

A Quick Guide to Suitable Welding Consumables for Heat-Resistant Low-Alloy Steel

Steel type	ASTM / ASME steel grade		SMAW		FCAW	
	Plate	Pipe / Tube	Brand name	AWS class.	Brand name	AWS class.
Mn-Mo Mn-Mo-Ni	-A302Gr.B,C,D -A533Type A,B,C,D	-	BL-96 BL-106	E9016-G E10016-G	-	-
0.5Mo	-A204Gr.A,B,C	-A209Gr.T1 -A335Gr.P1	CMA-76	E7016-A1	-	-
0.5Cr-0.5Mo	-A387Gr.2 Cl.1, Cl.2	-A213Gr.T2 -A335Gr.P2	CMB-83 CMB-86	E8013-G E8016-B1	-	-
1Cr-0.5Mo 1.25Cr-0.5Mo	-A387Gr.12 Cl.1, Cl.2 -A387Gr.11 Cl.1, Cl.2	-A213Gr. T11,T12 -A335Gr. P11,T12	CMA-96 CMA-96MB CMA-96MBD CMB-95 CMB-98	E8016-B2 E8016-B2 E8016-B2 E7015-B2L E8018-B2	DW-81B2 DWA-81B2	E81T1-B2/B2M E81T1-B2M
2.25Cr-1Mo	-A387Gr.22 Cl.1, Cl.2	-A213Gr.T22 -A335Gr.P22	CMA-106 CMA-106N CMA-106ND CMB-105 CMB-108	E9016-B3 E9016-B3 E9016-B3 E8015-B3L E9018-B3	DW-91B3 DWA-91B3	E91T1-B3/B3M E91T1-B3M
2.25Cr-1Mo-V	-A542Type D Cl.4a -A832Gr.22V	-	CMA-106H CMA-106HD	- -	-	-
Low C 2.25Cr-W-V-Nb	-	-SA213Gr. T23 -SA335Gr. P23	CM-2CW	-	-	-
5Cr-0.5Mo	-A387Gr.5 Cl.1, Cl.2	-A213Gr.T5 -A335Gr.P5	CM-5	E8016-B6	-	-
9Cr-1Mo	-A387Gr.9 Cl.1, Cl.2	-A213Gr.T9 -A335Gr.P9	CM-9	E8016-B8	-	-
9Cr-1Mo-V-Nb	-A387Gr.91 Cl.2	-A213Gr.T91 -A335Gr.P91	CM-9Cb CM-96B9	E9016-G E9016-B9	-	-
9Cr-W-V-Nb 12Cr-W-V-Nb	-	-A213Gr.T92 -A335Gr.P92 -SA213Gr.T122 -SA335Gr.P122	CR-12S	-	-	-

SMAW: Shielded Metal Arc Welding; FCAW: Flux Cored Arc Welding; GMAW: Gas Metal Arc Welding; GTAW: Gas Tungsten Arc Welding; SAW: Submerged Arc Welding

Tips for Selecting Appropriate Welding Consumables

1. This guidance is to help users select appropriate welding consumables. Users are requested to confirm whether the selected brand can satisfy the requirements including tensile strength, impact toughness and hardness in conjunction with postweld heat treatment for a particular job before use.
2. A change of electric polarity may affect the usability of welding consumables, chemical composition and mechanical properties of weld metals; therefore, it is recommended to confirm the performances of the brand you selected, using the polarity of the power source available for a particular job. SMAW electrodes of EXX16 use AC or DC-EP. EXX15 uses DC-EP only; EXX13 uses AC, DC-EN or DCEP. FCAW and GMAW wires use DC-EP. GTAW wires use DC-EN. SAW flux/wire combinations use generally AC and occasionally DC-EP (In the case of DC, please contact the nearest KOBELCO office to confirm the performance of the brand you select).
3. Brands designated with DW or DWA are flux-cored wires, whereas those denoted with MGS or MG are solid wires. DW wires use CO₂ or 75-85%Ar/bal.CO₂, whereas DWA wires use 75-85%Ar/bal.CO₂ for shielding gas. MGS wires use Ar/bal.2-5%O₂ or Ar/bal.5-20%CO₂.
4. TGS wires use pure argon gas for shielding.

GMAW		GTAW		SAW	
Brand name	AWS class.	Brand name	AWS class.	Brand name	AWS class.
MGS-56 MGS-63S	ER80S-G ER90S-G	TGS-56	ER80S-G	MF-27 / US-56B PF-200 / US-56B PF-200 / US-63S	F9P4-EG-G F9P4-EG-G F10P2-EG-G
MGS-M MG-M	ER80S-G ER80S-G	TGS-M	ER80S-G	MF-38 / US-40	F8P6-EA3-A3 F9A6-EA3-A3
MG-CM	ER80S-G	TGS-CM	-	MF-38 / US-49	F8P6-EG-A4 F8A4-EG-A4
MGS-1CM MG-1CM	ER80S-G ER80S-G	TGS-1CM TGS-1CML TGS-80B2	ER80S-G ER80S-G ER80S-B2	MF-38 / US-A4	F8P6-EA4-A4 F8A4-EA4-A4
MGS-2CM MGS-2CMS MG-2CM	ER90S-G ER90S-G ER90S-G	TGS-2CM TGS-2CML TGS-90B3	ER90S-G ER80S-G ER90S-B3	-	-
-	-	TGS-2CMH	-	MF-29A / US-511 PF-200 / US-511N PF-200D / US-511ND	F7PZ-EG-B2 F8P2-EG-B2 F8P2-EG-B2
MGS-2CW	-	TGS-2CMH	-	MF-29A / US-521 PF-200 / US-521S PF-200D / US-521S	F8P2-EG-B3 F9P2-EG-B3 F9P2-EG-B3
MGS-5CM	ER80S-B6	TGS-2CMH	-	PF-500 / US-521H PF-500D / US-521HD	- -
MGS-9CM	ER80S-B8	TGS-2CW	-	PFH-80AK / US-2CW	-
MGS-9Cb	ER90S-G	TGS-5CM	ER80S-B6	PF-200S / US-502	F7P2-EG-B6
MGS-12CRS	-	TGS-9CM	ER80S-B8	-	-
		TGS-9Cb TGS-90B9	ER90S-G ER90S-B9	PF-200S / US-9Cb	F10PZ-EG-G
		TGS-12CRS	-	PF-200S / US-12CRS PF-200SD / US-12CRSD	-

5. Brands symbolized with MF are fused-type SAW fluxes, whereas those indicated with PF are bonded-type fluxes for SAW.

7. For details of individual brands, refer to KOBELCO WELDING HANDBOOK.

8. In the welding of Cr-Mo steels, how to prevent hot, cold and delayed cracking is essential. Hot cracking can be prevented by controlling heat input and appropriately preparing welding groove configuration. To prevent cold and delayed cracking, preheating is predominant. The most appropriate preheat temperature depends on the type of steel, thickness of components, and diffusible hydrogen in weld metals. Unless in conflict with particular job specifications, Kobe Steel recommends the following minimum preheat and interpass temperatures for general applications.

Steel type	Preheat & interpass temperature (°C)	Steel type	Preheat & interpass temperature (°C)
0.5Mo	100-200	Low C-2.25Cr-W-V-Nb	150-250
0.5Cr-0.5Mo	150-250	5Cr-0.5Mo	250-350
1-1.25Cr-0.5Mo	150-300	9Cr-1Mo	250-350
2.25Cr-1Mo	200-350	9Cr-1Mo-V-Nb	250-350
2.25Cr-1Mo-V	200-350	9-12Cr-W-V-Nb	250-350

CMA-96

AWS A5.5 E8016-B2

A world-class 1.25Cr-0.5Mo electrode of persistent quality since 1952

Since its inception, CMA-96 has persistently earned a good reputation in the high-temperature high-pressure fields such as boilers and refineries in which 1.25Cr-0.5Mo steel is used at a large consumption ratio for steam power generating equipment and reactor vessels.



Heat-resistant low-alloy steel is a main material for coal firing power plants

In welding Cr-Mo steel, the weld metal should have the essential qualities: (1) low susceptibility to cold cracking, (2) low susceptibility to hot cracking, (3) resistibility to extended postweld heat treatment for better mechanical properties, and (4) stable microscopic structure for better creep resistance at elevated temperatures

In order to fulfill these essential requirements, CMA-96 is ingeniously designed. First, it is of the extra-low hydrogen type; consequently, the amount of diffusible hydrogen in the weld metal can be kept lower than with conventional low hydrogen type electrodes, thereby reducing the susceptibility to cold cracking. Second, the phosphorous and sulfur content of the weld metal is kept low to decrease the susceptibility to hot cracking. Thirdly, the elaborate chemical composition of CMA-96 provides a stable weld metal microstructure, which allows the weld metal to maintain adequate mechanical properties over extended postweld heat treatment (PWHT) of high temper parameter (Figures 1 and 2) and to increase creep resistance.

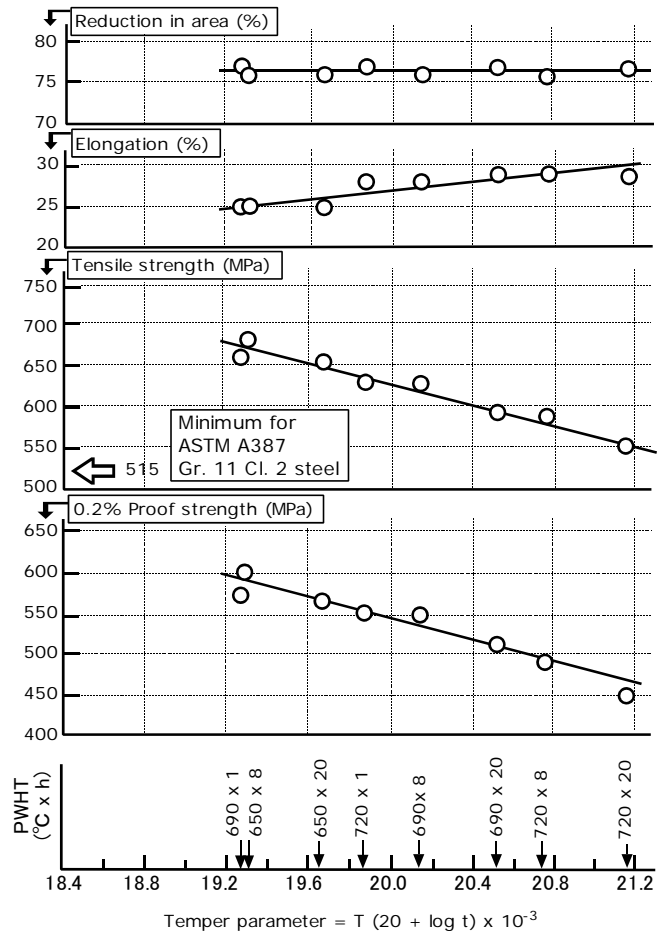


Figure 1: Tensile properties of CMA-96 (5Ø) weld metal vs. temper parameter (T: temperature in deg. K; t: soaking time in hours) by AC welding in flat position

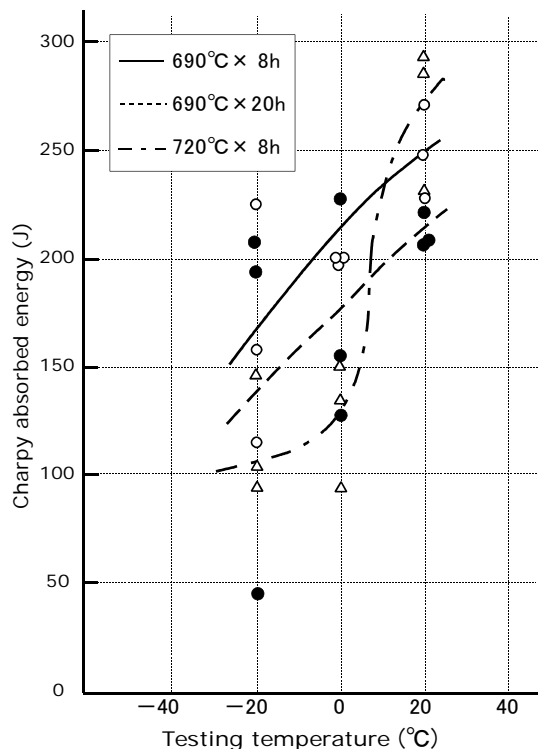
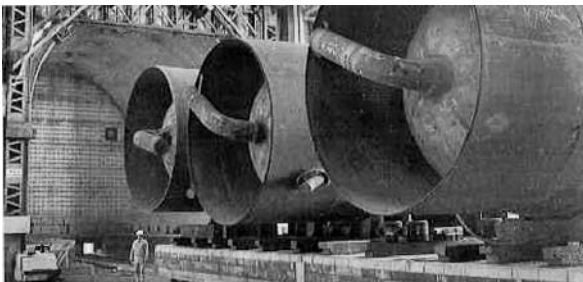


Figure 2: Charpy impact properties of CMA-96 (5Ø) weld metal in the PWHT condition by AC welding in flat position

CMA-96MB

AWS A5.5 E8016-B2

The best choice for moderate-PWHT fabrication of 1.25Cr-0.5Mo components to strict notch toughness and hardness restriction



CMA-96MB shines in the fabrication of pressure components where PWHT uses lower temper parameters and strict control of temper embrittlement is required

With lower temper parameters (either with lower PWHT temperature or with shorter PWHT time), weld hardness is prone to be higher—hence lower ductility—and notch toughness tends to be lower in general. The temper parameter of PWHT will necessarily be lower depending on the thickness of the weldment, the specification or code to follow, and the base metal used.

