Metrode Products Limited

Technical Profiles

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P92 welding consumables for the power generation industry

Figure 1 A modern, high efficiency, fossil-fuelled power station designed to have minimum emissions and environmental impact - Black Point, Hong Kong

1 Introduction

One of the major challenges facing the power generation industry is to achieve targets for increased efficiency demanded by both mature economies and developing nations. Environmental regulations requiring reduced CO_2 emissions coupled with inevitable pressures on reliability, availability and maintainability are all major driving forces, Figure 1. Material developments, in particular advanced creep resisting steels for high temperature pressure components, continue to play a significant role in new projects as well as improvements to existing power plant as shown in Figure 2. The modified 9CrMo steel (T/P91) is now well established and is in use worldwide. Attention is now being directed to more advanced variants such as T/P92 and this steel has already been used in some projects and is being considered for many others, Table 1.

P92 is still a relatively new material and R&D continues particularly in the areas of welding, fabrication and creep performance of fabricated components in practical service. Metrode has been an active participant in the European collaborative project, COST 522 and 536. This is a project on advanced materials for modern power plants and Metrode has made considerable contributions to the development of welding consumables suitable for P92. The benefits of these steels can be exploited by either a reduction in wall thickness and weight for a given operating condition or by increasing design/operating temperatures with a consequent improvement in thermal efficiency. Such advantages can only be fully exploited if the steels can be welded with appropriate welding consumables to give joints which will not compromise the integrity and operating lifetime of the plant.

This technical profile presents the range of welding consumables designed specifically for the welding of P92 steels, together with information on specifications, welding processes and properties.

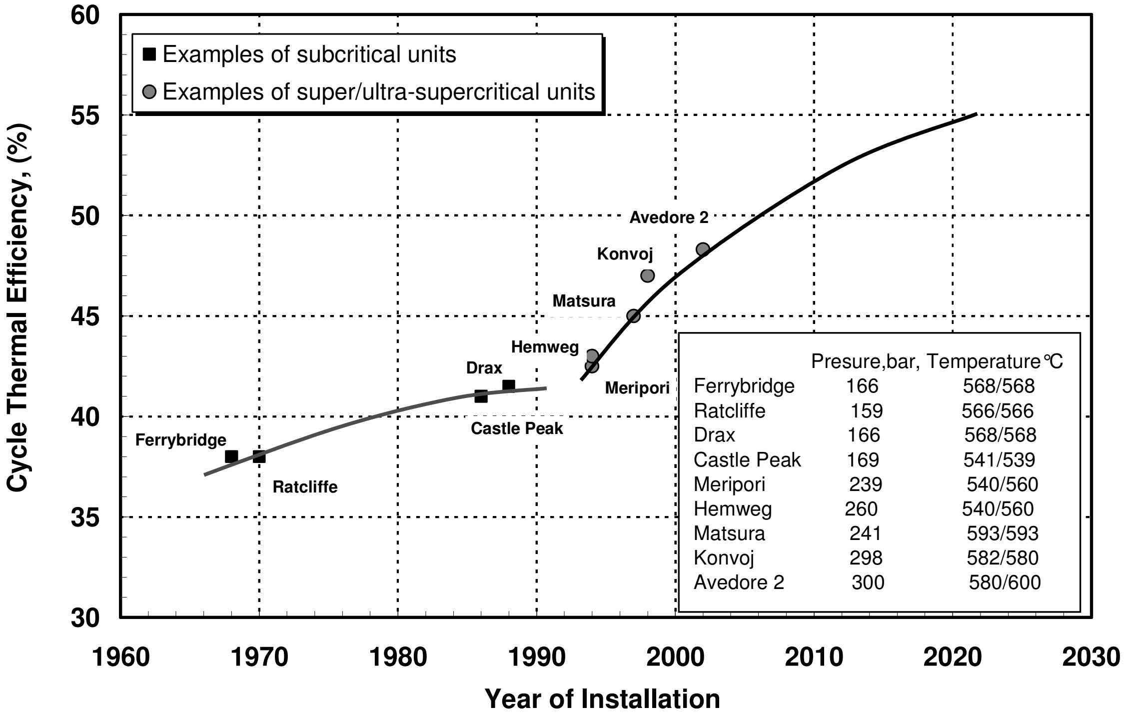


Figure 2 Evolution of power station thermal efficiency with time

Table 1 Selected installations that have used P92

Country	*Project*	*Size IDxWT mm (inch)*	*Component*	*Steam Temperature °C (°F)*	*Steam pressure bar (ksi)*	*Date*
Denmark	Vestraft Unit 3	240 x 39 (9.45 x 1.54)	Main steam pipe	560 (1040)	250 (3.6)	1996
Denmark	Nordjyllands ET	160 x 45 (6.30 x 1.77)	Header	582 (1080)	290 (4.2)	1996
Germany	Keil/GK	480 x 28 (18.9 x 1.1)	Header	545 (1015)	53 (0.8)	1997
Germany	Westfalen	159 x 27 (6.30 x 1.06)	Steam loop	650 (1200)	180 (2.6)	1998
Denmark	Avedøre 2/ Elkraft	400 x 25 (15.75 x 1.0) 490 x 30 (19.7 x 1.18)	Main steam pipes	580 (1076) 600 (1112)	300 (4.3)	1999 - 2001

2 Background to alloy design

P92 is a development of the now well established alloy P91. The P91, 9%Cr-1%Mo plus microalloying composition, is modified by reducing the molybdenum content to about 0.5% and adding about 1.7% tungsten plus a few parts per million of boron. Controlled microalloying in the form of niobium (columbium), vanadium and nitrogen is retained. This composition modification gives rise to very stable carbides and carbo-nitrides which improve long term creep strength. This steel is designed to operate at temperatures up to 625°C and it is claimed that high temperature rupture strengths are up to 30% greater than for P91. For example at 600°C (1112°F) the 100,000 hour creep rupture strength of P91 base material is about 95MPa (13.8ksi) whereas P92 is about 123MPa (17.8ksi).

Exploitation of P92 is relatively limited and further confidence and experience in the fabrication and use of the alloy still has to be developed. However, a number of installations were completed in the late 1990s and more are under construction or being planned. A selected list of installations which have used P92 is given in Table 1.

P92 was originally developed in Japan in the 1990s as NF616 and was subsequently incorporated into ASTM and the ASME code as Grade 92. Parallel developments in Europe resulted in a grade of steel designated E911*, in which the molybdenum is maintained at about 1% and a further 1% of tungsten is added.

** Note: Contact Metrode for further information and consumables for welding E911*

2.1 P92: Specifications and product forms

ASTM/ASME specified composition range is given in Table 2 and the various product forms, required properties and heat treatments are given in Table 3. The commonly used descriptors are given below and for the remainder of this document the material will be referred to as P92.

T92 (ASTM/ASME A213): **92 tube**
P92 (ASTM/ASME A335): **92 pipe**
F92 (ASTM/ASME A182): **92 forging**

Table 2 Specified composition for P92 steels

	C	*Mn*	*Si*	*S*	*P*	*Cr*	*Ni*	*Mo*	*W*	*Nb*	*V*	*N*	*Al*	*B*
min	0.07	0.30	-	-	-	8.50	-	0.30	1.50	0.04	0.15	0.030	-	0.001
max	0.13	0.60	0.50	0.010	0.020	9.50	0.40	0.60	2.00	0.09	0.25	0.070	0.04	0.006

Table 3 Heat treatment and mechanical property requirements for P92 steels

ASTM/ASME specifications	*Alloy*	*Heat treatment*		*Tensile strength MPa (ksi)*	*0.2% proof stress MPa (ksi)*	*Longitudinal elongation %*	*Hardness HB*
		Normalising temp, °C (°F)	*Tempering temp, °C (°F)*				
A213-A335	T/P92	≥1040 (1900)	≥730 (1350)	≥620 (90)	≥440 (64)	≥20	≤250
A182	F92	≥1040 (1900)	≥730 (1350)	≥620 (90)	≥440 (64)	≥20	≤269

3 Welding processes

The choice of welding process depends on a number of factors, including:

- The size and thickness of the components to be welded
- Shop fabrication or on-site installation/repair
- Availability of suitable equipment
- The necessary skilled staff
- Availability of suitable welding consumables
- Mechanical properties required, particularly toughness

Table 4 shows the arc welding process options for high temperature power plant fabrication.

