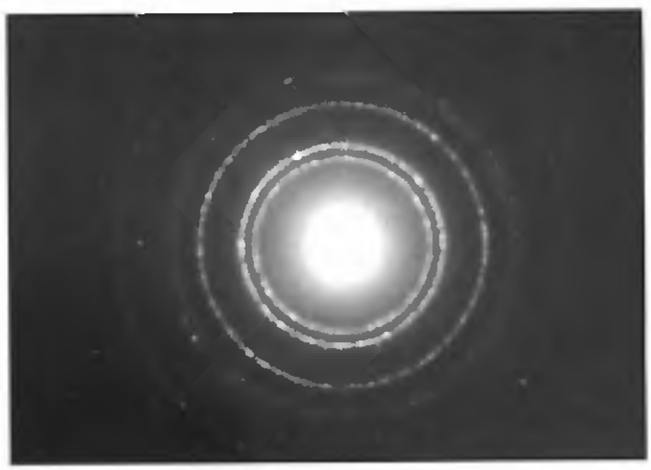
fect on creep rupture strength as seen from the comparison between CM1 and CM3.

Table 10 shows the tensile strengths of these three materials at room temperature and 755 K (900°F) after two types of PWHT. Both carbon and manganese remarkably raise the tensile strength at room temperature and at elevated temperatures despite the fact that an increase in these elements does not improve creep rupture strength. Detailed investigations have been conducted to understand the mechanism of an influence of manganese on creep rupture strength.

Gotoh, *et al.*, supposed that manganese promoted the formation of precipitates (Ref. 3). Fig. 13 shows the effect of carbon and manganese on the quantity of precipitates, mostly M_7C_3 and $M_{23}C_6$, in creep rupture test specimens after PWHT with each temper parameter. Figure 13 indicates that the quantity of precipitates increases with an increase in carbon, though manganese has no significant effect on the quantity of the precipitates. As these results indicate, there is no evidence that manganese promoted precipitation in this study.

Figure 14 shows the optical microstructure of three kinds of weld metal. As these welds were made with multilayered welding, the weld metal was heat affected by subsequent weld passes. Two types of microstructures can be observed in each weld metal. One is bainite in the as-welded zone, and the other is a mixed structure composed of ferrite and bainite that is surrounded by refined prior austenite grain boundaries in the zone reheated over A_{c1} temperature. In comparing CM2 with CM1, an increase of manganese reduces the bainite lath length and width in the as-welded zone and refines the grain size in the reheated zone. Similarly, it is found by comparing CM3 with CM1, that an increase of carbon refines microstructures in the two regions. The Bs (bainite transformation starting temperature) depends on carbon and manganese contents in the steel. For in-





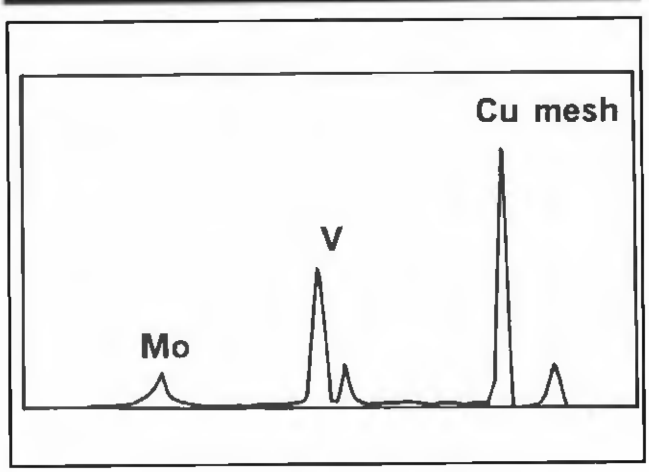


Fig. 10 — Example of AEM observations by extracted replicas of modified 2.25Cr-1Mo steel weld metal (n = 245 wt-ppm; PWHT 690°C for 8 h). A — Bright field image; B — electron diffraction pattern of the precipitates in the circle in A; C — result of EDS on the precipitates in the circle in A. According to the results of B and C, fine precipitates in A are identified as (V, Mo) (C, N).

