P91 and Beyond

Welding the new-generation Cr-Mo alloys for high-temperature service

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Creep strength-enhanced ferritic steel (CSEF) and advanced chromium-molybdenum steels are experiencing worldwide usage. The desire to increase efficiency has introduced a need for advanced materials with superior material properties at higher temperatures. Advanced chromium-molybdenum pipe and tubing such as 9 CrMoV [P(T)91], tungsten, and/or boron-enhanced materials (i.e., Grades 92, 122, E911, 23, 24, etc.) are now being specified. The lessons learned thus far with P(T)91 weldments have truly demonstrated that CSEF steels are quite different and require significantly more attention than the P(T)22 and lesser materials.

Of the candidate advanced base materials and consumables, T23 appears to have the highest priority among challenges to P91, followed by P92 and then to a lesser extent the higher chromium- and nickel-based alloys. Emphasis placed herein on Grade 91 and the importance of maintaining preheat, interpass temperature, and dangers inherent in interrupted heating cycles or improper postweld heat treatment plus detailed attention to filler metal procurement to avoid metallurgical complications is equally true for the other advanced chromium-molybdenum alloys.

Comparison of Properties

These CSEF alloys have similar compositions within a given alloy family. Specific properties, particularly strength or enhanced corrosion resistance at elevated temperatures, are achieved by controlled alloy additions such as tungsten, vanadium, or boron. Compositions and specifications for candidate advanced chromium-molybdenum steels for high-temperature service are shown in Tables 1 and 2.

Base material development and code acceptance have preceded effort and research in the areas of weld properties and welding consumables for the advanced chromium alloys. Information presented at recent conferences on advanced materials suggest that although the base metals offer potentially superior properties, restoration of heat-affected zones (HAZ) created by welding or remediation of cold work/bending effects may not have been fully examined and need further investigation. Like P(T)91, dealing with the HAZ in other CSEF alloys may in fact offer the most challenges. Figure 1 illustrates the typical "soft zone" that forms in CSEF HAZs. (See Refs. 1–10.)

Comparison of P91 Steel and other CSEFs

Use of P91 is now worldwide. There are various sources for base materials, welding consumables, and fabrication. (See Refs. 1–13.) The art is such that few welding problems are encountered. Fabrication and field erection problems have been noted, but are typically related to improper or inadequate heat treating and bending operations. Design and implementation of dissimilar weldments continue to be a subject of much discussion. Review of creep performance for welding consumables remains a key factor for selection. Other CSEFs can be summarized as follows:

- P92: Similar to P91, but with 0.5Mo-1.7W
- E911: Similar to P91, but with 1%W
- P122: Like P92, but with 11%Cr + 1%Cu
- T23: Similar to P22, but stronger with ~ 2%W
- T24: Similar to T22, but with V + Ti + B

Representative creep rupture results for selected CSEFs are shown in Fig. 2.

Code Acceptance — Base Material

ASME/AWS specifications are approved for using P91 base material and weld metal. Table 3 illustrates base metal code cases that have been issued for ASME Section I construction. (See Refs. 15, 16.)

The American Welding Society's D10 Committee on Piping and Tubing decided to remove P(T)91 materials from its existing guideline publication on welding CrMo piping and tubing (D10.8) and prepare a new document (D10.21, pending) for P(T)91 and the other advanced chromium-molybdenums. The AWS document is pending resolution of technical items, due to lessons learned, now being deliberated in various ASME committees.

Comparing Base Metal, Heat-Affected Zone, and Weld Metal Strength

Differences in hardness between the base metal, weld metal, and HAZ for a P91 weldment are shown in Fig. 1. This trend for the HAZ to be a "soft zone" exists with all the CSEFs. Given that hardness can be an indicator for strength in low-alloy materials, the HAZ offers the least performance, regardless of the weld metal or base metal involved. Even when matching CSEF weld metal is used, it tends to be stronger than the base metal and definitely stronger than the HAZ. Increased times at temperature could be employed to reduce the weld metal strength, but this approach is usually not used for economic reasons. (See Refs. 14, 15, 17.)

Welding Consumables

A variety of welding consumables with AWS or other national specifications are available for P91 materials. (See Refs. 15, 18–25.) This is not the case for the other CSEF alloys. Table 4 provides examples of welding consumables, and Table 5 lists consumables for welding P91. Where an AWS classification is shown, specific consumables are available from more than one source. Those without an AWS classification are available on a commercial basis and characteristically mirror base