Table 4 Welding process options for P92 steels for power plant

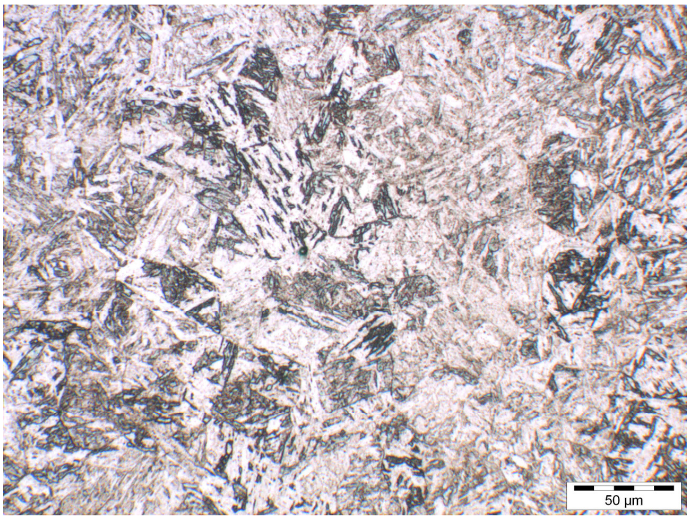
Component	*Joint type*	*Possible arc welding processes*
Boiler panels *(small bore tube)*	Site welding/repair	Manual TIG and MMA Manual/orbital TIG and MMA
Superheaters *Reheaters* *Economisers* *(small bore tube)*	Tube to tube	Fixed/orbital TIG Manual TIG and MMA
	Spacers and attachments	Manual TIG and MMA
	Site welding	Manual TIG and MMA Orbital TIG
Steam pipework and headers	Butt welds	TIG, MMA, FCAW and Sub Arc
	Stub to header butt welds	Manual TIG/MMA. FCAW, Mechanised TIG/MIG
	Site welding	Manual TIG and MMA Orbital TIG, FCAW
Pressure vessels *e.g. steam drums*	Butt welds	TIG, MMA, FCAW and Sub Arc
Valve chests	Butt welds	Mainly TIG, MMA, FCAW and possibly Sub Arc
Loop pipework	Butt welds	Mainly TIG, MMA and possibly Sub Arc
	Site welding	TIG, MMA, FCAW

4 P92 welding consumable specifications

At the time of writing there are no national or international standards for P92 welding consumables. It is expected that future standards will follow those already in existence for P91 and composition limits will be similar to those of the parent steel. Metrode limits are shown on the data sheet in Appendix 1.

5 Weld metal chemical composition

The P92 parent composition is essentially 0.1% carbon, 9% chromium, 0.5% molybdenum, 1.7% tungsten with controlled micro alloying in the form of vanadium, niobium (columbium), nitrogen and boron to give long term, high temperature creep strength. The composition is carefully balanced to give a fully martensitic microstructure with little or no retained delta ferrite. The microstructure is designed to be tempered martensite solid solution strengthened by Mo and W, with $M_{23}C_6$ carbides and V/Nb carbo-nitrides for high temperature creep strength.



The weld deposit compositions are designed to be as close as possible to the parent P92 steel consistent with achieving optimum properties, weldability and microstructures. Work on fully matching properties has shown that the toughness of weld metal, particularly those using flux shielded processes, is rather low. Weld metal toughness can be improved by raising the PWHT times and temperatures but it is important not to exceed the Ac_1 temperature. In order to achieve the optimum balance of creep properties and toughness, the weld metals differ slightly from the parent steel composition as follows:

Niobium	Work on both P91 and P92 consumables has shown that reducing the niobium towards the lower end of the parent alloy specification range has a beneficial effect on toughness. For this reason most weld deposits have niobium levels of 0.04 or 0.05%. One exception is P92 solid wire, which gives deposits with somewhat better inherent toughness, and has a typical Nb content of 0.06%.
Nickel	Is beneficial in improving toughness for two reasons, it lowers the Ac_1 temperature and this improves the response to tempering and it reduces the tendency for undesirable δ ferrite formation. However, excessive nickel (>1%), is detrimental in that it can reduce the Ac_1 below the PWHT temperature and so result in the formation of fresh untempered martensite. Excessive nickel may result in reduced creep properties. Nickel is therefore controlled at about the 0.5% level.
Cobalt	Ni+Mn content needs to be restricted because if the Ni+Mn content is excessive it can reduce the Ac_1 temperature. It has been found that Co can be substituted for Ni to provide more consistent toughness.

Manganese	Is generally controlled to a higher level than the parent plate to promote deoxidation and ensures a sound weld deposit. However it is important that the combination of manganese and nickel is not so high that the Ac_1 temperature is reduced and there is a risk of austenite reformation at the higher PWHT temperatures. It is possible that some future specifications may limit Mn+Ni to 1.5% or less as is the case with P91.
Silicon	Is an essential deoxidant and in conjunction with chromium it contributes, in a small way, to the alloy's oxidation resistance at higher steam temperatures. However lower levels of silicon benefit weld toughness. Weld deposits made with Metrode consumables generally have silicon levels in the range 0.2 to 0.3%.
Vanadium *Carbon* *Nitrogen*	All have a minor influence on toughness, unless incorrect balance leads to ferrite formation. Therefore values and ranges are essentially the same as the parent P92 alloy to maintain good creep performance.

6 Preheat, interpass temperature, post-heat and PWHT

Some references have already been made to PWHT, but this section clarifies the situation regarding various thermal operations in the light of practical considerations.

6.1 Preheat and interpass

The welding of P92 requires the use of preheat to avoid the risk of hydrogen cracking. Although the hardenability of P92 is higher than that of P22 (2¼Cr-1Mo) and slightly greater than that of P91, the preheat required to eliminate hydrogen cracking in the Y-groove test is lower than that required for P22 and only slightly higher than that required for P91 as shown in Figure 3. This may be explained by the lower transformation temperatures of both P92 and P91 combined with the beneficial influence of a little retained austenite within the preheat-interpass temperature range.

Except possibly for some TIG applications a preheat of 200°C (400°F) is standard irrespective of material thickness. For TIG welding, with a very low hydrogen potential, this can be relaxed to about 100-150°C (200-300°F). Maximum interpass temperature is usually restricted to about 300°C (575°F) to ensure that each weld bead substantially transforms to martensite which will be partially tempered by subsequent beads, see Figure 4 which shows the CCT diagram for P92.

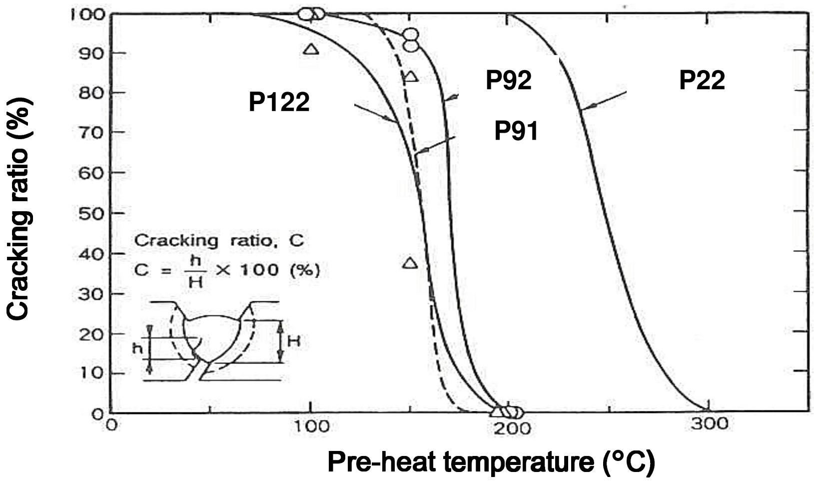


Figure 3 P92 results of Y-groove weld cracking tests showing the cracking ratio/preheat temperature relationship compared with P22, P91 and P122.