In contrast to CMA-96, CMA-96MB is more suitable for moderate PWHT of lower temper parameter. With moderate PWHT, CMA-96MB provides better notch toughness and lower hardness—thus higher ductility—compared with CMA-96. In addition, CMA-96MB more strictly controls impurity elements such as phosphorous (P), tin (Sn), antimony (Sb), and arsenic (As) to minimize temper embrittlement. Figure 1 shows results of Charpy impact tests of CMA-96MB weld metal that sustained low temper parameter PWHT. The weld metal exhibits adequate notch toughness over the range of temper parameters.

As shown in Figure 2, the susceptibility to temper embrittlement of CMA-96MB weld metal is quite low with almost no temperature shift at the standard absorbed energy of 54J specified for fabricating pressure vessels for high temperature service.

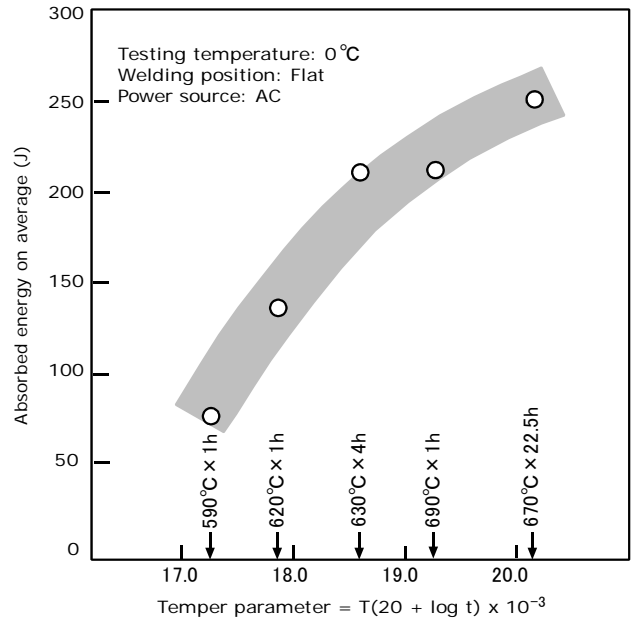


Figure 1: Charpy impact absorbed energy of CMA-96MB (5Ø) weld metal as a function of temper parameter (T: PWHT temperature in deg. K; t: soaking time in hours)

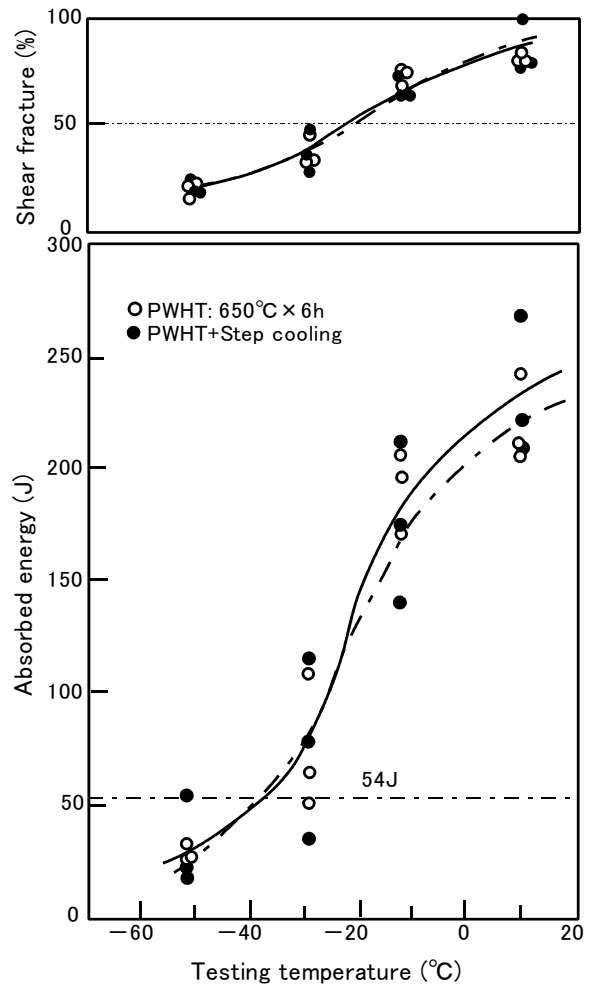


Figure 2: Temper embrittlement test results of CMA-96MB (6Ø) weld metal by AC welding in flat position (Step cooling is a heat treatment to accelerate temper embrittlement)

TGS-1CM

AWS A5.28 ER80S-G

A 1.25Cr-0.5Mo GTAW filler wire, unbeatable in pipe welding in refineries and boilers



1.25Cr-0.5Mo steel is used for the equipment operated at the temperatures from 350-550°C. For such high-temperature applications, the materials must metallurgically be stable, resisting elevated temperature oxidation and creep rupture. Kobe Steel has used its accumulated technical expertise to pursue quality control of TGS-1CM, maintaining its high performance for the piping of oil refineries and power boilers.

Unlike conventional 1.25Cr-0.5Mo GTAW filler wires classified as AWS E5.28 ER80S-B2, TGS-1CM is classified necessarily as ER80S-G because of its unique chemical composition. TGS-1CM weld metal contains, as shown in Table 1, comparatively low carbon, phosphorous and sulfur along with a higher manganese content. This improves usability (better fluidity of the molten pool) and the resistance to hot cracking that is likely to occur in root-pass welding of pipes.

Table 1. Typical chemical composition of TGS-1CM weld metal by GTAW with pure argon gas shielding (%)

C	Si	Mn	P	S	Cr	Mo
0.06	0.50	0.99	0.007	0.005	1.22	0.54

The mechanical properties of TGS-1CM weld metal are sufficient for tubular steel base metals such as ASTM A199Gr.T11, A213Gr.T11, A250Gr.T11, and A335Gr.P11 after extended PWHT—Table 2.

Table 2: Typical mechanical properties of TGS-1CM weld metal by GTAW with pure argon gas shielding

PWHT (°C×h)	0.2% OS (MPa)	TS (MPa)	EI (%)	IV (J)
650×1	550	620	25	270
690×1	540	630	28	270
700×5	510	590	25	260
ASTM A335P11	205 min	415 min	22 min	-

A335P11: 1.25Cr-0.5Mo seamless pipe
IV: Charpy impact energy on average at 0°C

Tips for Welding with TGS-1CM

- (1) Use direct current with electrode negative polarity.
- (2) Pure argon gas is suitable for both torch shielding and back shielding. The shielding gas flow rate should be 10-15 liter/min. In apparent ambient wind over 1m/sec, use a windscreen to protect the molten pool from the wind, or the wind may cause porosity, oxidation, and poor reverse bead formation.
- (3) In the use of an automatic GTAW process, the welding procedure should be determined in accordance with the quality of the weld in advance. This is because, with a high feeding rate of filler wire—hence a high deposition rate—in automatic GTAW, notch toughness of the weld metal tends to decrease because of coarser crystal grains.
- (4) Preheating and interpass temperature should be 150-200°C to decrease the cooling speed and thereby minimize hardness of the weld and prevent cold cracking.
- (5) Postweld heat treatment temperature should be 650-700°C to remove residual stresses, decrease hardness of the weld and improve the mechanical properties.
- (6) Heat input should be properly controlled because excessive heat input can cause hot cracking, and deteriorate tensile properties and notch toughness of the weld.

TGS-80B2

AWS A5.28 ER80S-B2

An AWS-type new brand of GTAW filler wire for 1Cr-0.5Mo and 1.25Cr-0.5Mo steel

This new brand has been developed by modifying the chemical composition of traditional TGS-1CM (AWS ER80S-G) to make it easier for international customers to select a suitable filler wire per the AWS chemical requirement designation (B2) for welding 1Cr-0.5Mo and 1.25Cr-0.5Mo steels. The welding usability, mechanical properties and crack resistibility of this new brand are comparable to the traditional brand. Table 1 shows typical chemical composition of TGS-80B2 and the AWS requirement for ER80S-B2.

Table 1: Typical chemical composition of TGS-80B2 filler wire in comparison with the AWS requirement (%)

Chemical element	TGS-80B2 (ER80S-B2)	AWS A5.28 (ER80S-B2)
C	0.11	0.07-0.12
Si	0.50	0.40-0.70
Mn	0.67	0.40-0.70
P	0.004	0.025 max.
S	0.004	0.025 max.
Cu	0.15	0.35 max.
Ni	0.01	0.25 max.
Cr	1.40	1.20-1.50
Mo	0.55	0.40-0.65

The mechanical properties of TGS-80B2 weld metal match the AWS requirements as shown in Table 2. In addition, as illustrated in Figure 1, this filler wire satisfies the ASTM requirement for tubular steels such as A213 Gr. T11 (1.25Cr-0.5Mo) after extended postweld heat treatment (PWHT).

Table 2: Typical mechanical properties of TGS-80B2 weld metal by GTAW with pure argon gas shielding

Filler wire	0.2%OS (MPa)	TS (MPa)	EI (%)	IV at -20°C (J)	PWHT (°C x h)
TGS-80B2	499	625	32	Av. 246	620 x 1
	476	593	32	Av. 256	690 x 1
	440	558	34	Av. 242	690 x 8
ER80S-B2	470 min	550 min	19 min	-	620±15 x 1

The soundness and bead appearance of the root pass welds by GTAW are essential performances of filler wires. TGS-80B2 offers good weldability and usability in root-pass welding, exhibiting good

weld-pool washing on the groove faces and thereby resulting in excellent penetration bead appearance on the reverse side of the root pass weld with argon gas back shielding.

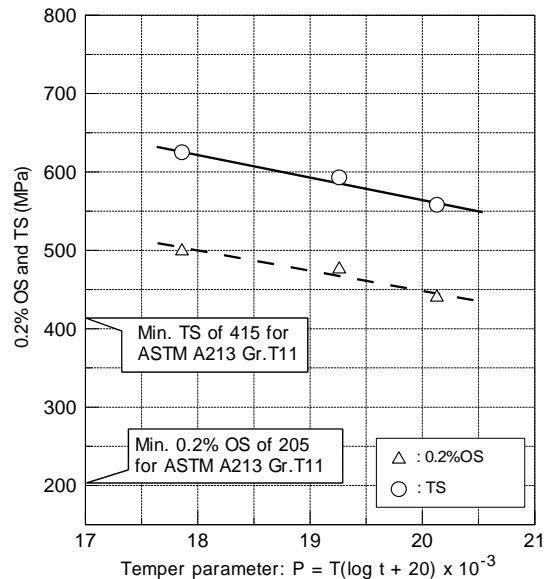
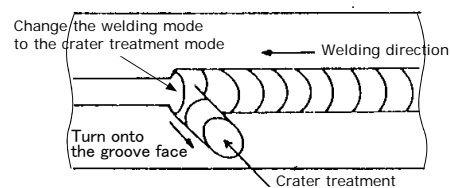


Figure 1: Tensile properties of TGS-80B2 weld metal as a function of PWHT (Temper parameter: 17.86 for 620°C x 1h; 20.13 for 690°C x 8h; 19.26 for 690°C x 1h)

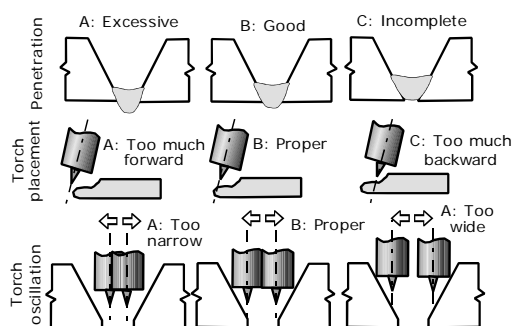
Tips for higher workmanship

In addition to the aforementioned tips for TGS-1CM, the following techniques are effective to prevent weld imperfections in root-pass welding of tubular work.

- (1) The weld crater should be terminated on the groove face in order to prevent hot cracks in the crater.



- (2) Use proper torch placement and oscillation for making good penetration.



TGS-1CML

AWS A5.28 ER80S-G

A low-carbon 1.25Cr-0.5Mo GTAW filler wire: The choice for cost savings in preheating and PWHT



The tube-to-tubesheet joint of a heat exchanger made of heat resistant steel is TIG welded by using an orbital welding machine and filler metal.

Although the AWS classification (ER80S-G) of TGS-1CML is the same as that of TGS-1CM, its welding performance is quite different. First, as to the chemical composition, the lower carbon content (Table 1) is effective to prevent hot cracking. Second, the lower tensile strength (or lower hardness)—hence higher ductility—is suitable for welds to be left in the as-welded condition or when more moderate postweld heat treatment (PWHT) of lower temper parameter is applied, as shown in Tables 2 and 3. Figures 1 and 2 show the tensile properties and hardness of TGS-1CML weld metal as a function of the temper parameter.