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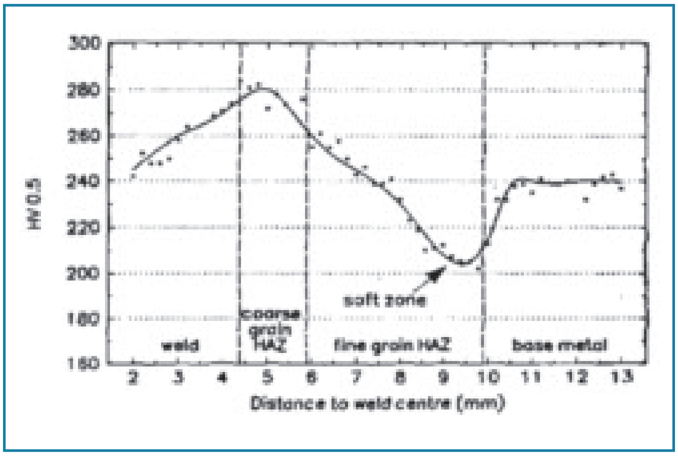

Fig. 1 — Representative microhardness across a typical P91 weldment (Ref. 10).

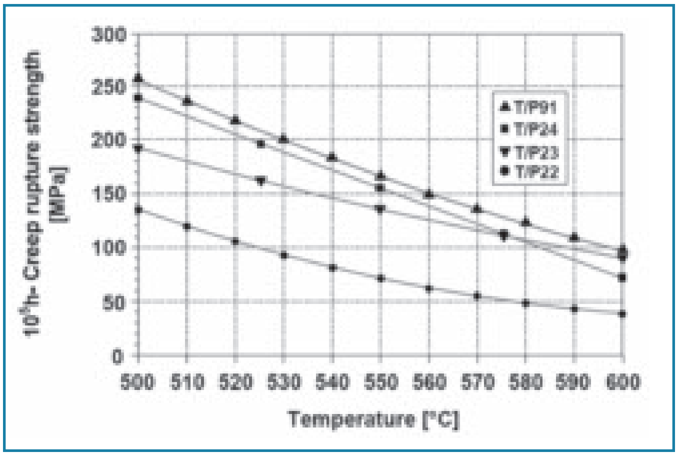

Fig. 2 — 10^3 h creep rupture values of T/P22, T/P23, T/P24, and T/P91 as a function of temperature. (Kimura/Prager, Refs. 13–15).

metal compositions. In most cases, AWS A5.01, *Filler Metal Procurement Guidelines*, provides the means to specify and obtain satisfactory material for materials with a classification and those that must be ordered with the "-G" classification.

Welding consumables for Type P/T 92, 122, 23, or 24 alloys do not have recognized specifications at this writing. Filler metals for these alloys are formulated to provide weld deposits similar in composition and performance as the base material. In lieu of a specification, manufacturers should be consulted for consumables that are available for these alloys. Typical compositions are shown in Table 6.

Crater cracking and other undesirable grain boundary phenomena can be minimized by ordering weld metal with low residual element content and a –15 coating as well as observing a Mn/S ratio greater than 50. These recommendations are offered to reduce the potential for problems that occur as a result of low melting constituents or other precipitates that influence grain boundary integrity.

Shielded metal arc welding (SMAW) and flux cored arc welding (FCAW) electrodes should undergo actual chemical and mechanical testing. A satisfactory chemical analysis does not guarantee acceptable mechanical properties, especially toughness. Mechanical testing, including tensile and impact tests, is recommended on a lot to lot, per size per diameter basis.

Testing and reporting only actual chemical analysis on a per size, per heat supplied basis for gas tungsten arc welding (GTAW) and submerged arc welding (SAW) bare wires is normally satisfactory.

Heating Operations

Proper application of heating operations is critical to success. Application and rigorous control of preheat, interpass, and postweld heat treatment operations are required to ensure that desired toughness and creep resistance are obtained. Control of preheat and interpass temperatures and even postbaking operations are necessary to avoid hydrogen retention/cracking problems in this extremely hardenable alloy family. Flame, furnace heating, electrical resistance, and electrical induction heating have been used successfully. Temperature monitoring and control of thermal gradients is extremely important. For these reasons, local flame heating is **not** recommended and should **not** be permitted. Changes in section thickness, chimney, and position effects must also be considered. If unknown, mock-ups should be used to establish heated band, soak times, and actual thermal gradients. (See Refs. 18, 22–26.)