6.2 Post-heat

Post-heat is a term used to describe the practice of maintaining the preheat temperature, ~200°C (400°F) for 2-4 hours, or more for very thick fabrications, after completion of the joint. This procedure is designed to remove hydrogen by diffusion and allow the safe cooling of thick weldments down to ambient temperature. To be effective in P92, partial cool-out below the preheat temperature would be necessary to eliminate untransformed austenite before reheating for post-heat, because hydrogen is trapped in the austenite and diffuses from it far slower than from martensite.

Fortunately, unlike the earlier higher carbon alloy X20 (12CrMoV), post-heat is not considered to be necessary with P92 (and P91) and in practice, welds less than 50mm (2inch) thick can be cooled slowly to ambient temperature without problems. However, care should be taken to avoid mechanical and thermal shock until components have been subjected to PWHT. For sections above 50mm (2inch) the current recommendation is to cool no lower than 80°C (175°F).

Untempered weldments may be subject to stress corrosion cracking if exposed to damp conditions for any length of time.

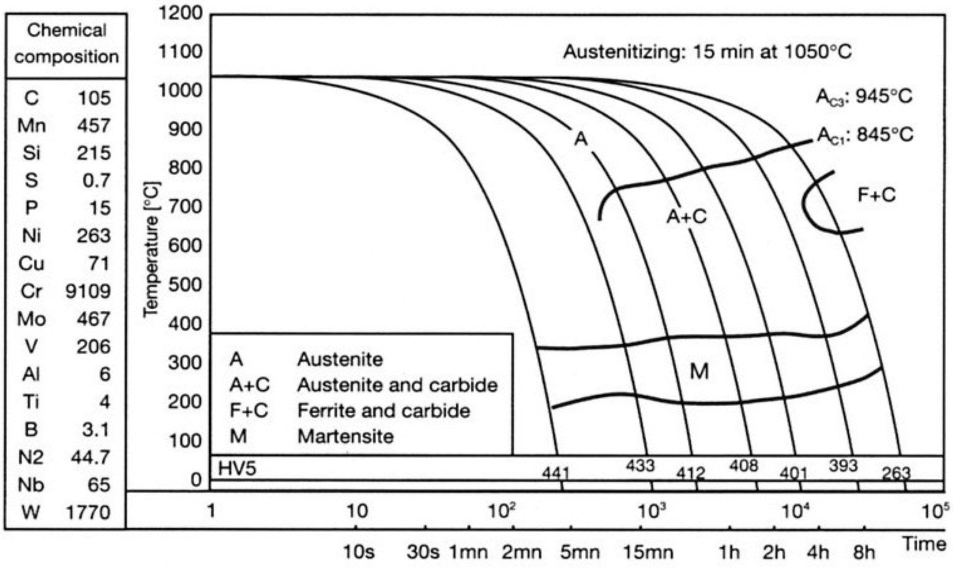


Figure 4 Continuous cooling transformation (CCT) diagram for P92

6.3 Post weld heat treatment (PWHT)

The hardness of as-transformed martensitic P92 weld metal and HAZ is similar to P91 at around 400-450HV so that PWHT is viewed as mandatory irrespective of thickness. On completion of welding it is important to cool down to below about 100°C (200°F) before full PWHT; this ensures that the martensite transformation is completed prior to PWHT and resultant tempering. The continuous cooling transformation (CCT) diagram given in Figure 4 shows that the martensite start (Ms) temperature lies between 300 and 400°C (575-750°F) and the martensite finish temperature (Mf) between 200 and 300°C (400-575°F), depending on cooling rate. The data shown relates to the parent alloy and tests on P92 weld metals have shown Mf temperatures as low as 105°C (220°F). But it is recommended that fabrications should be cooled to below ~100°C (~200°F) for a minimum of 2 hours before PWHT.

There are certain constraints placed on the selection of a suitable PWHT temperature. The minimum temperature should not be less than the 730°C (1350°F) given in the ASME code but in practice for weld metal tempering to take place within a reasonable period of time, the temperature needs to be significantly above this minimum eg. 760°C (1400°F). One base material manufacturer tempers base material in the range 750-780°C (1380-1450°F). Some specifications give a maximum temperature but in any case PWHT should not exceed the Ac_1 temperature since this will result in the formation of fresh austenite and therefore untempered martensite on subsequent cool-out. There is some uncertainty about the exact Ac_1 temperature for weld metal but it is likely to be less than the value of 845°C (1550°F) usually given for the parent steel. The value for weld metals containing significant amounts of manganese and nickel (both depress the Ac_1) could be lower than this. Measurements carried out on Metrode weld deposits (MMA, SAW and FCW) found Ac_1 temperatures in the range 790-810°C (1455-1490°F). This results in a rather narrow allowable PWHT temperature range and 760°C (1400°F) is the most frequently selected PWHT temperature.

The tempering response of P92 is such that a minimum of two hours PWHT is advisable and four hours is preferable for processes other than TIG. Shorter durations may be appropriate for thin wall tube welds (0.5 hours has been applied to P91) but it should be recognised that tempering (and hence hardness/toughness) is temperature-time dependent.

7 Metrode range of P92 welding consumables

Table 5 gives a summary of the Metrode welding consumables available for P92. A brief description of each of the consumables is given in this section along with representative welding parameters, where appropriate. Typical weld deposit compositions for each consumable type are given in Table 6, which also includes for comparison, the specified composition range for alloy P92.

Table 5 Metrode P92 welding consumables

Metrode brand name	*Welding process*	*Specification*
Chromet 92	MMA (SMAW)	There are as yet no specifications
9CrWV	TIG (GTAW)	There are as yet no specifications
Supercore F92	Flux Cored Wire (FCW)	There are as yet no specifications
9CrWV	Submerged Arc Wire (SAW)	There are as yet no specifications
LA491	Submerged Arc Flux	BS EN 760 *SA FB 2 55 AC*
LA492	Submerged Arc Flux	BS EN 760 *SA CS 1 55 DC*
9CrWV + LA491	SAW + Flux	There are as yet no specifications

Table 6 Typical P92 weld metal deposit compositions

Element, wt%	*C*	*Mn*	*Si*	*S*	*P*	*Cr*	*Ni*	*Mo*	*W*	*Nb*	*V*	*N*	*Al*	*B*
P92 alloy min	0.07	0.30	-	-	-	8.50	-	0.30	1.50	0.04	0.15	0.030	-	0.001
P92 alloy max	0.13	0.60	0.50	0.010	0.020	9.50	0.40	0.60	2.00	0.09	0.25	0.070	0.040	0.006
9CrWV wire[1]	0.12	0.71	0.29	0.008	0.009	9	0.5	0.5	1.7	0.06	0.20	0.05	<0.01	0.003
9CrWV TIG deposit	0.10	0.74	0.23	0.006	0.007	8.5	0.5	0.4	1.7	0.05	0.17	0.03	<0.01	0.002
Chromet 92 MMA deposit	0.11	0.60	0.25	0.008	0.008	9	0.6	0.5	1.7	0.05	0.20	0.05	<0.01	0.003
Supercore F92 FCW deposit[2]	0.11	0.8	0.29	0.006	0.017	9	0.5	0.5	1.7	0.04	0.20	0.04	<0.01	0.003
9CrWV/LA491 Sub Arc deposit[3]	0.09	0.76	0.29	0.005	0.010	8.5	0.5	0.4	1.7	0.04	0.16	0.04	0.015	0.001

Notes:
[1] solid TIG/SAW wire composition
[2] shielding gas: Ar + 20%CO_2
[3] flux: LA491

7.1 MMA (SMAW) – Chromet 92

MMA (SMAW) welding is still the most adaptable of the arc welding processes and therefore is still widely used for construction and fabrication work, particularly for on-site repair work. Typical areas of application are given in Table 4. Typical deposit analysis is given in Table 6 and mechanical properties are covered in Section 8.