Table 1: Typical chemical composition of TGS-1CML weld metal by GTAW with pure argon gas shielding (%)

C	Si	Mn	P	S	Cr	Mo
0.02	0.48	1.10	0.009	0.006	1.38	0.50

Table 2: Typical mechanical properties of TGS-1CML weld metal by GTAW with pure argon gas shielding

PWHT (°C×h)	0.2% OS (MPa)	TS (MPa)	EL (%)	IV (J)
As-weld	540	620	32	290
620×1	490	580	32	290
690×1	440	540	37	290
ASTM A213Gr.T11	205 min.	415 min.	30 min.	-

A213Gr.T11: 1.25Cr-0.5Mo seamless tube
IV: Charpy impact energy on average at 0°C

Table 3: Typical Vickers hardness of TGS-1CML weld metal by GTAW with pure argon gas shielding

PWHT (°C×h)	Vickers hardness (Hv) (1)	
	Cross section	Surface
As weld	196	255
620×1	187	237
690×1	177	206

(1) Hv: The average of five individual measurements

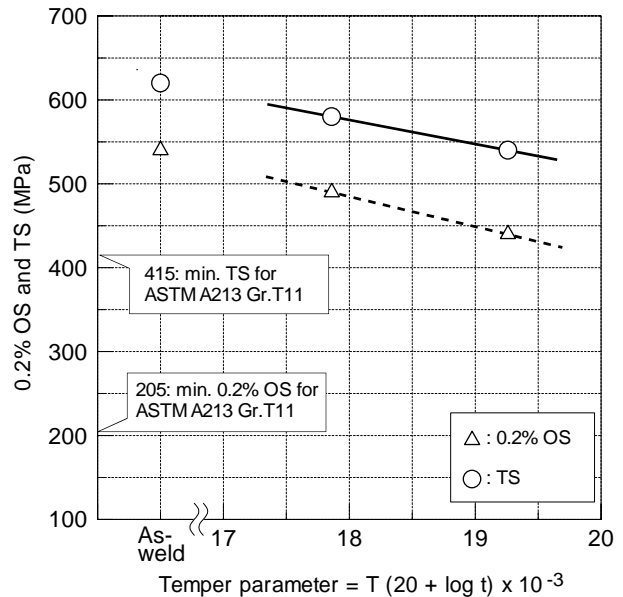


Figure 1: Tensile test results of TGS-1CML weld metal in the as-welded and PWHT conditions

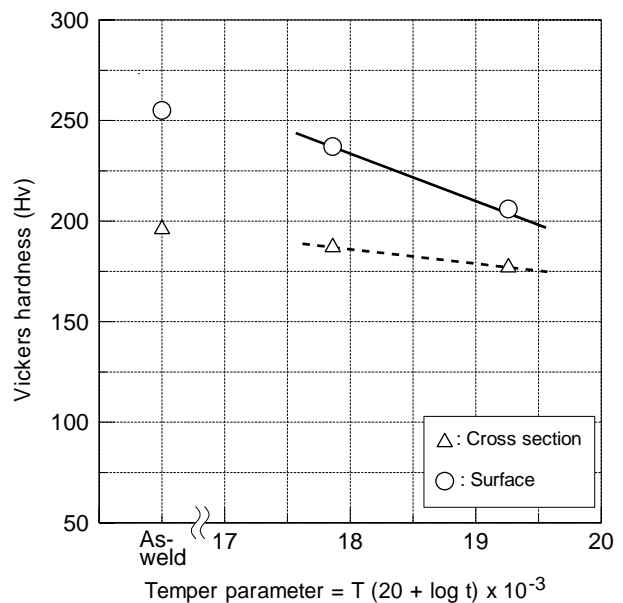


Figure 2: Hardness test results of TGS-1CML weld metal in the as-welded and PWHT conditions

CMA-106

AWS A5.5 E9016-B3

When it comes to welding 2.25Cr-1Mo steels, CMA-106 is the most reliable stick electrode with its 50-year industrial experience.



2.25Cr-1Mo steel is an indispensable material in a coal-fired power plant (Kobe Steel's power plant)

Among Cr-Mo steels, 2.25Cr-1Mo steel is widely used in the petroleum industry and in steam power generating equipment. In particular, heavy-wall pressure vessels are often constructed from this type of Cr-Mo steel because of its excellent high-temperature strength, corrosion resistibility, and resistance to high-temperature hydrogen attack. CMA-106 covered electrode was developed in 1953. Since its inception, it has been used for various applications of 2.25Cr-1Mo steel and has earned a high reputation due to Kobe Steel's persistent control of quality for many years.

2.25Cr-1Mo steel products include plates, tubes/pipes, and forgings. Table 1 shows typical 2.25Cr-1Mo grades for which CMA-106 is often used due to its unsurpassed quality, by both Japanese and international fabricators, in the construction of power boilers, reactor vessels and plant pipelines.

Table 1: Typical grades of 2.25Cr-1Mo steel by product type

Product	ASTM	JIS
Plate	A387Gr.22 Cl.1, Cl.2	SCMV4
	A542Type B Cl.4	SCMQ4E
Tube/Pipe	A199Gr.T22	STBA24
	A213Gr.T22	STPA24
	A250Gr.T22	
	A335Gr.P22	
Forging	A182Gr.F22 Cl.1, Cl.3	SFVAF22A
	A336Gr.F22 Cl.1, Cl.3	SFVAF22B
	A508Gr.22 Cl.3	SFVCMF22B
	A541Gr.22 Cl.3	

Postweld heat treatment (PWHT) is normally required before 2.25Cr-1Mo steel welds can be placed in service. This is to reduce hardness and to increase ductility and impact notch toughness. As shown in Figure 1, CMA-106 weld metal exhibits sufficient notch toughness after PWHT.

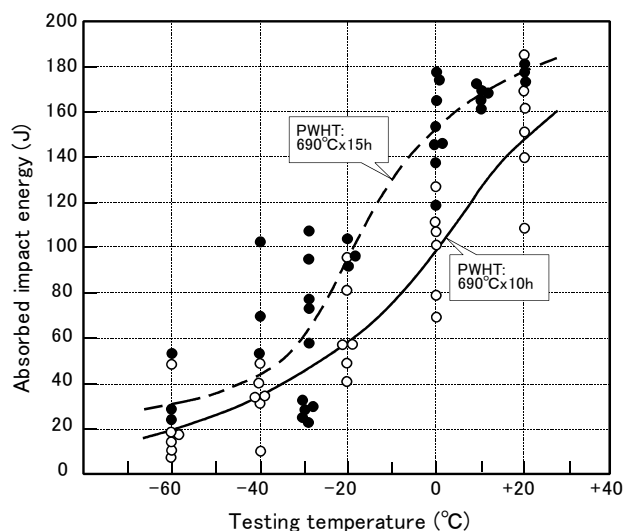


Figure 1: Charpy impact test results of CMA-106 (5Ø) deposited metal by AC welding in flat position

In contrast, PWHT reduces strength due to the tempering effect; therefore, it is essential to control the temper parameter. CMA-106 ensures high tensile strength and yield strength of weld metal even when temper parameter is high—Figure 2.

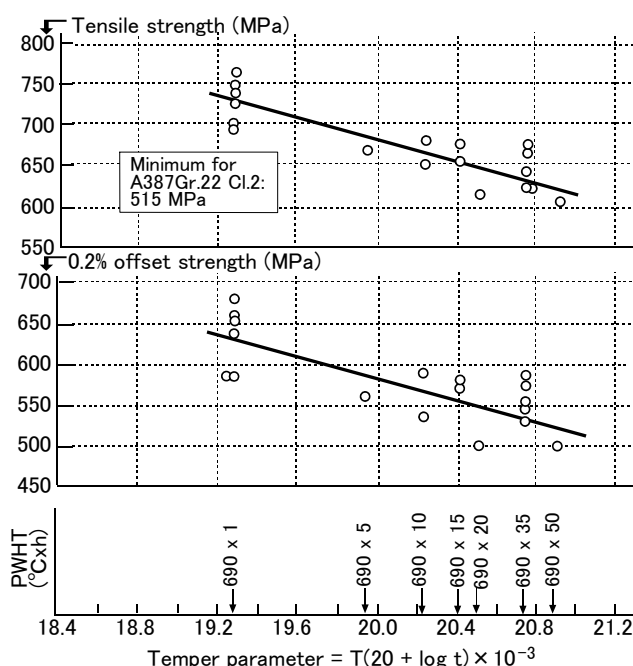


Figure 2: Tensile properties of CMA-106 (5Ø) deposited metal vs. temper parameter (T: temperature in deg. K; t: soaking time in hours) by AC welding in the flat position

CMA-106N

AWS A5.5 E9016-B3

Where temper embrittlement resistance is strictly required, CMA-106N is an unbeatable covered electrode.



Hydro-desulfurization reactor is a typical pressure vessel for which temper embrittlement resistance is strictly required.

Temper embrittlement, which occurs in low-alloy steels, such as Cr-Mo steels, is a decrease in impact toughness (or an increase in the ductile-to-brittle transition temperature) after long service at high temperatures in the 371 to 593°C range. Temper embrittlement is a primary concern in the fabrication of 2.25Cr-1Mo steel pressure vessels that are operated at about 454°C, a temperature at which temper embrittlement is most likely to occur.

In principal, this form of brittleness is believed to occur due to the segregation of phosphorous (P), antimony (Sb), tin (Sn), and arsenic (As) at the grain boundaries of the steel and weld metal. Manganese (Mn) and silicon (Si) are also believed to be involved. Based on these common theories on the causes of temper embrittlement, Kobe Steel has researched extensively to develop CMA-106N that fulfills the strict requirement for heavy-wall pressure vessels. Table 1 shows the typical chemical composition of CMA-106N weld metal designed to minimize temper embrittlement.

Table 1: Typical chemical composition of CMA-106N (5Ø) weld metal by AC welding in the flat position (%)

C	Si	Mn	P	S	Ni	Cr
0.11	0.27	0.79	0.008	0.006	0.19	2.42
Mo	Sb	Sn	As	X-bar (1)	J-factor (2)	
1.03	0.002	0.003	0.002	10	117	

(1) (2): See the top of the right column.

(1) $X\text{-bar} = (10P + 5Sb + 4Sn + As) / 100$ (ppm)
 (2) $J\text{-factor} = (Mn + Si)(P + Sn) \times 10^4$ (%)

In addition to the chemical elements, the microstructure of the weld metal is an essential factor in temper embrittlement. CMA-106N is designed so as to possess a fine microstructure in the weld metal after postweld heat treatment to minimize temper embrittlement—Figure 1.

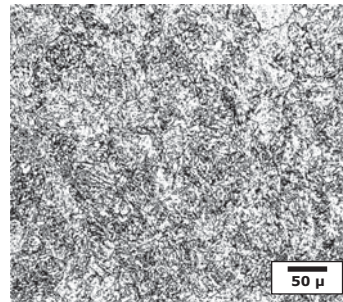


Figure 1: A very fine bainitic microstructure of CMA-106N (4Ø) weld metal after PWHT

The susceptibility to temper embrittlement is evaluated with a step-cooling test using cyclical thermal aging as shown in Figure 2. Typical test results are shown in Figure 3, revealing excellent notch toughness with a very little shift of impact energy between the as-SR and SR+SC conditions.

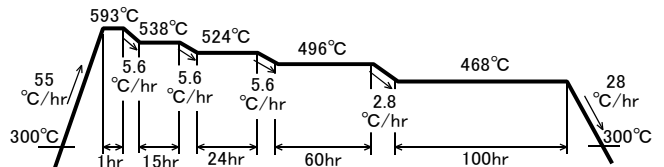


Figure 2: A typical step cooling cycle for detecting the susceptibility to temper embrittlement

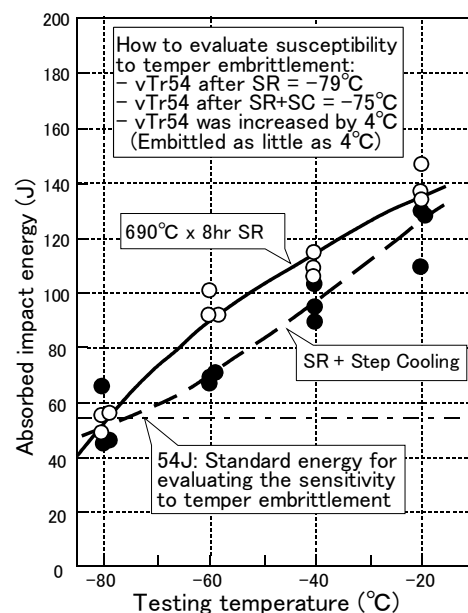


Figure 3: Temper embrittlement test results of CMA-106N (5Ø) weld metal by Charpy impact test (AC current, flat welding position)

TGS-2CM

AWS A5.28 ER90S-G

A highly reputed GTAW wire for 2.25Cr-1Mo tubes and pipes

Unlike conventional 2.25Cr-1Mo filler wires classified as ER90S-B3, TGS-2CM is classified necessarily as ER90S-G due to its unique chemical composition. As shown in Table 1, TGS-2CM weld metal contains comparatively low silicon (Si) compared with conventional ER90S-B3 wires. In addition, TGS-2CM restricts phosphorous (P), antimony (Sb), tin (Sn), and arsenic (As). This elaborate chemical composition reduces temper embrittlement (Figure 1) and improves resistance to hot cracking that is likely to occur in root-pass welding of tubes and pipes.