Preheat

The literature suggests that 200°C (~400°F) is adequate for preheating P91 and P92 weldments. Fabricators typically

Table 1 — CSEF Base Material Typical Composition Ranges

	Base Material Specification					
	P91	P92	E911	T23	T24	P122
C	0.08–0.12	0.07–0.13	0.10–0.13	0.04–0.10	0.05–0.10	0.07–0.14
Mn	0.30–0.60	0.30–0.60	0.30–0.60	0.10–0.60	0.30–0.70	0.30–0.70
Si	0.20–0.50	<0.50	0.10–0.30	<0.50	0.15–0.45	<0.50
S	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
P	<0.020	<0.020	<0.020	<0.030	<0.020	<0.020
Cr	8.00–9.50	8.50–9.50	8.50–9.50	1.9–2.6	2.2–2.6	10.00–12.50
Ni	<0.40	<0.40	(<0.40)	—	—	<0.50
Cu	—	—	—	—	—	0.30–1.70
Mo	0.85–1.05	0.30–0.60	0.90–1.10	0.05–0.30	0.90–1.10	0.25–0.60
W	–	1.50–2.00	0.90–1.10	1.45–1.75	—	1.50–2.50
V	0.18–0.25	0.15–0.25	0.15–0.25	0.20–0.30	0.20–0.30	0.15–0.30
Nb	0.06–0.10	0.04–0.09	0.06–0.10	0.02–0.08	—	0.04–0.10
N	0.030–0.070	0.030–0.070	0.050–0.080	<0.030	<0.012	0.040–0.10
B	—	10–60 ppm	—	5–60 ppm	15–70 ppm	<0.005
Al	<0.040	<0.040	—	<0.030	<0.020	<0.040
Ti	—	—	—	—	0.05–0.10	—

Table 2 — Example Specification Designations (Refs. 1–7, 11, 12)

Alloy	Code/Jurisdiction	Specification or Designation
91	ASTM	A 213 T91 (seamless tubes)
		A 335 P91 (seamless pipes)
		A 387 Gr 91 (plates)
		A 182 / A336 F91 (forgings)
		A 217 C12A (castings)
		A 234 WP91
		A 369 FP91
	DIN/EN	EN 10222-2; 1.4903 (X10CrMoVNb 9-1)
	BS	1503 Gr 91
	AFNOR	NF A-49213/A-49219 Gr TU Z 10 CDVNb 09-01
	Japan	
911	DIN	1.4905 (X11CrMoWVNb 9 1 1)
		G-X12CrMoWVNbN 10 1 1 (cast)
92	ASTM	A 213 T92 (seamless tubes)
		A 335 P92 (seamless pipes)
		A 387 Gr 92 (plates)
		A 182 F92 (forgings)
		A 369 FP92 (forged & bored pipe)
	EN	X10CrWMoVNb 9-2
	Japan	Nf 616
		KA-STPA29 (pie)
		KA-SFVAF29 (forging)
		KA-STBA29 (tube)
122	Japan	HCM12A
		HCM12, KA-SUS410J2TB
T23	ASTM	A 213 T23 (seamless tubes)
	EN	
	Japan	HCM2S
		KA-STPA24J1 (pipe)
		KA-SFVAF22AJ1 (forging)
		KA-STBA24J1 (tube)
T24	Germany	7 CrMoVTiB 10-10

Table 3 — ASME Code Acceptance

Trade Name	Grade	Material (seamless)	Code Case	Issue Date
NF616	P92	9Cr-2W	2179	August 8, 1994
HCM12A	P122	12Cr-2W	2180	August 8, 1994
HCM2S	T23	2.25Cr-1.6W-V-Cb	2199	June 5, 1995
E911	E911	9Cr-1Mo-W-Cb	2327	May 2, 2000

Table 4 — Example Welding Consumables

	P91	P92*	E911*	T23*	T24*	P122*
SMAW	E9015-B9	X	X	X	X	X
GTAW	ER90S-B9	X		X	X	X
FCAW	E91T1-B9	X		X		
SAW	EB9	X		X		X

* Filler metals available to manufacturer or OEM specifications only.

Table 5 — Consumables Listed in ASME/AWS Specifications for Welding P91

Process	Specification, A/SFA	Classification
SMAW	5.5	E90XX-B9
SAW	5.23	EB9 + flux
GTAW	5.28	ER90S-B9
FCAW	5.29	E91T1-B9

aim for 200°–250°C (~400°–500°F), but will go as low as 121°C (250°F) for root and hot pass layers, thin-walled components, or where GTAW is utilized. Experience indicates that no elevated preheat is required for T23 or T24 weldments; however, some code bodies including ASME require preheat or postweld heat treatment (PWHT) for these alloys (Table 7).

Interpass

A typical maximum interpass temperature is 300°C (572°F); less is acceptable but no more than 370°C (700°F). The interpass maximum helps to prevent the possibility of hot cracking due to the silicon and niobium content of the weld metal. Field operations rarely have problems with interpass temperature on heavy sections (Refs. 9, 20).

Postweld 'Bake-Out'

A postweld "bake-out" may be of critical importance, especially for heavy sections or where flux-type processes are used. This involves maintaining the preheat/interpass temperature for an extended period of time subsequent to interruption or completion of the weld. When establishing the length of time necessary, factors that play a role include thickness of the material, length of time the weldment has been exposed to the heat regime, and the extent of "low hydrogen" practices used. Where proper preheat, consumables, and storage/handling are implemented, bake-outs can be minimized or even eliminated.