P92 steels are fully martensitic under virtually all cooling conditions, and therefore as-welded hardness values are high (~450HV). This means that precautionary measures to avoid hydrogen cracking are particularly important. Preheat requirements are covered in Section 6.1, but in relation to MMA electrodes, coating moisture and hence hydrogen potential are critical. To ensure a low moisture content, as supplied, and after some atmospheric exposure, the electrodes are manufactured using a specially designed flux binder system.

Chromet 92 electrodes are supplied in hermetically sealed metal cans as defined by AWS A5.5 Paragraph 22.2. The as-packed moisture content of the electrodes is ≤0.15%, and the exposed moisture content is ≤0.40%, as per A5.5 (27°C/80°F-85%RH). In AWS terminology, these electrodes are classified with the H4R suffix.

Chromet 92 is a basic low hydrogen electrode with a moisture resistant coating designed to give low weld metal hydrogen levels. The electrode is manufactured on a fully matching alloy 92 core wire. The electrode operates on DC+ and on AC (70V min OCV) but DC+ is preferred for most applications. The electrode is all-positional, except vertical down, and is suitable for welding fixed pipework in the ASME 5G/6G positions.

7.2 TIG (GTAW) - 9CrWV

There is a need for a solid P92 welding wire suitable for TIG (GTAW) welding. This process is commonly used for root welding and for small diameter pipework. Some fabricators have invested in equipment for automatic orbital welding (auto TIG) particularly for welding thicker walled pipes. For these applications the wire is available in small diameters on spools.

7.2.1 9CrWV TIG wire analysis

Metrode's 9CrWV typical TIG wire analysis and deposit analysis are given in Table 6.

In national standards, for example P91, solid wire classification is based on wire analysis. As can be seen from Table 6 the deposit analysis will be slightly different from the certified wire composition. In the TIG process the wire is melted into the weld pool, rather than being transferred across an arc, and therefore there is very little loss of primary alloying elements; however, small losses of deoxidants, Mn, Si and C could occur. Typical loss of carbon content could be 0.01-0.02%.

7.2.2 Procedural aspects

TIG welding of P92 using 9CrWV is carried out using pure argon shielding gas with the electrode DC- polarity. As many applications are for the deposition of root runs, it is important to ensure protection of the weld bead under surface by the use a gas purge, which should be maintained for at least the first three runs. The most commonly used size for manual TIG root welding is 2.4mm (3/32in) diameter used in conjunction with a similar diameter 2% thoriated tungsten electrode. Using DC-, typical parameters would be about 90A, 12V; with a gas flow rate of about 10 l/min (20cu.ft/hr).

7.3 Flux cored wire (FCAW) – Supercore F92

Metrode flux cored wires for creep resisting CrMo steels are now well established and are being exploited because of their ease of use and the productivity benefits that can be achieved. These benefits are apparent in both shop and site welding applications, but the main interest is in the productivity advantages that can be achieved in the positional welding of thick walled pipes in the fixed ASME 5G/6G positions. Supercore F92 flux cored wire has been developed specifically for this type of application.

7.3.1 Procedural aspects

Ar-20%CO_2 mixed gas is the preferred shielding gas for use with Supercore F92. Improved toughness can be achieved, with slightly inferior arc characteristics, by using Ar-5%CO_2. For situations where Ar-20%CO_2 shielding gas is not readily available, Supercore F92 can also be welded with 100%CO_2 although slightly higher arc voltages, about 2 volts, are required. Typical gas flow rates are 20-25 l/min (40-50cu.ft/hr). A typical Supercore F92 deposit analysis made with Ar-20%CO_2 is given in Table 6.

Welding should be carried out on DC+ and it should be noted that the optimum welding conditions to be used depend on the welding position. Suggested welding conditions are given in Table 7.

Table 7 Welding parameters for Supercore F92

	Shielding gas	*Stickout (mm)*	*Current (A)*	*Voltage (V)*
Parameter range	Ar-20%CO_2	10 - 25	140 - 280	24 - 30
Down hand - typical		15-20	200	28
5G/6G - typical		15	150	25
Parameter range	100%CO_2	10 - 25	140 - 280	26 - 32
Down hand - typical		15-20	200	30
5G/6G - typical		15	150	27

7.4 Submerged arc (wire/flux combination) - 9CrWV + LA491 / LA492

For components where mechanised welding is practicable and joints can be manipulated into the flat position (or rotated), SAW is often the preferred and most productive welding process. The use of 2.4mm (3/32in) diameter 9CrWV wire in combination with Metrode LA492 flux is recommended but LA491 can also be used. The 9CrWV wire supplied on sub-arc coils is the same composition as that supplied for TIG welding.

The typical sub arc weld metal composition is given in Table 6. There is a modest influence of the flux but the chemical analysis is very close to that produced by the other Metrode P92 consumables. It can be seen that there is slight reduction in carbon content and a little silicon pick up from the flux.

7.4.1 Procedural aspects

9CrWV submerged arc wire is supplied in 2.4mm (3/32inch) diameter as standard. Typical welding parameters for 2.4mm (3/32in) diameter wire using DC+ with LA491 flux are given in Table 8.

Table 8 Welding parameters for P92 submerged arc

Flux	*Wire dia, mm (in)*	*Electrode extension, mm (in)*	*Current, A*	*Voltage, V*	*Travel speed mm/min (in/min)*
LA491 or LA492	2.4 (3/32)	20 – 25 (0.8-1.0)	350 – 500 (DC+)	28 - 32	400 – 500 (15-20)

The LA491 flux produces good slag release and good bead appearance. The LA491 flux is a fluoride basic agglomerated flux with a Basicity Index of approximately 2.7. The LA492 flux produces excellent slag release and cosmetic bead appearance. LA492 is a calcium silicate agglomerated flux with a Basicity Index of ~2.2. As with the submerged arc welding of any low alloy steel, hydrogen control is important (see Section 7.1 on MMA) which means that correct housekeeping for the flux is imperative. A flow chart outlining general flux handling procedures is shown in Figure 5. If flux is recycled, the machine hopper should be periodically topped-up with new flux to prevent the build-up of fines. Flux that has got damp or has been exposed to the atmosphere for 10 hours, or more, should be re-baked at 350-400°C (650-750°F) for 2 hours.