Table 1: Typical chemical composition of TGS-2CM weld metal by GTAW with pure argon gas shielding (%)

C	Si	Mn	P	S	Cr	Mo
0.10	0.26	0.70	0.009	0.008	2.31	1.04
Sb	Sn	As	X-bar (1)		J-factor (2)	
0.004	0.003	0.003	12		115	

(1) X-bar = (10P + 5Sb + 4Sn + As)/100 (ppm)

(2) J-factor = (Mn + Si)(P + Sn) × 10⁴ (%)

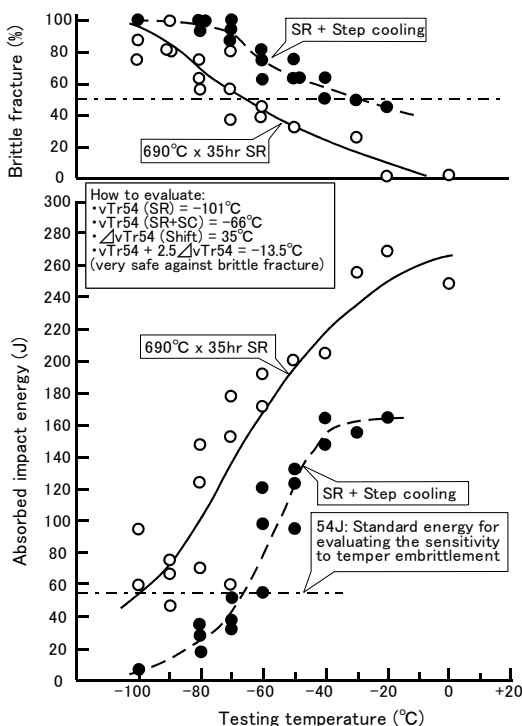


Figure 1: Temper embrittlement test results of TGS-2CM weld metal by Charpy impact testing

TGS-2CM is available in both cut rod and spooled wire. Spooled wires are suitable for mechanized gas tungsten arc welding (GTAW). Bend-to-flange joints of reactors, Tube-to-tubesheet joints of heat exchangers and pipe-to-pipe joints of process piping are typical applications for the automatic GTAW.

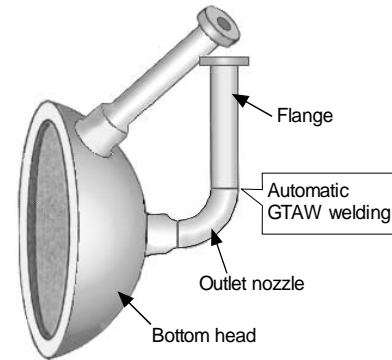


Figure 2: An example of automatic GTAW application for joining the 90-degree bend and flange extended from the bottom head of a reactor pressure vessel.

Tips for Welding with TGS-2CM

- (1) Back shielding with argon gas is indispensable to provide a smooth root-pass bead with regular penetration. The torch shielding gas flow rate should be 10-15 liter/min. In apparent ambient wind over 1m/sec, use a windscreen to protect the weld pool from the wind, or the wind may cause porosity.
- (2) In mechanized GTAW, the welding procedure should be determined in consideration of the quality requirements for the weld beforehand. This is because, with a high feeding rate of filler wire—thus a high deposition rate—in automatic GTAW, notch toughness of the weld tends to decrease because of coarser crystal grains.
- (3) Preheat and interpass temperature should be 200-250°C to decrease the cooling speed and thereby minimize hardness of the weld and prevent cold cracking.
- (4) Postweld heat treatment temperature should be 680-730°C to remove residual welding stresses, decrease hardness and improve the mechanical properties of the weld.
- (5) Heat input should be controlled to prevent hot cracking and ensure mechanical properties of the weldment.

TGS-90B3

AWS A5.28 ER90S-B3

An AWS-type new brand of GTAW filler wire for international customers

This new brand has been developed by modifying the chemical composition of traditional TGS-2CM (ER90S-G) to make it easier for international customers to select a suitable filler wire per the AWS chemical requirement designation (B3) for welding 2.25Cr-1Mo steels. The welding usability, mechanical properties and crack resistance of the new brand are comparable to the traditional brand. Table 1 shows typical chemical composition of TGS-90B3 and the AWS requirement for ER90S-B3.

Table 1: Typical chemical composition of TGS-90B3 filler wire in comparison with the AWS requirement (%)

Chemical Element	TGS-90B3 (ER90S-B3)	AWS A5.28 ER90S-B3
C	0.11	0.07-0.12
Si	0.64	0.40-0.70
Mn	0.67	0.40-0.70
P	0.006	0.025 max.
S	0.006	0.025 max.
Cu	0.14	0.35 max.
Ni	0.01	0.25 max.
Cr	2.44	2.30-2.70
Mo	1.09	0.90-1.20

The mechanical properties of TGS-90B3 weld metal match the AWS requirements as shown in Table 2. In addition, as illustrated in Figure 1, this filler wire satisfies the ASTM requirement for tubular steels such as A213 Gr. T22 (2.25Cr-1Mo), after extended postweld heat treatment (PWHT).

Table 2: Typical mechanical properties of TGS-90B3 weld metal by GTAW with pure argon gas shielding

Filler wire	0.2%OS (MPa)	TS (MPa)	EI (%)	IV at -20°C (J)	PWHT (°C x h)
TGS-90B3	596	725	27	Av. 237	690 x 1
	497	632	30	Av. 169	690 x 8
	452	595	30	Av. 156	690 x 32
ER90S-B3	540 min.	620 min.	17 min.	-	690±15 x 1

The soundness and bead appearance of the root pass weld by GTAW are essential performances of filler wires. TGS-90B3 offers good weldability and

usability in the root-pass welding, exhibiting a regular penetration bead appearance—Figure 2.

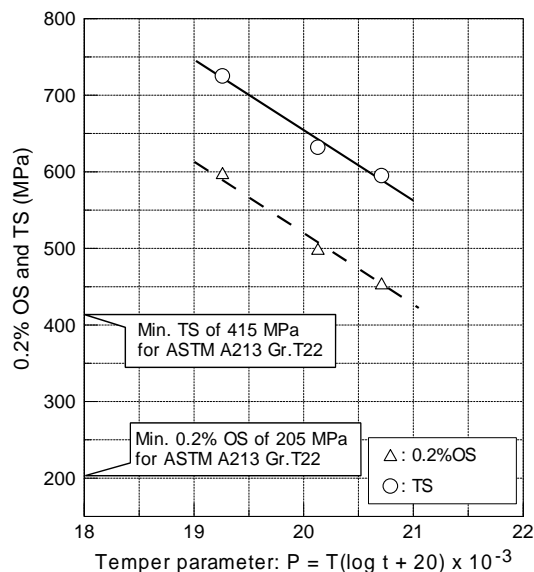


Figure 1: Tensile properties of TGS-90B3 weld metal as a function of PWHT (Temper parameter: 19.26 for 690°C x 1h; 20.13 for 690°C x 8h; 20.71 for 690°C x 32h)

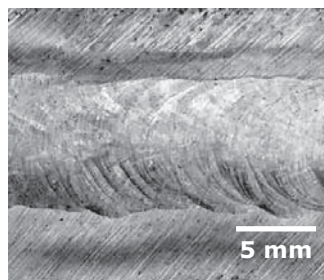


Figure 2: A bead appearance protruded on the reverse side of the root pass weld with argon gas back shielding

Spooled TGS-90B3 is available in addition to cut rod. Spooled wires are suitable for automatic GTAW (Figure 3). Tube-to-tubesheet joints of heat exchangers and tube-to-tube and tube-to-bend joints of steam boilers are typical applications for automatic GTAW.

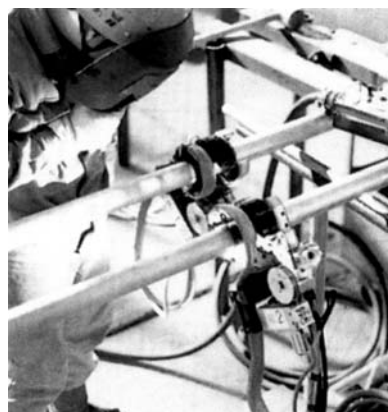


Figure 3: Automatic GTAW of tube-to-tube butt joints is a typical application for TGS-90B3

TGS-2CML

AWS A5.28 ER80S-G

A low-carbon 2.25Cr-1Mo GTAW filler wire, more suitable where preheat and postweld heat treatment are limited

In comparison with TGS-2CM, classified as AWS ER90S-G (TS: 90ksi min.), TGS-2CML features lower tensile strength, which is made clear by its classification, ER80S-G (TS: 80ksi min.). The lower tensile strength results from the low carbon content of TGS-2CML—Table 1.

Table 1: Typical chemical composition of TGS-2CML weld metal by GTAW with pure argon gas shielding (%)

C	Si	Mn	P	S	Cr	Mo
0.03	0.48	1.08	0.009	0.010	2.25	1.10

The low carbon content decreases hardness, resulting in high ductility and is effective to prevent hot cracking and cold cracking. High ductility enables the use of lower preheat temperature and removes the need for postweld heat treatment (PWHT). As shown in Table 2, TGS-2CML weld metal exhibits high ductility and impact energy with moderate hardness even in the as-welded condition. In addition, the weld metal satisfies the ASTM requirements for the tensile properties of A213 Gr. T22 tubes for boiler, superheater and heat exchanger after extended PWHT—Figure 1.

Table 2: Typical mechanical properties of TGS-2CML weld metal by GTAW with pure argon gas shielding (1)(2)(3)

PWHT	0.2% OS (MPa)	TS (MPa)	EI (%)	RA (%)	IV at 0°C (J)	Hv
As-weld	722	826	27	75	186	307
690°C x 1h	548	647	28	80	202	226
710°C x 1h	501	609	30	78	181	210

(1) Impact values are the average of 5 specimens. (2) Vickers hardness numbers are the average of 5 measuring points on the weld surface. (3) Testing temperature for tensile test and hardness test is room temperature.

Provided a proper preheat is used during welding, PWHT sometimes may be omitted for low-carbon welds in thin sections of 2.25Cr-1Mo steel, unless

otherwise required due to the presence of certain corrosives. As per ASME Sec 8 Div. 1, for example, circumferential butt welds in 2.25Cr-1Mo steel pipes and tubes having a diameter of 102 mm or less and a wall thickness under 15.8 mm can be placed in service in the as-welded condition when the weld is preheated at temperatures of 149°C or higher. However, the welding procedure specification must be qualified without PWHT.

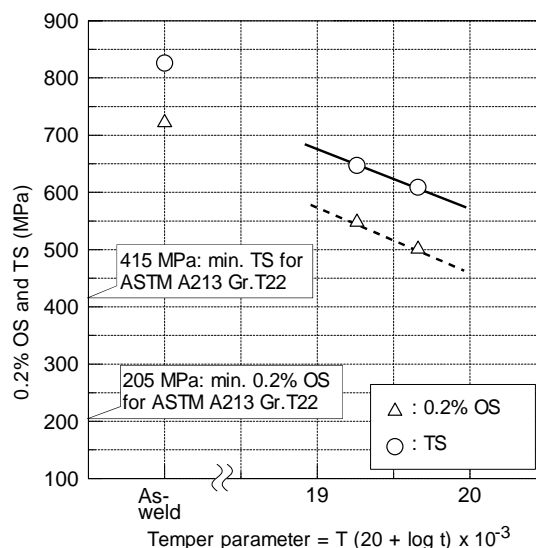


Figure 1: Tensile test results of TGS-2CML weld metal in the as-welded and PWHT conditions

Typical applications for TGS-2CML are pipe-to-pipe joints, and tube-to-tubesheet joints. In addition, this filler wire is suitable for repair welding on the welds of the equipment in service where preheat and PWHT are generally limited to avoid adverse effects of the heats to the equipment.

Spooled TGS-2CML is available in addition to cut rod. Spooled wires are suitable for automatic gas tungsten arc welding (GTAW). Tube-to-tubesheet joints of heat exchangers and tube-to-tube and tube-to-bend joints of process pipings (Figure 2) are typical applications for the automatic GTAW.

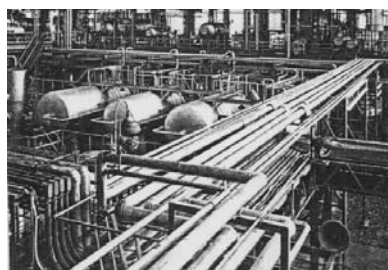


Figure 2: TGS-2CML is more suitable for welding process-piping joints subject to short-time postweld heat treatment—thus lower temper parameter.



CMA-96MBD PF-200D / US-511ND

AWS A5.5 E8016-B2

AWS A5.23 F8P2-EG-B2

CMA-106ND PF-200D / US-521S

AWS A5.5 E9016-B3

AWS A5.23 F9P2-EG-B3



Stricter requirements for weld metal quality Increasingly demanded for DC-spec. Cr-Mo filler metals

Most filler metals suitable for alternating current (AC) may be used with direct current (DC), unless the quality requirement is strict. When requirements are strict, the matter is treated seriously, even when a particular filler metal is classified by the AWS as an AC-or-DCEP type. This is because the polarity of welding current affects the chemical composition (C, Si, Mn, and O in particular)—thus the mechanical properties—of the weld metal.

Kobe Steel has long been producing Cr-Mo steel filler metals for oil refinery reactor vessels and heat exchangers, which include CMA-96MB (E8016-B2) and PF-200/US-511N (F8P2-EG-B2) for 1-1.25Cr-0.5Mo steel and CMA-106N (E9016-B3) and PF-200/US-521S (F9P2-EG-B3) for 2.25Cr-1Mo steel. These filler metals have a high reputation in the domestic and overseas markets. Unlike in the domestic market, DC power sources are often used overseas, increasing demand for filler metals designed for DC current use with better performance in notch toughness, resistance to temper embrittlement and high-temperature strength. To meet this demand, Kobe Steel, with its reputation for filler metal technical know-how, has developed brand new DC-spec. filler metals that are more suitable for DCEP welding and able to meet stringent requirements.

SMAW covered electrodes for 1-1.25Cr-0.5Mo and 2.25Cr-1Mo steel

With the elaborate chemical composition of the weld metal, CMA-96MBD and CMA-106ND exhibit excellent room and high-temperature tensile properties, low-temperature impact toughness and resistance to temper embrittlement, as well as good usability, with DCEP currents. Typical chemical and mechanical properties are shown in Tables 1 and 2, respectively.