Interruption of Heating Cycle

Interruption of the heat cycle should be avoided if at all possible. The mass of the weldment must be considered. Increases in pipe wall thickness translate into increases in the restraint on the weld and the cooling rate from welding temperatures. Therefore, the weld area is subjected to high residual stresses at a time when it may have minimum section thickness (or strength) and be less ductile. If interruption is unavoidable, at least one fourth of the wall thickness should be deposited and preheat must be maintained until the groove is completed or a post-bake implemented.

Postweld Heat Treatment

Application of PWHT is absolutely necessary with Grade 91, 911, 92, and 122 weldments, regardless of diameter or thickness.

- PWHT is one of the most important factors in producing satisfactory weldments. The PWHT methodology and implementation must be verified to ensure that the weldments are actually receiving PWHT at the proper temperature. Additional thermocouples or qualification testing may be required.

Proper tempering of the martensitic microstructure is essential for obtaining

Table 6 — Typical Weld Metal Deposit Compositions and Mechanical Properties (Refs. 15, 18–25)

Weld Metal	T23	T24	P911	P92
C	0.04–0.10	0.05–0.09	0.08–0.13	0.08–0.13
Mn	0.10–1.00	0.30–0.80	0.50–1.20	0.40–1.00
P, max	0.020	0.01	0.02	0.020
S, max	0.015	0.01	0.01	0.015
Si, max	0.50	0.15–0.45	0.15–0.50	0.40
Cr	1.9–2.6	2.10–2.60	9.0–10.0	8.0–9.5
Mo	0.05–0.30	0.80–1.10	0.9–1.1	0.30–0.60
W	1.45–1.75	1.5–2.0	0.9–1.1	1.5–2.0
Ni, max	0.80	0.2	0.40–0.80	0.80 (0.6)
V	0.20–0.30	0.25	0.18–0.25	0.15–0.25
Nb	0.02–0.08	0.01	0.04–0.07	0.04–0.07
N, max	0.03	0.03	0.04–0.07	0.03–0.07
Al, max	0.03	0.05	0.02	0.02
B	0.0005–0.0060	0.005	0.005	0.001–0.005
Ti	—	0.03-0.09	—	—
Cu, max	0.15	—	—	0.15
Ult, ksi	74[1] (110–138, as-welded) [90–102; 1365 2 h]	85[2] (116–136, as-welded) [91–126; 1365F 2 h]	90[3] (107–116; 1400°F 2–4 h)	90[4] (107–116; 1400F 2–4 h)
Yield, ksi	58[1] (126, as-welded) [74–89; 1365 2 h]	65[2] (96–102, as-welded) [74–86; 1365F 2 h]	64[3] (91–102; 1400°F 2–4 h)	64[4] (91–102; 1400F 2–4 h)
Elong. %	20[1] (18–19, as-welded) [19; 1365 2 h]	20[2] (17–19, as-welded) [20–22; 1365F 2 h]	20[3] (16–22; 1400°F 2–4 h)	20[4] (16–22; 1400F 2–4 h)

1. Base Material; ASME Code Case 2199
2. Base Material; Vallourec-Mannessman
3. Base Material; ASME Code Case 2327
4. Base Material; ASME Code Case 2179.

Table 7 — Recommended Preheat Temperatures

Alloy	Max. Preheat, F (C)	Max. Interpass, F (C)
23	w/o or 340 (170)	660 (350)
24	400 (200)	
91		480 (250)
92		
122		

reasonable levels of toughness. In practice, this involves selecting both an appropriate temperature and time in accordance with governing code requirements.

Conclusions

Base material development and code acceptance has preceded effort and research in the areas of weldment properties and welding consumables for advanced chromium alloys. Although the base metals offer potentially superior properties, restoration of weld heat-affected zones (HAZ) or remediation of cold work/bending effects may not have been fully examined and need further investigation. From a welder's standpoint, the ability to weld the creep strength-enhanced ferritic steel is rather straightforward. For the majority of the CSEFs, proper preheat and PWHT are not optional, they are mandatory.

Lessons learned with P(T)91 weldments have truly demonstrated that these advanced chromium-molybdenum (CrMo) steels are quite different and require significantly more attention than the P(T)22 and lesser chromium-molybdenum alloys. The members of the American Welding Society's D10 Committee on Piping and Tubing decided to remove P(T)91 materials from their existing guideline publication on welding CrMo piping and tubing (D10.8) and prepare a new document (D10.21, pending) for it and the other advanced chrome-molys such as P(T) 92, etc. Greater attention to weld metal selection, preheating, and rigorous postweld heat treatment schedules were offered as some of the reasons that the CSEF alloys must be treated differently. However, the AWS document is pending resolution of technical items, due to lessons learned, now being deliberated in various ASME committees.◆

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