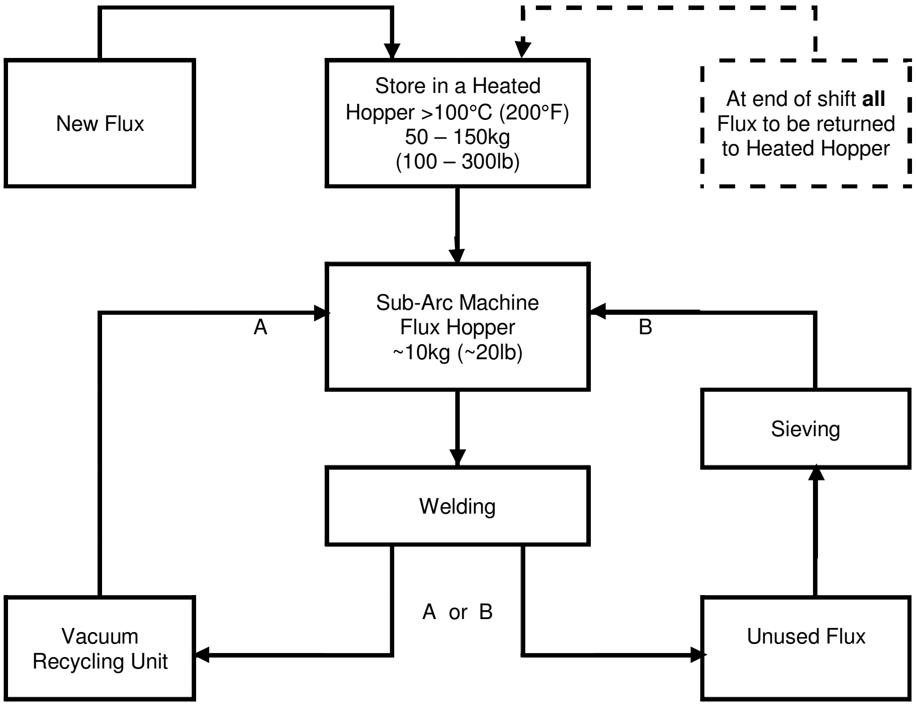


Figure 5 Control and storage of LA491 or LA492 submerged arc flux

8 Weld metal mechanical properties

8.1 Ambient temperature tensile properties

A high resistance to softening by PWHT (temper resistance) is an intrinsic feature of P92 weld metals. This is also a feature of the high temperature (supercritical) HAZ of weldments. Therefore all-weld metal tensile strengths will always overmatch P92 parent steel and cross weld tests typically fail in parent steel, beyond the hardened HAZ. Typical all-weld metal tensile properties at ambient temperature, for weld metals produced using Metrode P92 consumables are given in Table 9. The general similarity to P91 weld metals is shown in Figure 6 by the relationship between strength and hardness taken at the mid-section of weld slices.

In Table 9, data for TIG and MMA weld metals is given after PWHT at 760°C (1400°F) for both 2 and 4 hours, whereas that for FCW and submerged arc welding is for 4 hours. It can be seen that there is little effect on reducing tensile strength by extending the soaking time of PWHT and the strengths are very similar for all four processes. The only noticeable difference is the slightly better elongation shown by the TIG welds.

Table 9 Metrode P92 weld metal tensile properties at ambient and elevated temperatures

Consumable Type	*PWHT temp/time °C (°F)/hr*	*Test temperature °C (°F)*	*Tensile strength MPa (ksi)*	*0.2% proof strength MPa (ksi)*	*Elong. 4d%*	*R of A %*	*Mid-section hardness HV*
9CrWV TIG/GTAW	760 (1400)/2	20 (68)	766 (111)	650 (94)	25	70	256
	760 (1400)/4	20 (68)	751 (109)	645 (94)	29	70	259
		550 (1022)	455 (66)	374 (54)	25	82	-
		600 (1112)	387 (56)	282 (41)	21	85	-
		650 (1202)	312 (45)	200 (29)	28	89	-
Chromet 92 MMA/SMAW	760 (1400)/2	20 (68)	752 (109)	627 (91)	21	49	246
	760 (1400)/4	20 (68)	764 (111)	635 (92)	22	50	245
		550 (1022)	511 (74)	419 (61)	15	64	-
		600 (1112)	422 (61)	320 (46)	20	73	-
		650 (1202)	340 (49)	229 (33)	20	80	-
Supercore F92 FCAW	760 (1400)/4	20 (68)	774 (112)	649 (94)	21	50	252
		550 (1022)	471 (68)	385 (56)	19	68	-
		600 (1112)	400 (58)	294 (43)	25	77	-
		650 (1202)	308 (45)	194 (28)	27	81	-
		700 (1292)	215 (31)	125 (18)	26	86	-
9CrWV + LA491 Sub Arc	760 (1400)/4	20 (68)	715 (104)	584 (85)	24	62	241
9CrWV + L2N Sub Arc	760 (1400)/4	20 (68)	722 (105)	590 (86)	20	50	247

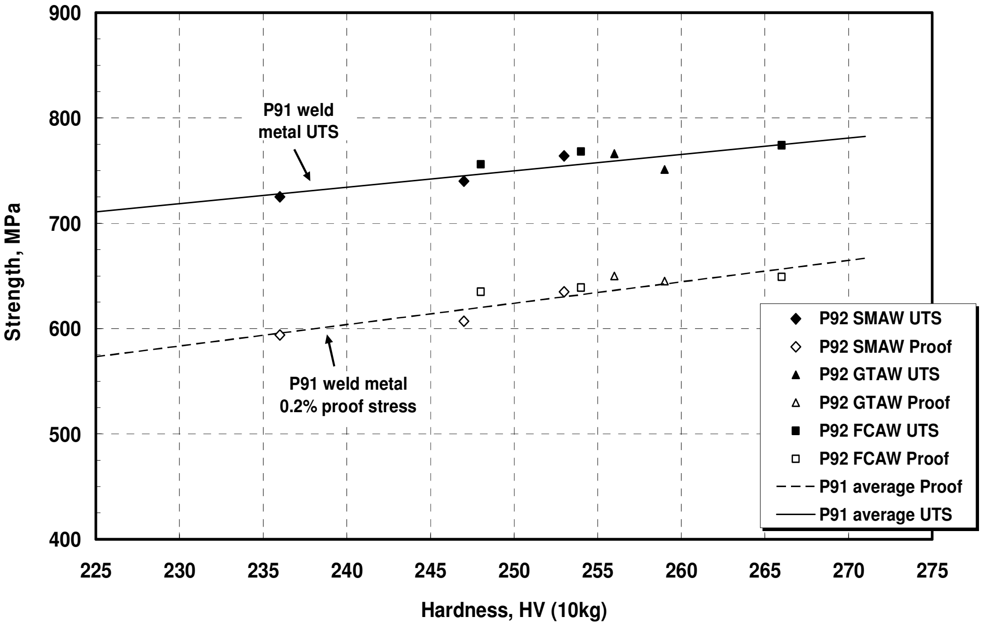


Figure 6 ***The relationship between strength (UTS and 0.2% proof) and hardness for P92. The data points are for P92 and for comparison the two lines show the same relationship for P91***

8.2 Elevated temperature tensile properties

For an alloy designed to be used at 500-625°C (930-1160°F), the high temperature properties of P92 weld metal are of considerable importance.

Hot tensile tests are not representative of long-term service conditions for P92 weld metal, because of the short term nature of the test but they do provide a convenient method for the comparison of weld metals with base material data generated under similar conditions. High temperature tensile data in the range 550-700°C (1020-1300°F) is given in Table 9 and is shown plotted in comparison with base material data in Figures 7 and 8. It can be seen that the ultimate tensile strengths and 0.2% proof strengths of Metrode weld metal, from all P92 consumables, are higher than those of the base material minimum over the temperature range of interest. However, there is some convergence of the results at temperatures approaching 700°C (1290°F) and at temperatures over 600°C (1112°F) the weld metal results are lower than the average base material 0.2% proof stress.

The all-weld metal hot tensile tests reported were carried out on specimens with a gauge diameter of only 5mm. There is some evidence that strength values on small gauge size specimens may be conservative when compared to results from specimens with larger gauge diameter. The results reported are from longitudinal all-weld metal tests, when tensile tests are carried out transversely on welded joints failure will occur in the base material at a UTS about 10-15% lower than the all-weld metal values reported here.