Table 1: Typical chemical properties of CMA-96MBD and CMA-106ND weld metals (1)

Brand (Application)	CMA-96MBD (1-1.25Cr-0.5Mo)		CMA-106ND (2.25Cr-1Mo)	
	4Ø, 45-deg. vertical-up	5Ø, Flat	4Ø, 45-deg. vertical-up	5Ø, Flat
C (%)	0.06	0.06	0.11	0.11
Si	0.37	0.49	0.32	0.42
Mn	0.76	0.79	0.84	0.84
P	0.006	0.006	0.004	0.004
S	0.004	0.004	0.002	0.002
Cu	0.01	0.02	0.032	0.031
Ni	0.03	0.02	0.13	0.14
Cr	1.29	1.30	2.41	2.42
Mo	0.57	0.56	1.04	1.03
Sb	0.002	0.002	0.002	0.002
Sn	0.002	0.002	0.002	0.002
As	0.002	0.002	0.002	0.002
X-bar (2)	8 ppm	8 ppm	6 ppm	6 ppm
J-factor (3)	90.4	102.4	69.6	75.6

- (1) Base metal: ASTM A387 Gr. 11, Cl. 2 for CMA-96MBD; A387 Gr. 22, Cl. 2 for CMA-106ND; Plate thickness: 19 mm
- (2) X-bar = (10P + 5Sb + 4Sn + As) / 100 (ppm)
- (3) J-factor = (Si + Mn) (P + Sn) × 10⁴ (%)

Table 2: Typical tensile properties of CMA-96MBD and CMA-106ND weld metals (1)

Brand (Application)	Size, welding position	PWHT (°C × h)	Test temp. (°C)	0.2% OS (MPa)	TS (MPa)	EI (2) (%)	RA (%)
CMA-96MBD (1-1.25Cr-0.5Mo)	4Ø, 45-deg. vertical-up	690 × 1	RT	515	617	27	76
			454	394	484	19	73
		690 × 8	RT	469	583	29	76
			454	368	456	25	76
	5Ø, Flat	690 × 1	RT	476	588	29	77
			454	371	468	24	76
		690 × 8	RT	435	557	30	76
			454	342	438	24	78
CMA-106ND (2.25Cr-1Mo)	4Ø, 45-deg. vertical-up	690 × 8	RT	501	635	26	72
			454	402	483	19	73
		690 × 26	RT	440	588	28	72
			454	343	446	23	73
	5Ø, Flat	690 × 8	RT	504	644	28	71
			454	405	489	20	73
		690 × 26	RT	435	594	30	72
			454	344	449	23	73

- (1) Base metal: ASTM A387 Gr. 11, Cl. 2 for CMA-96MBD; A387 Gr. 22, Cl. 2 for CMA-106ND; Plate thickness: 19 mm
- (2) Gauge length: 4D for RT, 5D for 454°C

X-bar and J-factor, shown in Table 1, are the index of control against the susceptibility to temper embrittlement of the weld metal: the higher the index, the more susceptible the weld metal becomes, according to the most commonly-accepted embrittlement mechanism. To confirm the temper embrittlement susceptibility, Charpy impact testing is conducted for the weld metal in

the as-PWHT and PWHT + step-cooling (Figure 1) conditions. Figure 2 shows typical Charpy impact test results of CMA-96MBD and CMA-106ND weld metals that confirm their high resistance to temper embrittlement.

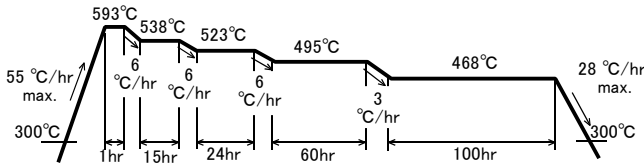


Figure 1: Step-cooling (SC) heat treatment (Socla No. 1)

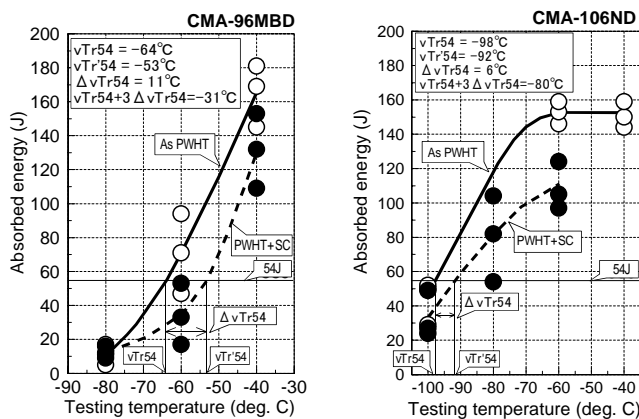


Figure 2: Temper embrittlement test results of CMA-96MBD and CMA-106ND weld metals in the as-PWHT (690°C x 8 h) and PWHT+ SC (4Ø, 45-deg. vertical-up position)

SAW flux/wire combinations for 1-1.25Cr-0.5Mo and 2.25Cr-1Mo steel

With sophisticated wire electrode chemistry and a unique bonded flux, PF-200D/US-511ND and PF-200D/US-521S offer first-class performance in room and high-temperature tensile strength and ductility, low-temperature notch toughness and resistance to temper embrittlement, as well as outstanding usability, with DCEP currents.

Table 3 shows typical chemical composition and temper embrittlement index values of the weld metals. Table 4 presents typical tensile properties of the weld metals, as a function of PWHT, tested at room and high temperatures. Figure 3 exhibits the unsurpassed resistance of the weld metals against temper embrittlement, with a comparison of 55-J absorbed energy transition temperatures in the as-PWHT and PWHT + SC conditions.

Table 3: Typical chemical properties of PF-200D/US-511ND and PF-200D/US-521S weld metals by single SAW (1)

Brand (Application)	PF-200D/US-511ND (1-1.25Cr-0.5Mo)	PF-200D/US-521S (2.25Cr-1Mo)
C (%)	0.08	0.09
Si	0.21	0.16
Mn	0.82	0.81
P	0.007	0.006
S	0.003	0.003
Cu	0.09	0.13
Ni	0.15	0.13
Cr	1.39	2.41
Mo	0.56	1.07
Sb	0.002	0.002
Sn	0.002	0.002
As	0.002	0.002
X-bar (2)	9 ppm	8 ppm
J-factor (3)	93	78

- (1) Base metal: ASTM A387 Gr. 11, Cl. 2 for PF-200D/US-511ND; A387 Gr. 22, Cl. 2 for PF-200D/US-521S; Plate thickness: 20 mm; Wire size: 4Ø
- (2) X-bar = (10P + 5Sb + 4Sn + As) / 100 (ppm)
- (3) J-factor = (Si + Mn)(P + Sn) x 10⁴ (%)

Table 4: Typical tensile properties of PF-200D/US-511ND and PF-200D/US-521S weld metals by single SAW (1)

Brand (Application)	PWHT (°C x h)	Test temp. (°C)	0.2% OS (MPa)	TS (MPa)	EI (2) (%)	RA (%)
PF-200D/US-511ND (1-1.25Cr-0.5Mo)	640 x 5	RT	522	630	25	69
		454	408	491	17	64
	690 x 4	RT	477	589	27	73
		454	376	465	17	72
	691 x 20	RT	424	546	29	73
		454	336	437	21	73
PF-200D/US-521S (2.25Cr-1Mo)	690 x 6	RT	507	621	26	75
		454	414	485	17	70
	690 x 13	RT	484	602	28	73
		454	403	472	17	72
	690 x 28	RT	468	584	28	72
		454	380	452	20	72

- (1) Base metal: ASTM A387 Gr. 11, Cl. 2 for PF-200D/US-511ND; A387 Gr. 22, Cl. 2 for PF-200D/US-521S; Plate thickness: 20 mm Wire size: 4Ø
- (2) Gauge length: 4D for RT, 5D for 454°C

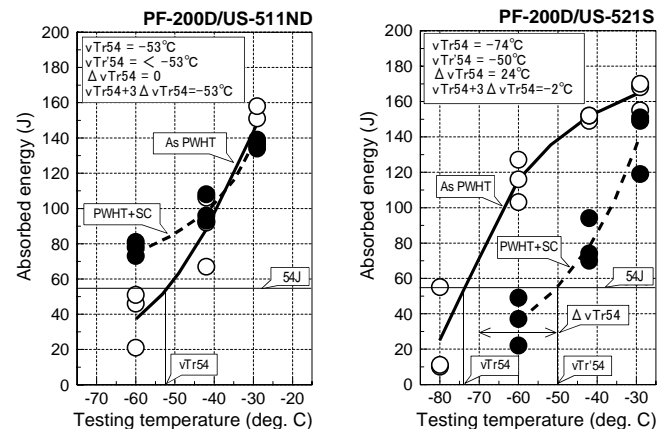


Figure 3: Temper embrittlement test results of the weld metals made with PF-200D/US-511ND in the as-PWHT (640°C x 5 h) and PWHT + SC conditions and with PF-200D/US-521S in the as-PWHT (690°C x 6 h) and PWHT + SC conditions (Wire size: 4Ø, single SAW)

CMA-106H PF-500 / US-521H CMA-106HD PF-500D / US-521HD TGS-2CMH

State-of-the-art welding technology enables fabrication of high-temperature high-pressure reactor vessels using high-strength 2.25Cr-1Mo-V steel and matching filler metals for SMAW, SAW and GTAW by AC or DC:

Why high-strength 2.25Cr-1Mo-V steel is needed

Desulfurization reactors are thick heavy section pressure vessels that remove, by chemical reaction, sulfur impurities contained in crude oil in the refining of heavy hydrocarbons into lighter, more valuable products in refineries (Figure 1).



Figure 1: Refineries are composed of a variety of such sophisticated equipment as reactors, towers, heat exchangers, and pipelines.

The reactors for refineries are operated in a high-temperature high-pressure hydrogen atmosphere. In order to efficiently carry out the desulfurization reaction, the service temperature and pressure are increased, causing increases in thickness and scale of the reactor. The world's largest heavy oil desulfurization reactor that uses high strength 2.25Cr-1Mo-V steel has a shell of 330-mm thick and weighs 1400 tons (Figure 2).

This explains the need for specific steels—advanced steel with higher strength and resistance to hydrogen at higher operation temperatures—that are superior to conventional 2.25Cr-1Mo steel. The high-strength 2.25Cr-1Mo-V steel is the one for this application; it has been used to fabricate reactors since 1998.

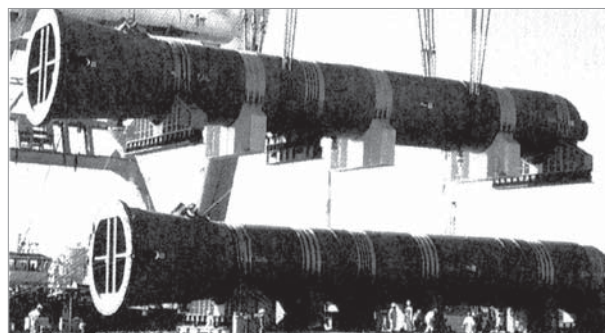


Figure 2: The world's largest heavy oil desulfurization reactor vessel having a shell of 330-mm thick and weighing 1400 tons (Photo source: Welding Technique Vol.47, Japan Welding Engineering Society)

How high-strength 2.25Cr-1Mo-V steel and matching welding filler metals are specified in ASME

Table 1 shows steel grades and requirements for chemical composition and mechanical properties of 2.25Cr-1Mo-V steel, as specified by ASME Boiler and Pressure Vessel Code Sec. 8 Div. 1 Appendix 31 and Div. 2 Appendix 26. In using these specific materials for the fabrication of pressure vessels, these ASME Code Appendixes require to use welding filler metals that satisfy the requirements of chemical composition and mechanical properties of weld metal, as shown in Table 1.

What are the advantages of high-strength 2.25Cr-1Mo-V steel and filler metal?

As shown in Table 1, the high-strength 2.25Cr-1Mo-V steel and matching filler metals contain small amounts of vanadium and columbium (or niobium).

Table 1: Requirements of chemical composition and mechanical properties of high-strength 2.25Cr-1Mo-V steel and weld metal (ASME Boiler and Pressure Vessel Code Sec. 8 Div. 1 Appendix 31 and Div. 2 Appendix 26)

Steel spec. and grade	Chemical composition of steel (%) (1)													
	C	Mn	P	S	Si	Cr	Mo	Cu	Ni	V	Cb	Ti	B	Ca
SA-182, F22V	0.11-0.15	0.30-0.60	0.015	0.010	0.10	2.00-2.50	0.90-1.10	0.20	0.25	0.25-0.35	0.07	0.030	0.0020	0.015
SA-336, F22V														
SA-541, 22V	Mechanical properties of steel (2)													
SA-542, D-4a	- Tensile strength (MPa):					585-760			- Elongation (%):			18 min.		
SA-832, 22V	- 0.2% offset strength (MPa):					415 min.			- Impact energy at -18°C (J):			54/47 min. (3)		
Welding process	Chemical composition of weld metal (%) (1)													
	C	Mn	Si	Cr	Mo	P	S	V	Cb					
SMAW	0.05-0.15	0.50-1.30	0.20-0.50	2.00-2.60	0.90-1.20	0.015	0.015	0.20-0.40	0.010-0.040					
SAW	0.05-0.15	0.50-1.30	0.05-0.35	2.00-2.60	0.90-1.20	0.015	0.015	0.20-0.40	0.010-0.040					
GTAW	0.05-0.15	0.30-1.10	0.05-0.35	2.00-2.60	0.90-1.20	0.015	0.015	0.20-0.40	0.010-0.040					
Welding process	Mechanical properties of weld metal (2)													
	- Tensile strength (MPa):					585-760			- Impact energy at -18 °C (J):			54/47 min. (3)		
	- 0.2% offset strength (MPa):					415 min.			- Creep rupture life at 538°C and 205 MPa: (4)					
	- Elongation (%):					18min			Exceed 900h					

- (1) Single values are the maximum.
- (2) The heat treatment conditions for tensile test are specified based on the maximum and minimum vessel-portion temperatures and holding time. The heat treatment condition for impact test is specified based on the minimum vessel-portion temperature and holding time in fabrication. The heat treatment condition for creep rupture tests is specified based on the maximum vessel-portion temperature and holding time.
- (3) For Charpy impact energy requirement, 54J is for three-specimen average and 47J is for one specimen
- (4) Specified by ASME Sec. 8 Div.2 Appendix 26 for category A welds (both all weld metal and welded joint)

Alloying these elements is, first, to strengthen the Cr-Mo steel by the precipitation of vanadium and columbium carbides in the matrix. Second, stable vanadium and columbium carbides improve resistance to high temperature hydrogen attack. High temperature hydrogen attack is believed to be one form of hydrogen damage, where molecular hydrogen dissociates into the atomic form, atomic hydrogen readily enters and diffuses through the steel rapidly, and hydrogen may react with carbon in the steel ($Fe_3C + 4H \rightarrow CH_4 + Fe$) to cause either surface decarburization or internal decarburization and fissuring. Thirdly, fine particles of vanadium carbide improve resistance to hydrogen embrittlement, by trapping diffusible hydrogen to prevent its concentration at crack tips.