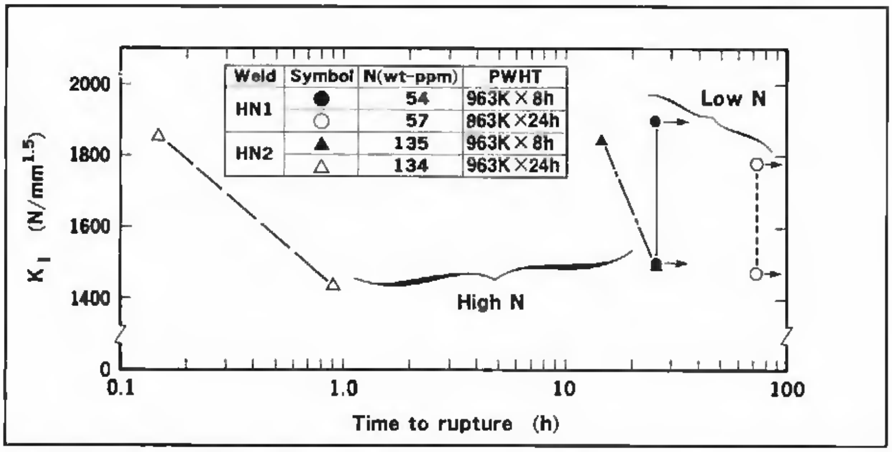


Fig. 11 — Influence of nitrogen contents on hydrogen embrittlement characteristics of modified 2.25 Cr-1Mo steel weld metal. Hydrogen charging condition: 755 K, 21 MPa.

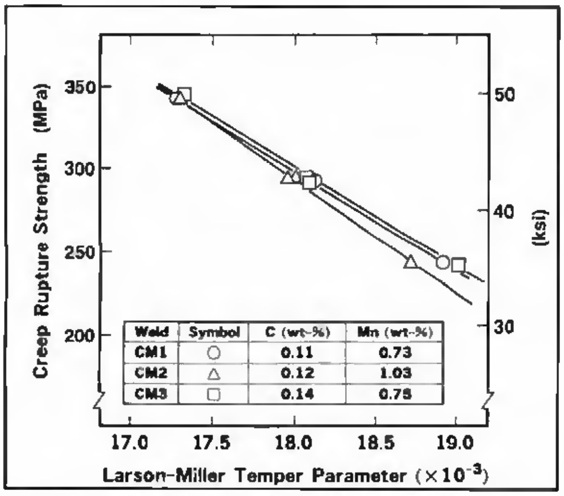


Fig. 12 — Influence of carbon and manganese contents on creep rupture strength of modified 2.25Cr-1Mo steel weld metal.

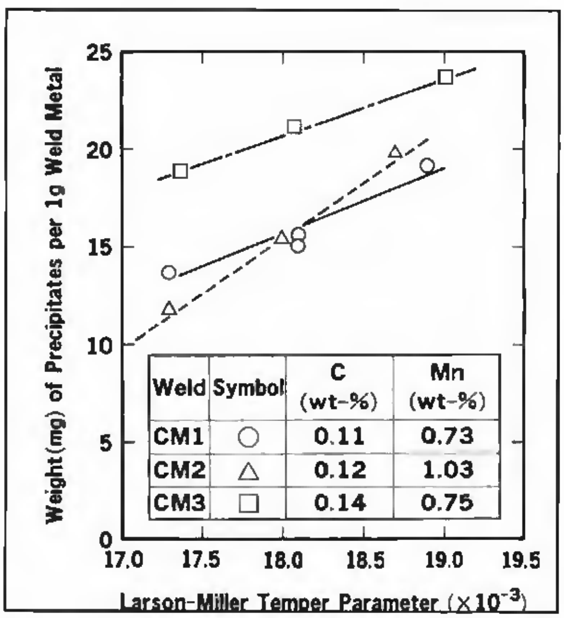


Fig. 13 — Influence of carbon and manganese on precipitation behavior in modified 2.25Cr-1Mo steel weld metal.

stance, Bs can be calculated empirically, as follows (Ref. 10):

$$Bs(^\circ C) = 830\text{-}270(\%C)\text{-}90(\%Mn)\text{-}37(\%Ni)\text{-}70(\%Cr)\text{-}83(\%Mo) \quad (2)$$

It might be considered that the microstructure refinement by increases of carbon and manganese was caused by the lowering of the Bs temperature.

The grain size, which means in this case the bainite lath length and width, affects tensile strength and creep rupture strength. Yield strength is generally proportional to the reciprocal of the square root of average grain size (Ref. 11). However, with regard to creep rupture strength, it is well known that a decrease in average grain diameter degrades creep resistance (Ref. 12). In this study, it seems that coarsened grains have fewer sites of grain boundary sliding or void nucleation than refined grains. According to the above results, the effect of manganese could be explained by the difference in the microstructures.

Although the reduction of manganese is one way to increase creep rupture strength, this causes a reduction in toughness. Figure 15 represents the results of Charpy V-notch impact tests for welds CM1, CM2 and CM3. As Fig. 15 shows, a decrease of manganese deteriorates toughness because it causes the microstructure as mentioned above. A decrease of carbon also deteriorates toughness for the same reason as in the case of manganese.