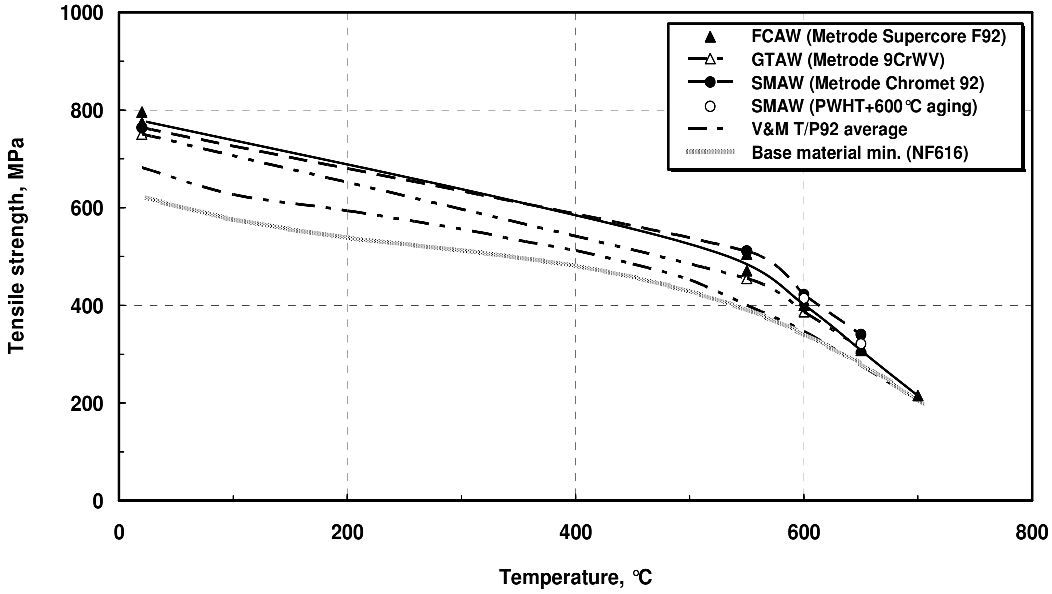


Figure 7 ***Elevated temperature UTS data for Metrode P92 weld metals compared with base material***

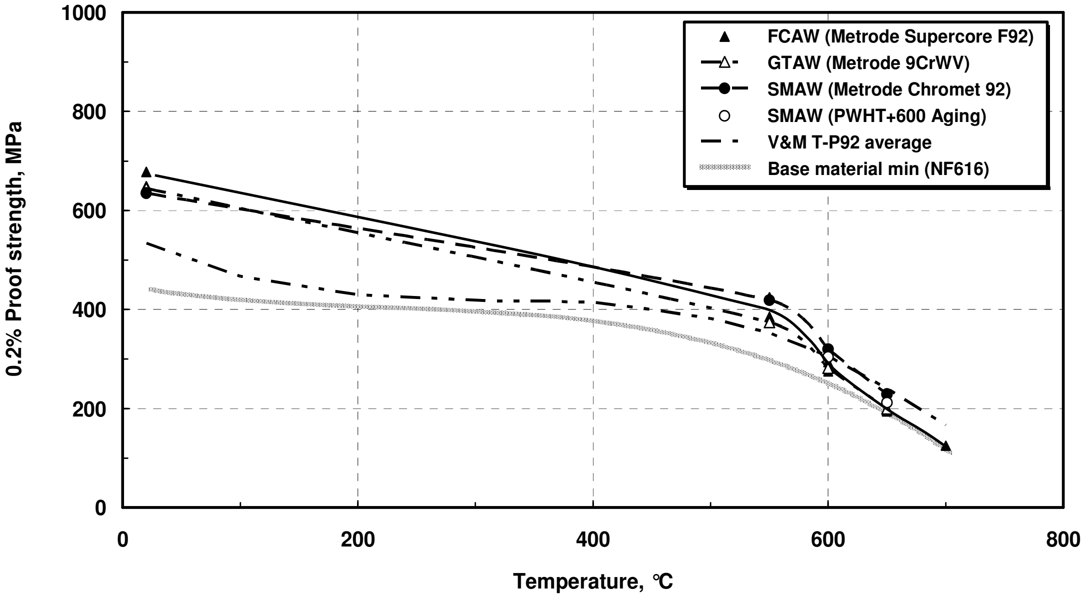


Figure 8 Elevated temperature 0.2% proof strength data for Metrode P92 weld metals compared with base material

8.3 Creep properties

Stress rupture tests on all-weld metal specimens show that properties are within the parent material envelope and generally at or above the parent material average. Figure 9 presents a Larson-Miller plot comparing representative TIG, MMA, FCW and SAW weld metal with parent material.

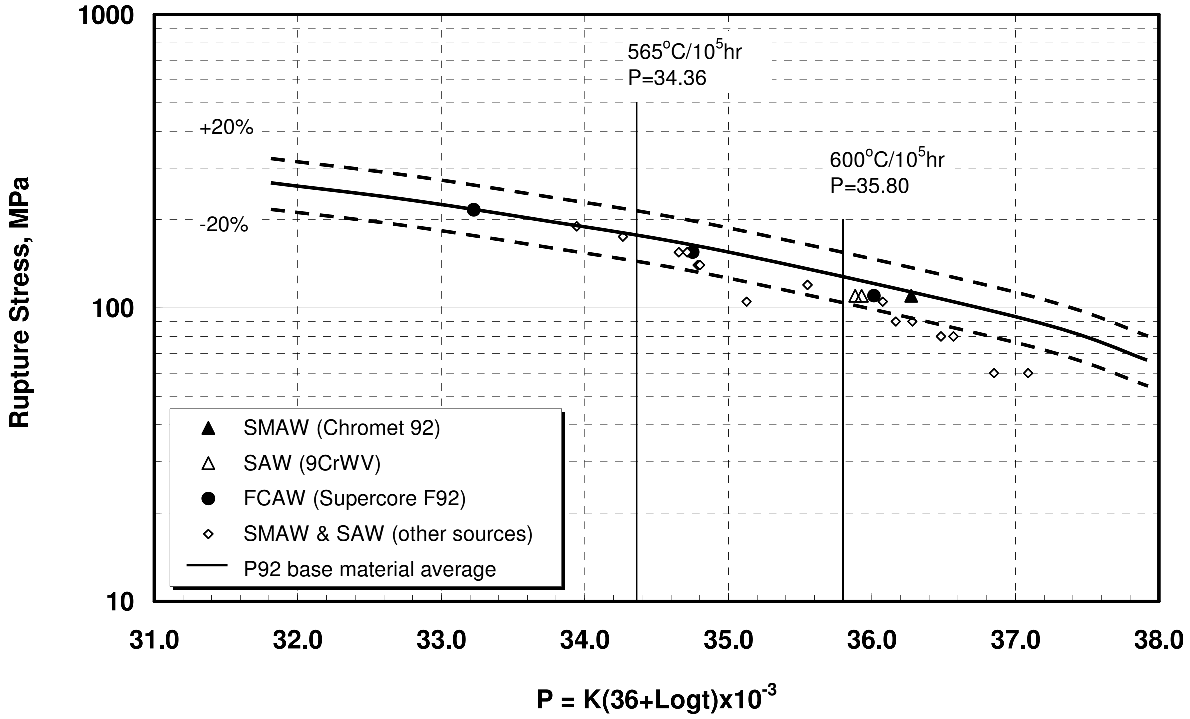


Figure 9 All weld metal stress rupture tests

8.4 Weld metal toughness

It can be argued that the toughness of P92 weld metal, which is designed to operate in the temperature range 500-625°C (930-1160°F) is an irrelevant consideration, since this is far above the temperature where there is any risk of fast brittle fracture. However there are situations where components might be pressurized or loaded structurally at ambient temperatures during testing or construction.

One example is hydrotesting, which depending on code requirements, may be carried out at a temperature between 0 and 30°C (32-86°F). ASME guidelines recommend a minimum hydrotest temperature of 20°C (68°F).