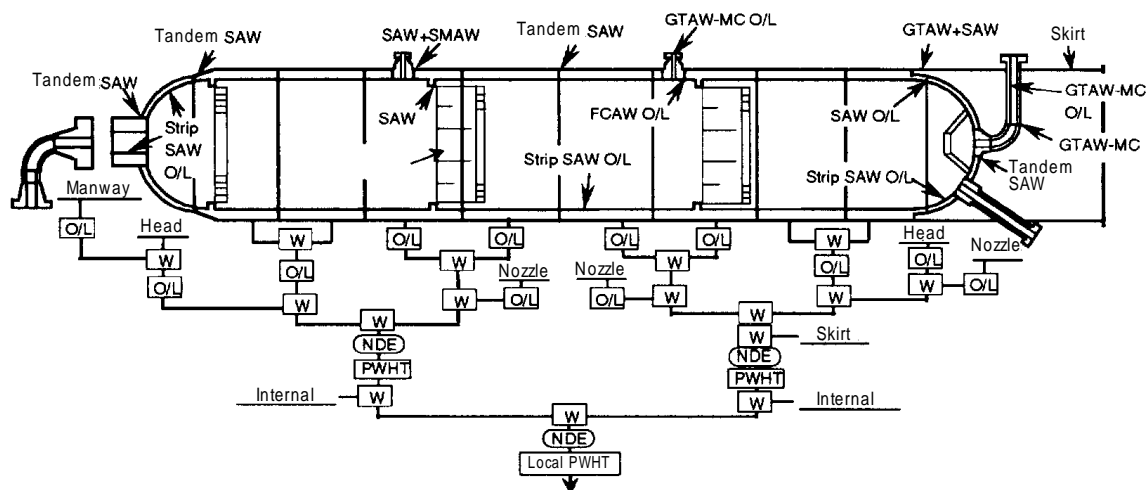
With higher strength, the wall thickness of a 2.25Cr-1Mo-V steel pressure vessel can be reduced by about 12% when compared with conventional 2.25Cr-1Mo steel because the allowable stress can be increased by about 12%. Thinner material means welding can be finished faster and time for postweld heat treatment soaking can be reduced, thereby reducing fabrication costs. Superior resistance to high temperature hydrogen attack and hydrogen embrittlement facilitates more effi-

cient operation of the reactor vessel at higher temperatures (482°C max. for operation temperature) and higher atmospheres of hydrogen pressure.

How reactor vessels are fabricated

Figure 1 shows a fabrication procedure for reactor pressure vessels. Stainless steel overlay welding of the internal surfaces of the Cr-Mo shell ring forgings is carried out on a single ring forging or two ring forgings joined by circumferential welding.

Overlay stainless steel welds protect the Cr-Mo base metal and weld metal from high-temperature high-pressure hydrogen during desulfurization. After this process, the shell ring forgings are joined by circumferential SAW welding accompanied by SMAW of nozzles in the shell rings. The heads of a reactor have a thickness about one half of that of the shell, and they are produced by hot pressing Cr-Mo steel plates without joints. The heads are processed by stainless steel overlay welding on their internal surfaces, followed by SAW of nozzles and SAW of head-to-shell circumferential joints. Bend pipe-to-nozzle neck and bend pipe-to-flange pipe girth joints are welded by automatic GTAW.



SAW: Submerged arc welding	W: Joint welding
Strip SAW: SAW with strip electrodes	O/L: Overlay welding
GTAW-MC: Automatic gas tungsten arc welding	NDE: Nondestructive examination
FCAW: Flux cored arc welding (CO ₂ shielding)	PWHT: Postweld heat treatment
SMAW: Shielded metal arc welding	

Figure 1: An example of fabrication procedure for reactor vessels by arc welding
 (Source: Welding Technique Vol.47, Japan Welding Engineering Society)

All the welds are subjected to nondestructive examinations (NDE) such as X-ray, ultrasonic, magnetic particle and liquid penetrant tests, followed by postweld heat treatment (PWHT). After PWHT, the soundness of the welds is again checked by NDE to ensure no cracking has developed. Next, the vessel is subjected to a pressure test, followed by the final NDE. The completed pressure vessel is then shipped. More than 95% of the welding operations in fabrication of reactor vessels are reportedly automated to assure consistent quality.

Unbeatable characteristics of Kobelco 2.25Cr-1Mo-V filler metals

Kobe Steel has long carried out research in welding metallurgy of Cr-Mo weld metals and has developed innovative filler metals suited specifically for 2.25Cr-1Mo-V steel. These filler metals are SMAW covered electrode of CMA-106H for AC and CMA-106HD for DC, SAW flux and wire of PF-500/US-521H for AC and PF-500D/US-521HD for DC, and GTAW filler wire of TGS-

2CMH for DC. These filler metals fulfill the requirements of ASME Sec. 8 Div.1 Appendix 31 and Div.2 Appendix 26, which can be verified with the weld metal chemical and mechanical properties shown in Tables 2 and 3. These advanced filler metals are characterized by a sophisticated chemical composition that provides the weld metal with sufficient impact toughness and minimized temper embrittlement. The resulting weld metal also contains adequate amounts of vanadium and columbium to ensure tensile strength, creep rupture strength and resistance to high temperature hydrogen attack and hydrogen embrittlement. (Kobe Steel has been researching these SMAW and SAW filler metals to further reduce the Mn and Si content of the weld metal from the standpoint of minimizing the temper embrittlement.)

In addition, the coating fluxes of CMA-106H and CMA-106HD are designed so as to perform sufficient usability in all position welding. The coating fluxes are of extra-low hydrogen type; therefore, these covered electrodes deposit very low hydrogen weld metal, thereby minimizing the susceptibility to delayed cracking.

Table 2 : Typical chemical compositions of weld metals by 2.25Cr-1Mo-V filler metals

Filler metal brand name	Power source	Chemical composition (%)								
		C	Mn	Si	P	S	Cr	Mo	V	Cb
CMA-106H	AC	0.08	1.15	0.29	0.007	0.003	2.41	1.00	0.28	0.016
PF-500/US-521H	AC	0.08	1.09	0.14	0.004	0.004	2.50	1.03	0.33	0.014
CMA-106HD	DCEP	0.08	1.12	0.24	0.005	0.002	2.48	1.05	0.27	0.012
PF-500D/US-521HD	DCEP	0.07	1.26	0.17	0.007	0.001	2.44	1.03	0.34	0.011
TGS-2CMH	DCEN	0.10	0.38	0.14	0.003	0.004	2.21	1.02	0.21	0.025

Table 3: Typical mechanical properties of weld metals by 2.25Cr-1Mo-V filler metals (1)

Filler metal brand name	Power source	PWHT (°C x h)	0.2% OS (MPa)	TS (MPa)	EL (%)	Av. IV (J)
CMA-106H	AC	705 x 7	612	713	23	-18°C: 147
PF-500/US-521H	AC (2)	705 x 7	616	706	24	-18°C: 106
		705 x 26	533	639	26	-18°C: 142
CMA-106HD	DCEP	705 x 26	520	636	24	-18°C: 137
		705 x 8	598	713	21	-18°C: 121
PF-500D/US-521HD	DCEP	705 x 26	518	634	26	-18°C: 142
		705 x 8	603	708	24	-18°C: 125
TGS-2CMH	DCEN	705 x 7	623	730	22	-18°C: 300

(1) Testing temperature for tension test: Room temp. (2)Tandem SAW

PF-500 and PF-500D are ultra-low hydrogen bonded type fluxes for SAW. PF-500 and PF-500D pick up moisture at slower rates as compared with conventional bonded type fluxes. Furthermore, these SAW fluxes offer unsurpassed usability providing self-peeling slag removability in the narrow groove of heavy thick section work. TGS-2CMH offers excellent usability with sufficient wetting of the weld pool in narrow groove work, which ensures good performance in automatic or mechanized welding processes. These outstanding characteristics of the filler metals are provided by Kobe Steel’s persistent quality control for each lot or heat of filler metal.

The high strength 2.25Cr-1Mo-V weld metals have fine bainitic structures as shown in Figure 2 for CMA-106H and in Figure 3 for PF-500/US-521H. This is the reason why the weld metal exhibits high tensile strength, adequate creep rupture strength, sufficient impact toughness, and low susceptibility to temper embrittlement. As shown in Tables 2 and 3, AC-spec filler metals and DC-spec filler metals are comparable to each other about chemical and mechanical properties due to consistent fine microstructure.

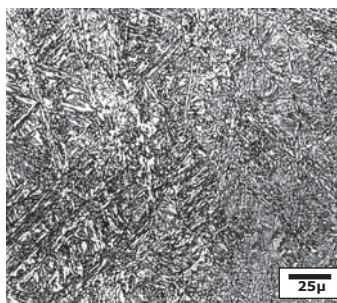
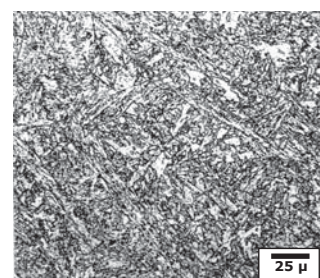


Figure 2: Microstructure of the dendritic zone of CMA-106H weld metal of fine bainite (2% nital etching)

Figure 3: Microstructure of the dendritic zone of PF-500/US-521H weld metal of fine bainite (2% nital etching)



Resistance to temper embrittlement is essential for filler metals for reactor vessels

Figures 4, 5 and 6 show Charpy impact and temper embrittlement test results of CMA-106H, PF-500/US-521H and TGS-2CMH weld metals, respectively. These test results exhibit quite high notch

toughness satisfying the ASME Code requirement of Charpy impact absorbed energy at minus 18°C in the as-PWHT condition and sufficiently low susceptibility to the temper embrittlement by step cooling heat treatment.

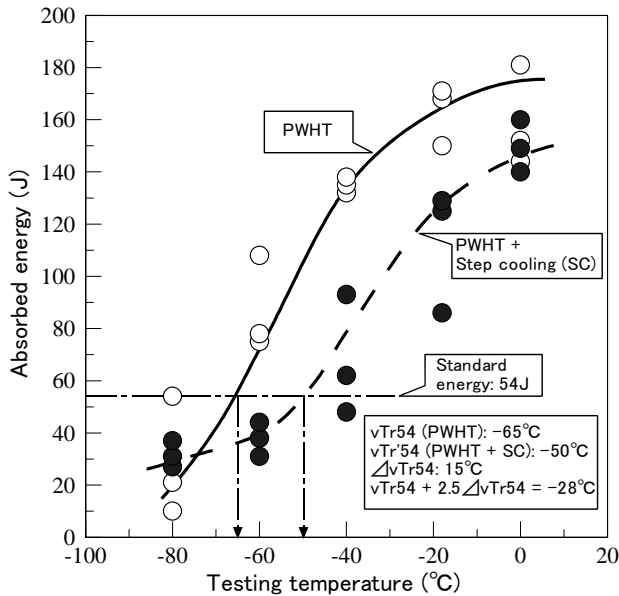


Figure 4: Charpy impact test results of CMA-106H (40) weld metal after PWHT (715°C × 7h) and PWHT + Step Cooling (Power source: AC; Welding position: flat)

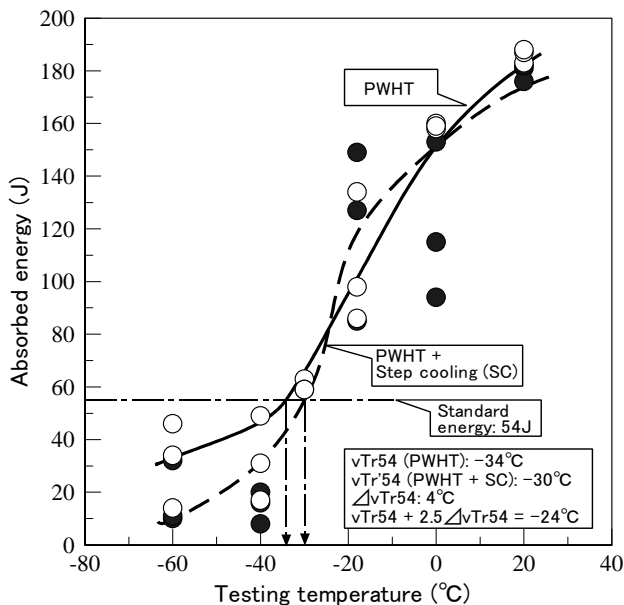


Figure 5: Charpy impact test results of PF-500/US-521H weld metal after PWHT (705°C × 7h) and PWHT + Step Cooling (Power source: AC; Tandem SAW)