From the above results, a decrease of

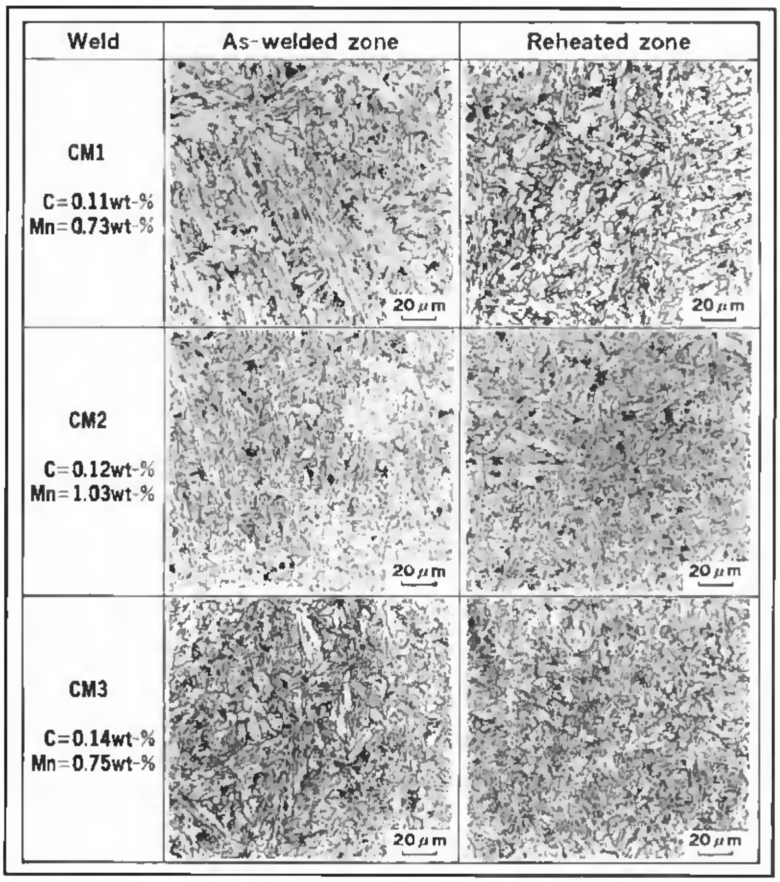


Fig. 14 — Influence of carbon and manganese contents on microstructure of modified 2.25Cr-1Mo steel weld metal (creeped with Larson-Miller temper parameter = 17.3 ~ 17.4).

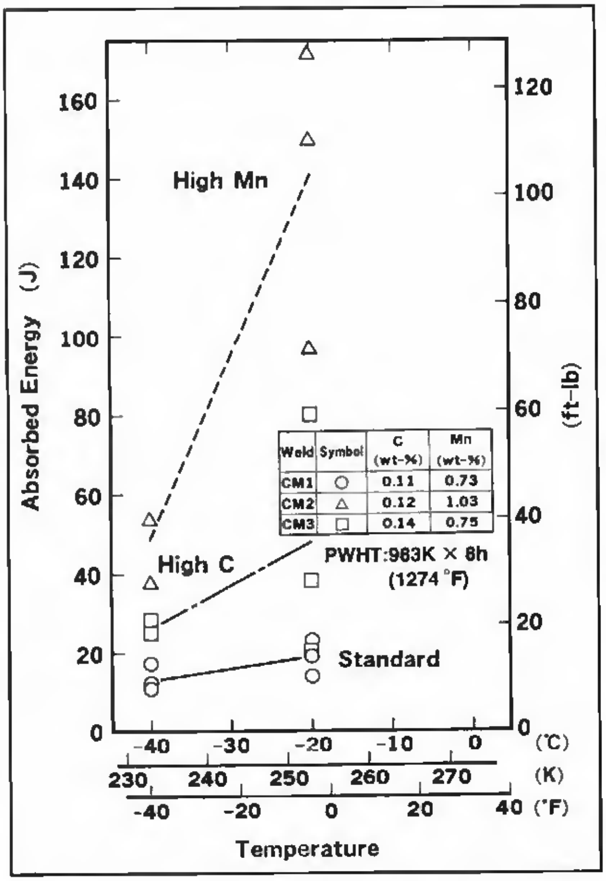


Fig. 15 — Influence of carbon and manganese on Charpy absorbed energy of modified 2.25Cr-1Mo steel weld metal.

manganese effectively improves creep rupture strength but deteriorates toughness. Therefore, gas elements such as oxygen and nitrogen should be lowed enough to maintain preferable toughness.

Conclusions

For the weld metal of SA welded modified 2.25Cr-1Mo steel, the following results were obtained:

1) Reduction of gas elements such as oxygen and nitrogen improve toughness. Reduction of nitrogen also improves hydrogen embrittlement characteristics through a decrease in diffusible hydrogen.

2) Reduction of manganese coarsens grains and improves creep rupture strength. A remarkable effect of carbon on creep rupture strength was not recognized. As carbon raises tensile strength, a high carbon content is undesirable from a viewpoint of hydrogen-induced cracking.

In conclusion, the optimum composition for the modified 2.25Cr-1Mo steel weld metal is a low-carbon, low-manganese, low-oxygen, low-nitrogen type with microalloyed vanadium and niobium.

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