To cater for these situations, it is considered by some authorities that the weld metal should exceed a minimum toughness at +20°C (68°F). There are as yet no national specifications for P92 welding consumables but the non-mandatory appendix to A5.5-96 proposes that suitable test criteria can be agreed between purchaser and supplier if required. On the other hand, the European specification BS EN 1599:1997 requires a minimum average value of 47J (35ft-lbs) and a minimum single value of 38J (28ft-lbs) at +20°C (68°F) for P91 MMA weld metal. It is possible that future specified values for P92 will be of a similar magnitude but reference to Table 10 will show that such levels may be difficult to achieve with some consumables in combination with realistic PWHT temperatures and times. The PWHT temperatures and times given in the table are both greater than those used for P91 and reflect the higher temper resistance of P92. As was stated before, the PWHT temperature is limited by the Ac_1 temperature and the PWHT times reflect practical and economic considerations. In addition it may be difficult to justify the need for higher Charpy values than those specified in the same BS EN standard for X20 (12CrMoV), a well-established weld metal with a requirement of 34J (25ft-lbs) average and 22J (16ft-lbs) minimum single value at +20°C (68°F).

Table 10 Typical all-weld metal toughness values for Metrode P92 welding consumables

Welding Consumable	*Gas or Flux*	*PWHT °C (°F)/hr*	*Test temperature °C (°F)*	*Toughness [1]*	
				J (ft-lb)	*mm (inch)*
9CrWV GTAW/TIG	Pure Argon	760 (1400)/2	0 (32)	90 (66)	1.08 (0.043)
			20 (68)	168 (124)	2.06 (0.081)
		760 (1400)/4	0 (32)	182 (134)	2.13 (0.084)
			20 (68)	212 (156)	2.25 (0.088)
Chromet 92 SMAW/MMA	N/A	760 (1400)/2	20 (68)	50 (37)	0.80 (0.030)
		760 (1400)/4	0 (32)	37 (27)	0.61 (0.024)
			20 (68)	70 (52)	1.10 (0.043)
Supercore F92 FCAW	Argon–20%CO_2	760 (1400)/4	20 (68)	26 (19)	0.39 (0.015)
			70 (158)	60 (44)	0.94 (0.037)
		760 (1400)/8	20 (68)	29 (21)	0.41 (0.016)
9CrWV Sub Arc	LA491 Flux	760 (1400)/2	20 (68)	35 (26)	0.52 (0.020)
		760 (1400)/4	20 (68)	43 (32)	0.76 (0.030)

Note:

[1] There will inevitably be a certain degree of batch to batch variation in impact properties, but the values quoted above are representative of recent tests.

Although +20°C (68°F) is the test temperature usually specified for impact testing, minor variations in this test temperature can result in significant changes in impact values. This arises because the transition temperature for P92 MMA weld metal occurs in the temperature range 0-40°C (30-105°F).

The typical impact properties achieved for Metrode P92 consumables are shown in Table 10. It can be seen that the TIG and MMA consumables are capable of achieving 47J (35ft-lbs) average at +20°C (68°F), although the MMA deposits only just achieve this value. The FCAW and submerged arc welds fall short of this particular requirement.

An overview of the relationships found between Charpy absorbed energy and lateral expansion is shown in Figure 10. This log-log plot includes the results of tests at 0°C and 20°C and additional statistics from development data. Lateral expansion is not usually invoked as a notch ductility criterion for power plant materials or welds, but here it seems that when compared to the average trend for P91 weld metal, P92 welds may have a little more notch ductility.

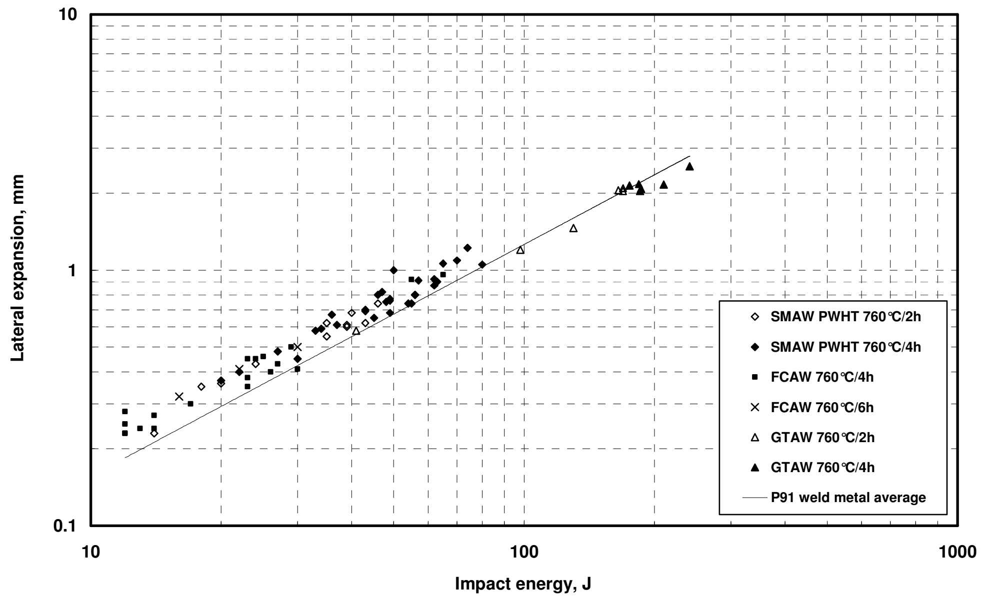


Figure 10 Relationship between Charpy impact energy and lateral expansion for P92 weld metals, compared with the average trend for P91 weld metals

There are four factors which have an influence on weld metal toughness: composition, PWHT, welding process and microstructural refinement. These are reviewed in more detail in the following sections.

The high temper resistance is also one factor which increases the difficulty of obtaining good toughness in P92 deposits with realistically short PWHT regimes or at lower temperatures within the permitted tempering range. The composition modifications for weld metals, already discussed in Section 5, are designed primarily to improve toughness by promoting a more rapid tempering response.

8.4.1 Composition

In general terms, those elements which are beneficial in improving creep performance are detrimental in terms of toughness, i.e. Nb, V, W and to a lesser extent N and Si. A composition balanced to restrict delta ferrite formation, also detrimental to toughness, and to give a fully martensitic microstructure helps to contribute to both optimum toughness and creep performance.

8.4.2 Post weld heat treatment

It is important not to set PWHT at too high a temperature because of the risk of austenite reformation and subsequent transformation to fresh untempered martensite, particularly with weld metals containing nickel and manganese. In practice for the P92 weld metals a PWHT temperature of 760°C (1400°F) should be used for a period of 2 to 4 hours, depending upon thickness and welding process. This should give satisfactory results and ensure that the hardness is below 300HV throughout the welded joint and typically 250HV in the weld metal.

8.4.3 Welding process

The choice of welding process can have a dramatic effect on the toughness of P92 weld metal because of the effects of fluxes and shielding gases. From Table 10 it can be seen that by far the highest toughness values are achieved with the TIG process which gives low weld metal oxygen contents typically less than 100-200ppm, The flux shielded processes such as MMA, FCAW and submerged arc, have oxygen contents in the range 400 to 800ppm and these higher oxygen contents result in significantly reduced toughness values.

8.4.4 *Microstructural refinement*

Although not reviewed in detail here, microstructural refinement, which is influenced by heat input, bead size and bead sequence can also influence the weld metal toughness. This is generally true of all weld metals which undergo austenite transformation during cooling and reheating in multipass welding.

It has been reported that thin weld beads result in superior weld metal refinement and hence produce better impact properties. For P91 MMA deposits, this was reported as resulting in improvements of up to 50% in impact values at +20°C (68°F). Tests carried out by Metrode have not shown such distinct differences in impact properties with variations in bead size/placement.