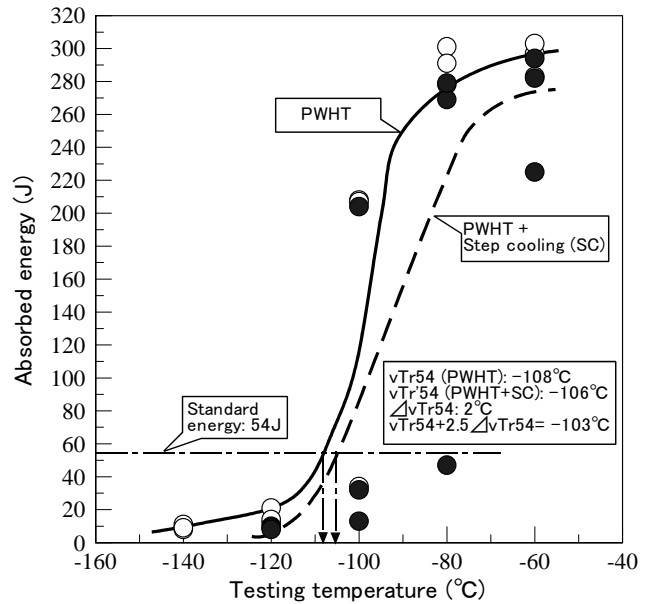


Figure 6: Charpy impact test results of TGS-2CMH weld metal after PWHT (705°C × 7h) and PWHT + Step Cooling (Power source: DCEN; Welding position: flat; Ar shielding)

Figure 7 shows creep rupture test results of CMA-106H and PF-500/US-521H weld metals after PWHT. It is obvious that the test results satisfy the ASME Code requirement. In this test, the testing temperature was 538°C that is higher than the permissible maximum operation temperature (482°C) as per the ASME Code. The use of higher temperature is to know the creep rupture strength with shorter hours, by accelerating creep of the specimen.

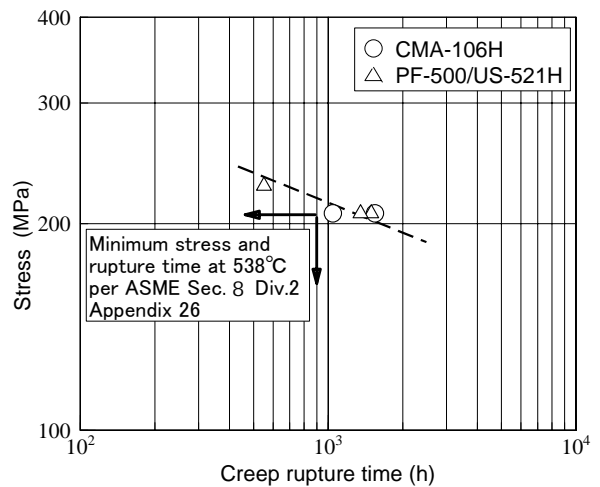


Figure 7: Creep rupture test results of CMA-106H and PF-500/US-521H weld metals after PWHT (705°C × 26h) (Power source: AC; Testing temperature: 538°C)

CM-9Cb CM-96B9 TGS-9Cb TGS-90B9

AWS A5.5 E9016-G AWS A5.5 E9016-B9 AWS A5.28 ER90S-G AWS A5.28 ER90S-B9

Advanced 9Cr filler metals in welding power boilers and oil refinery machinery

How advanced 9Cr filler metals help innovate power boilers

Steam boilers (Figure 1) produce high-temperature high-pressure steam by heating pressurized water contained in hermetically sealed vessels through combustion of such fuels as coal, LNG, and oil. Steam boilers are widely used for such various applications as power plants, ships, steel mills, textile processes, chemical processes, and oil refineries.



Figure 1: A coal-fired steam boiler consisting of the sophisticated piping system fabricated with tens of thousands of tubes and pipes made from carbon steel, Cr-Mo steel, and stainless steel

Steam boilers, also known as power boilers, used in power plants generate high-temperature high-pressure steam for better power generation efficiency. The steam temperatures and pressures of coal-fired power boilers have been increasing to improve thermal efficiency. As the efficiency becomes higher, the consumption of fuels for generating unit electrical power can be decreased, thereby helping to combat global warming.

Among power boilers, supercritical pressure boilers are operated at high temperatures (e.g. 538°C) and high pressures (e.g. 24.1 MPa). Ultra-supercritical (USC) pressure boilers are operated at even higher steam temperatures (e.g. 593°C) and pressures (e.g. 31.4 MPa). Steam temperature and pressure are apt to be higher for more efficient power generation for the future.

As a factor in the technology of advanced power boilers, Modified 9Cr-1Mo steel (9Cr-1Mo-V-Nb) is highlighted due to its superior high temperature performance relative to conventional 9Cr-1Mo steel and Type 304 stainless steel. That is, 9Cr-1Mo-V-Nb steel can be used with a higher allowable stress in comparison with 9Cr-1Mo and, up to 600°C, in comparison with Type 304, as shown in Figure 2.

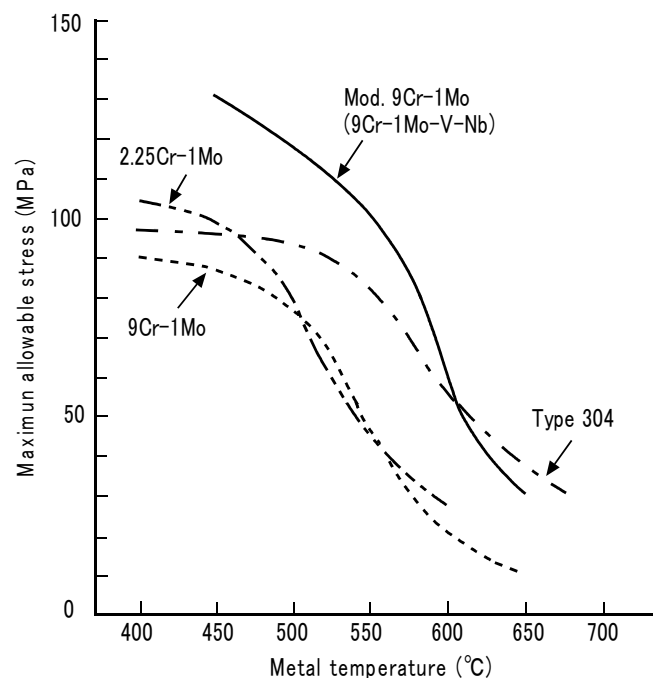


Figure 2: A comparison between 9Cr-1Mo-V-Nb and other steels on the maximum allowable stress for high-temperature equipment over a range of metal temperatures

The use of 9Cr-1Mo-V-Nb steel is expanding for ultra-supercritical pressure boilers. With ferritic 9Cr-1Mo-V-Nb steel, the countermeasures (e.g. use of expansion joints) to release thermal stresses in the tube bundle structures of steam boilers can be lessened than with austenitic Type 304, because the thermal expansion and contraction of ferritic 9Cr steels are less. The thermal stresses are raised by the thermal cycle during operation accompanied by the fluctuation of power generation in a day.

How to select suitable Kobelco advanced 9Cr filler metals that match the base metal

Table 1 is a quick guide to suitable brands of filler metals for shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) of 9Cr-1Mo-V-Nb steels. The base metal grades are in accordance with the ASTM standard but this guidance can also be used for other equivalent base metal grades per other national standards.

Table 1: A quick guide to matching filler metals for the 9Cr-1Mo-V-Nb base metal grades

Grade of steel (ASTM)			SMAW (AWS A5.5)	GTAW (AWS A5.28)
Plate	Tube/Pipe	Forging		
A387 Gr.91 Cl.2	A199Gr. T91 A213Gr. T91 A234Gr.WP91 A335Gr. P91	A182Gr.F91 A336Gr.F91	CM-9Cb (E9016-G) CM-96B9 (E9016-B9)	TGS-9Cb (ER90S-G) TGS-90B9 (ER90S-B9)

There are two choices for 9Cr-1Mo-V-Nb steel. One is the Kobelco original type (CM-9Cb, TGS-9Cb), which satisfies the mechanical properties requirement of the AWS standard but its chemical composition is unique and it has been used for many ultra-supercritical pressure boilers fabricated by Japanese manufacturers. The other one is the AWS type (CM-96B9, TGS-90B9), which has been developed by modifying the original type so as to conform with both the mechanical and chemical requirements of the AWS standard, taking into account the usual requirements of international customers.

CM-9Cb and TGS-9Cb: unmatched filler metals for ultra-supercritical pressure boilers

In the early 1980's when the research and development of coal-fired, ultra-supercritical pressure boilers began among the leading steel producers and boiler fabricators in Japan, Kobe Steel developed suitable filler metals for the Modified 9Cr-1Mo steel.

This advanced steel is alloyed with considerable amounts of vanadium, niobium and nitrogen in addition to chromium and molybdenum to improve elevated-temperature strength. However, filler metals, inherently, cannot accommodate as much niobium and nitrogen as contained in the steel because such elements result in poor weldability. This is why CM-9Cb and TGS-9Cb have unique chemical compositions that provide good performance in mechanical properties and welding workability in out-of-position welding. Table 2 shows the typical chemical compositions of these filler metals, in comparison with the chemical requirements for a 9Cr-1Mo-V-Nb steel tube of ASTM A213 T91.

Table 2: Typical chemical compositions of CM-9Cb and TGS-9Cb weld metals, in comparison with the A213 T91 tube chemistry range (%)

Brand	CM-9Cb	TGS-9Cb	ASTM A213 T91
Current	AC	DC-EN	
C	0.06	0.07	0.08-0.12
Mn	1.51	0.99	0.30-0.60
Si	0.31	0.16	0.20-0.50
P	0.006	0.008	0.020 max
S	0.003	0.006	0.010 max
Cr	9.11	8.97	8.00-9.50
Mo	1.06	0.90	0.85-1.05
Ni	0.94	0.68	0.40 max
V	0.18	0.18	0.18-0.25
Nb	0.03	0.04	0.06-0.1
N	0.030	0.022	0.030-0.070
Al	-	-	0.04 max

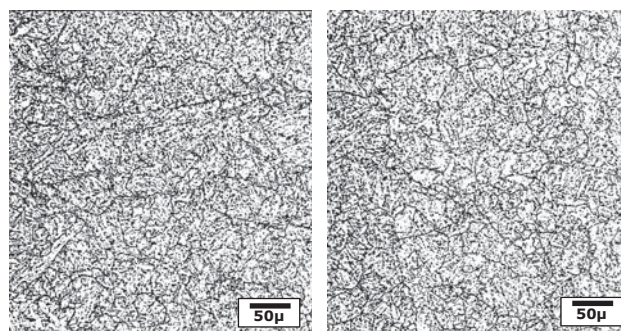


Figure 3: CM-9Cb deposits homogeneous microstructure consisting of tempered martensite with the absence of polygonal ferrite after PWHT (750°C x 5h), exhibiting a dendritic zone (left) and a pass-to-pass tempered zone (right)

Simple alloying of conventional 9Cr-1Mo filler metal with vanadium and niobium creates a heterogeneous microstructure consisting of coarse, polygonal ferrite precipitates in the martensitic matrix, thereby decreasing strength and impact toughness. However, CM-9Cb and TGS-9Cb offer fine, homogeneous microstructures (Figure 3) created by the elaborate chemical compositions.

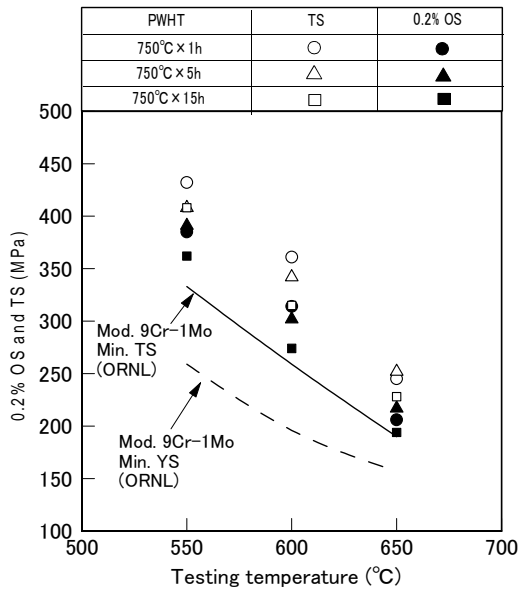


Figure 4: High-temperature strength of CM-9Cb (40) weld metal in the flat position, satisfying the minimum strength of Mod. 9Cr-1Mo steel within the given PWHT conditions

Typical applications for CM-9Cb and TGS-9Cb are girth welding of superheater tubes, reheater tubes and steam headers of USC boilers that are operated in the hard steam conditions (e.g. 593°C × 31.4 MPa). Therefore, strength at elevated temperatures is a key property of this kind of filler metals. Figures 4 and 5 show high-temperature strength and creep rupture strength of CM-9Cb weld metal, respectively. These figures verify that CM-9Cb satisfies the minimum yield strength, tensile strength and rupture strength of Modified 9Cr-1Mo steel.