A series of tests carried out using Chromet 92 MMA electrodes were designed to look at extreme variations in weld procedure, ranging from stringer beads, AWS classification procedure and wide weaves with varying thickness of bead (1.5mm to 4mm thick). The average toughness at +20°C ranged from 63J to 77J even with these significant variations in procedure. The stringer bead approach produced the highest average toughness.

9 Welding P92 to dissimilar materials

P92 is logically applied where its combination of properties are most appropriate. It is therefore inevitable that in many cases, welded joints will be required between P92 and other dissimilar creep resisting steels. These may include P91 or lower alloy ferritic-bainitic types such as P22 (2¼Cr-1Mo) or one of the lean CrMoV creep-resistant alloys. Occasionally welded joints may be required between P92 and an austenitic stainless heat resisting steel such as type 316H.

9.1 P92 to P91

It is probable that any project using P92 will also have components made of P91 which will need to be welded to each other. Considering the similarities between the two materials it should be possible to obtain sound weld joints between P92 and P91 using either a P92 or P91 weld metal. Because of the relative costs and better availability of P91 consumables these would probably be the most widely used for dissimilar joints between P92 and P91. The PWHT could then be carried out as normal eg. 760°C.

9.2 P92 to P22 or other low alloy steels

Two specifications which offer relevant guidance for welding dissimilar creep resisting steels are AWS D10.8 and BS 2633. In AWS D10.8 the four possible options for weld metal composition are listed; these are (1) matching the lower alloy, 2CrMo, (2) matching the higher alloy, P92, (3) an intermediate composition, possibly 5CrMo or 9CrMo, (4) different to any of these, in practice a nickel base alloy. Preference is given to the lower alloy option, on the grounds that it should be sufficient to match the weaker of the two materials being joined. A similar approach is presented in BS 2633 except that the intermediate type 9CrMo is suggested for dissimilar joints involving P91, so would presumably also be considered for joints involving P92. Greater emphasis is also given, in BS 2633, to considering a nickel base weld metal, whereas in AWS D10.8 this approach is considered unnecessary except where stainless steel or nickel alloy base materials are involved. The use of nickel base also limits the scope for NDT methods.

It is also important to consider the most appropriate PWHT regime to reconcile the different optimum ranges for P92 730-790°C (1345-1455°F); P22 usually 680-720°C (1255-1330°F) and the weld metal. BS 2633 explains that the PWHT temperature is a compromise and in general is applied at the lowest temperature for the higher alloy material, although for optimum creep properties the highest temperature allowed for the lower alloy material should be used. Hence a temperature around 720-730°C (1330-1345°F), for 1-3 hours, has been reported for P91 to P22 joints. This is sufficient to temper the P92 HAZ without over-tempering the P22, and is also a satisfactory temperature for welds using either 2CrMo or 9CrMo consumables. However, it is too low for satisfactory tempering if the weld metal is a P91/P92 type, for which 746°C (1375°F) has been reported for P91 to P22 joints; >2 hours or ~½ hour for small bore pipe <10mm (<0.4in) wall thickness.

PWHT is of course necessary for stress relief and to give the weldment satisfactory ductility and toughness. However, there is a tendency for PWHT (and long term service at operating temperature) to promote carbon migration around fusion boundaries towards the higher chromium alloy. Consequently a weakened carbon-depleted zone develops in the adjacent material with lower chromium, which may be located in the weld metal or base material, depending on weld metal composition. If this process is not too severe, ultimate failure is expected in the lower alloy base material (eg P22 type IV zone). It seems that the weld metal composition preferred by different authorities is influenced by their assessment of these issues.

9.3 P92 to austenitic or higher alloy steels

There is no significant diversity of opinion with respect to these combinations. Based on many years experience with dissimilar welds between ferritic and austenitic stainless steels, nickel base consumables are used because they provide the required metallurgical compatibility, long term creep strength and ductility.

Although there is a steep composition gradient at the P92 fusion boundary, carbon migration here is much slower with nickel base alloys and PWHT can be carried out without problems. In joints with austenitic stainless steels, the effect of PWHT on the stainless steel should be considered. If this must be avoided, the P92 will need to be buttered and given a PWHT to temper the HAZ before the joint is filled, unless elimination of PWHT itself is acceptable.

The use of 309 consumables with moderate ferrite content is indicated in AWS D10.8 for welding ferritic/martensitic steels to austenitic stainless steels where the joint service temperature is below 315°C (600°F). Above this temperature, excessive carbon migration, microstructural instability and the high expansion coefficient relative to the low alloy material leads to unsatisfactory performance.

The appropriate Metrode consumables, which correspond to the generic 2CrMo, 5CrMo, 9CrMo, 309, and nickel base descriptions used in this section are listed in Table 11.

Table 11 Metrode consumables for dissimilar joints involving P92

Alloy Group	*Product*	*Process*	*AWS*	*BS EN*
2CrMo	Chromet 2	MMA	E9018-B3	E CrMo2B
	2CrMo	TIG/MIG	ER90S-G	CrMo2Si
	ER90S-B3		ER90S-B3	-
	SA2CrMo	Sub Arc	EB3	CrMo2
	LA436	Sub Arc Flux	-	SA AB 1 67 AC
	Cormet 2 [1]	FCW	E91T1-B3	-
5CrMo/9CrMo	Chromet 5	MMA	E8015-B6	E CrMo5 B
	5CrMo	TIG/MIG	ER80S-B6	CrMo5
	Cormet 5	FCW	E81T1-B6M	-
	Chromet 9	MMA	E8015-B8	E CrMo9 B
	9CrMo	TIG/MIG	ER80S-B8	CrMo9
	Cormet 9	FCW	E81T1-B8M	-
309 [2]	Thermet 309CF	MMA	E309-16	-
	309S94	TIG/MIG	ER309	309S94
	SSB	Sub Arc Flux	-	SA AF2 DC
Nickel base	Nimrod 182KS [3]	MMA	ENiCrFe-3	E Ni6182
	Nimrod AKS [4]	MMA	ENiCrFe-2	E Ni6092
	EPRI P87 [5]	MMA	-	-
	20.70.Nb	TIG/MIG	ERNiCr-3	S Ni6082
	NiCr	Sub Arc Flux	-	SA FB 2

Notes:

[1] Cormet 2 FCW has been shown to have creep performance exceeding that of P22 parent steels as a result of controlled micro alloying.

[2] These 309 types have controlled ferrite and moderate ferrite content and are usually preferred to the low carbon 309L types for elevated temperature service.

[3] Nimrod 182KS with a high manganese content is most frequently specified, particularly for welds between P92 and austenitic stainless steels.

[4] Nimrod AKS which has a lower manganese content and lower thermal expansion coefficient than Nimrod 182KS maybe preferred for welds between P92 and P22 or nickel base alloys.

[5] The EPRI P87 composition was specifically developed to provide a weld metal with less tendency for carbide precipitation at the fusion boundary, thermal expansion coefficient that better matches the base materials and that has high temperature properties comparable to the new 9CrMo alloys.

10 Further reading

Vallourec & Mannesmann Tubes "*The T92/P92 Book*", 2000.

Marshall A W and Zhang Z: COST 522 Final Report *"Development of Welding Consumables for Advanced Cr-Mo Creep Resistance Steels"*, Metrode Products Limited, September 2003.

Marshall A W , Zhang Z and Holloway G B: *"Welding consumables for P92 and T23 creep resistance steels";* Conference Proceedings: 5th International EPRI RRAC Conference on Welding & Repairing Technology for Power Plants, Point Clear, Alabama, USA, June 2002.

Metrode Products Limited: *"Welding consumables for P91 steels for the power generation Industry".*

Masuyama F and Yokoyama T: *"NF616 Fabrication Trials in comparison with HCM12A";* Conference Proceedings: The EPRI/National Power Conference - New Steels for Advanced Plant up to 620°C, edited by E Metcalfe, London, UK, May 1995.