CM-96B9 and TGS-90B9: AWS class filler metals for international applications

These new brands have been developed by modifying the chemical composition of CM-9Cb and TGS-9Cb to make it easier for international customers to select a suitable filler metal per the AWS chemical requirement designation (B9) for 9Cr-1Mo-V-Nb steel. The welding usability, mechanical properties and crack resistibility of these new brands are comparable to the Kobelco original brands. Table 3 shows typical chemical compositions of these brands and the AWS requirements for both filler metals.

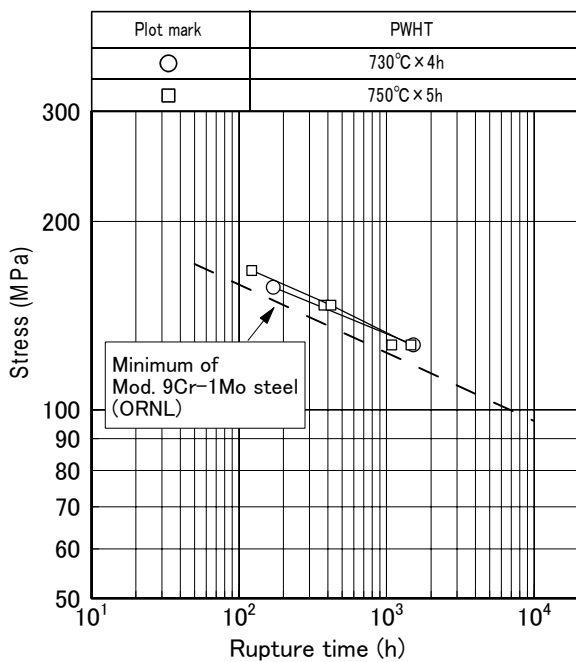


Figure 5: Creep rupture strength of CM-9Cb (40) weld metal in the flat position, satisfying the minimum rupture strength of Mod. 9Cr-1Mo steel

Table 3: Typical chemical compositions of CM-96B9 weld metal (DC-EP) and TGS-90B9 filler wire in comparison with the AWS requirements (%)

Brand	CM-96B9	TGS-90B9	AWS (1) E9016-B9	AWS (2) ER90S-B9
C	0.11	0.12	0.08-0.13	0.07-0.13
Mn	1.12	0.75	1.25 max	1.20 max
Si	0.23	0.25	0.30 max	0.15-0.30
P	0.009	0.007	0.01 max	0.010 max
S	0.002	0.005	0.01 max	0.010 max
Cu	0.01	0.10	0.25 max	0.20 max
Ni	0.83	0.49	1.0 max	0.80 max
Cr	9.13	9.20	8.0-10.5	8.00-10.50
Mo	0.99	1.00	0.85-1.20	0.85-1.25
V	0.23	0.21	0.15-0.30	0.15-0.30
Nb	0.037	0.038	0.02-0.10	0.02-0.10
Al	-	-	0.04 max	0.04 max
N	0.027	0.046	0.02-0.07	0.03-0.07

(1) Weld metal; (2) Filler wire

Table 4 shows the tensile properties of CM-96B9 and TGS-90B9 weld metals, which satisfy the AWS requirements. In addition, Figures 6 and 7 verify that both brands fulfill the ASTM require-

ments for A335 Gr. P91 even in the stricter condition of PWHT with a longer soaking time.

Table 4: Room temperature tensile test results of CM-96B9 (5Ø, DC-EP) and TGS-90B9 (1.2Ø, DC-EN) weld metals in the flat position in comparison with the AWS requirements (1)

Brand	PWHT (°C x h)	Temper parameter	0.2% OS (MPa)	TS (MPa)	El (%)
CM-96B9	740 x 1	20.26	754	850	20
	740 x 8	21.17	637	761	22
	745 x 1	20.36	752	839	23
TGS-90B9	760 x 2	20.97	657	785	25
	745 x 8	21.27	602	765	26
	AWS E9016-B9	740 x 1	20.26	530 min.	620 min.
AWS ER90S-B9	760 x 1	20.66	410 min.	620 min.	16 min.

(1) $\text{Temper parameter} = T(20 + \log t) \times 10^{-3}$

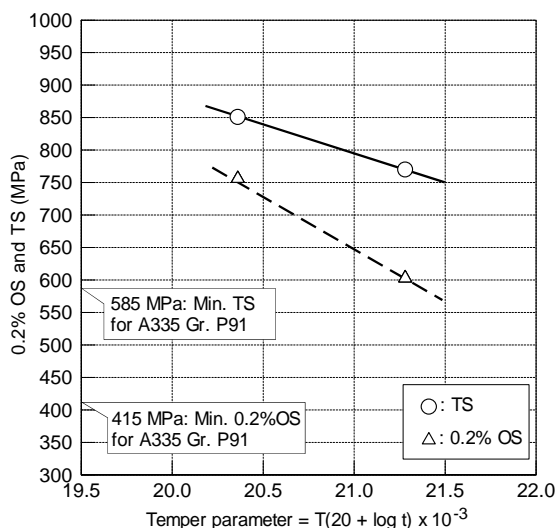


Figure 6: Tensile properties of CM-96B9 weld metal as a function of temper parameter where T is PWHT temp. in deg. K and t is soaking time in hours

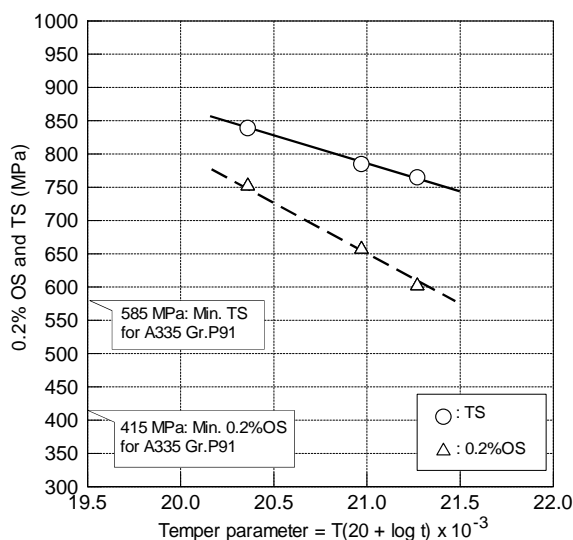


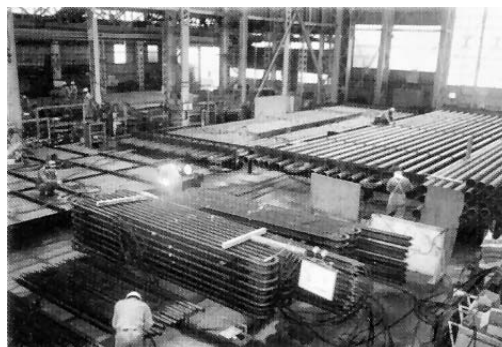
Figure 7: Tensile properties of TGS-90B9 weld metal as a function of temper parameter

Tips for successful welding of mod. 9Cr steel

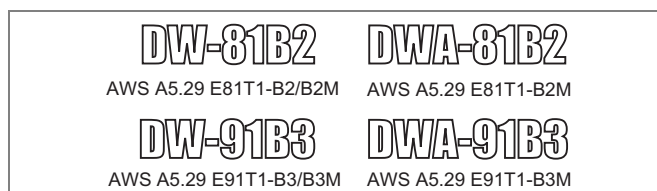
(1) Remedies to cold or delayed cracks: 9Cr-1Mo-V-Nb steels have higher self-hardenability relative to such Cr-Mo steels as 2.25Cr-1Mo, 1.25Cr-0.5Mo, and 0.5Mo. Therefore, preventive measures against cold cracking must be stricter. The most effective measures are preheating the work by 250-350°C and, if PWHT is not carried out before the weld cools down to the ambient temperature after welding is finished, postheating the weld by 250-350°C for 30-60 minutes. The preheating and postheating can decrease the hardness of the weld, promote hydrogen diffusion out of the weld, and thereby prevent cold cracking. Redrying the covered electrodes by 325-375°C for 1 hour is a must before use.

(2) Preventing hot or solidification cracks: Kobelco 9Cr-1Mo-V-Nb filler metals contain phosphorous and sulfur at quite low levels and sufficient manganese to minimize the susceptibility to hot cracking or solidification cracking. However, 9Cr-1Mo-V-Nb metals are inherently susceptible to hot cracking. Small diameter tubes having thin sections also sometimes suffer from hot cracks. Therefore, excessively high welding currents should be avoided.

(3) Proper PWHT temperature: PWHT temperature is a key factor to control the quality of welds. ASME Sec. 8 Div. 1, for instance, specifies a minimum PWHT temperature of 704°C for 9Cr-1Mo-V-Nb steel (e.g. A213 T91). However, for better quality in ductility and toughness of weld metal, the range 710-780°C is recommended for filler metals discussed in this article.



9Cr-1Mo-V-Nb steel is often used for super heater tubes, reheater tubes and steam headers of coal-fired steam boilers in the trend of higher steam conditions (Photo courtesy: Nagasaki Kogyosho Co., Ltd., Japan)



Competitive Cr-Mo flux-cored wires for CO₂ and Ar-CO₂ shielding

The main types of Cr-Mo steels used in high-temperature equipment such as boilers and pressure vessels are 1.25Cr-0.5Mo and 2.25Cr-1Mo. Kobe Steel has launched competitive rutile type flux-cored wires for these main types of steels in order to cope with the specific demands of international customers for welding accessories of high-temperature equipment.

DW-81B2 and DWA-81B2 are for 1.25Cr-0.5Mo steel and DW-91B3 and DWA-91B3 are for 2.25Cr-1Mo steel. DW-series wires use either 75-80%Ar/bal. CO₂ or 100%CO₂ and DWA-series wires use 75-80%Ar/bal. CO₂ for shielding in out-of-position welding. As shown in Tables 1 and 2, respectively, the chemical composition and tensile properties of the weld metals by the individual wires satisfy the AWS requirements. Also, DWA-series wires, containing lower Si and P and higher Mn, offer higher impact toughness in the postweld heat treated condition.

These flux-cored wires deposit weld metals featuring fine bainitic microstructures in both the dendritic and refined zones of the weld metal after postweld heat treatment (PWHT). The fine microstructure of weld metal contributes to sufficient impact properties

In addition to consistent mechanical properties and fine microstructure of postweld-heat-treated weld metals, these wires are characterized by a spray transfer, low spatter loss, flat to slightly convex bead configuration (Figures 1 and 2), and a moderate volume of slag, which completely covers the weld bead and exhibits self-peeling slag detachability.

Proper preheating and interpass temperatures in fabrication are, depending on plate thickness of the work, 150-250°C for DW-81B2 and DWA-81B2 and 200-300°C for DW-91B3 and DWA-91B3.

Table 1: Typical chemical compositions of weld metals by DW-81B2 and DW-91B3 and the AWS requirements (%)

Brand	C	Si	Mn	P	S	Ni	Cr	Mo
DW-81B2	0.05	0.62	0.60	0.008	0.010	0.02	1.29	0.50
DWA-81B2	0.05	0.48	1.09	0.005	0.009	0.03	1.39	0.55
E81T1-B2/B2M	0.05-0.12	0.80 max	1.25 max	0.03 max	0.03 max	-	1.00-1.50	0.40-0.65
DW-91B3	0.05	0.35	0.71	0.009	0.012	0.02	2.21	0.97
DWA-91B3	0.07	0.35	0.85	0.007	0.010	0.02	2.29	1.00
E91T1-B3/B3M	0.05-0.12	0.80 max	1.25 max	0.03 max	0.03 max	-	2.00-2.50	0.90-1.20

(1) Shield gas: 75%Ar+25%CO₂ for DW-81B2 and DW-91B3; 80%Ar-20%CO₂ for DWA-81B2 and DWA-91B3

(2) Welding parameters: DC-EP 230-250A/26-30V/approx. 20cm/min; 1G position

Table 2: Typical tensile properties of weld metals by DW-81B2 and DW-91B3 at room temperature and the AWS requirements

Brand	PWHT (°C x h)	0.2%OS (MPa)	T.S. (MPa)	El. (%)	Av. IV at 0 °C (J)
DW-81B2	690 x 1	578	659	26	-
DWA-81B2	690 x 1	568	657	26	70
E81T1-B2/B2M	690 x 1	470 min.	550-690	19 min.	-
DW-91B3	690 x 1	606	701	22	-
DWA-91B3	690 x 1	605	695	21	80
E91T1-B3/B3M	690 x 1	540 min.	620-760	17 min.	-

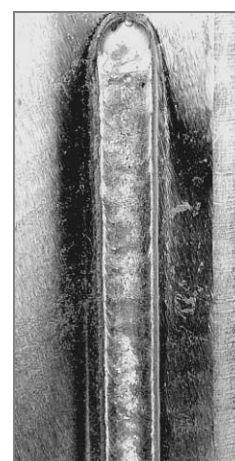


Figure 1 (right): Bead appearance made in straight-run vertical-up fillet welding, having a smooth regular surface with no undercut (Brand: DW-81B2; Wire size: 1.2Ø; Welding current and voltage: 220A (DCEP)/25V; Shielding gas: 75%Ar+25%CO₂; Leg length: 7 mm)

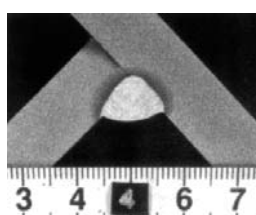


Figure 2 (left): Macrostructure of the fillet weld shown in Figure 1, having sufficient penetration and smooth fusion with the base metal