PROPERTIES OF T/P92 STEEL WELD METALS FOR ULTRA SUPER CRTITICAL (USC) POWER PLANT

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Abstract

In order to achieve higher efficiencies and reduce emissions of environmentally damaging gases, new power generation technology requires high pressure and high temperature parameters. These have directly resulted in the introduction of ultra super critical (USC) plant and applications of a series of advanced Cr-Mo creep resistant steels. Among these newly developed ferritic steels, T/P92 has creep strength 25%-30% higher than the currently widely used modified 9%Cr steel T/P91 and has been specified as one of the major alloys for the construction of USC plant. The present paper summarises the important phase transformation characteristics and properties of matching filler metals for T/P92 steel and discusses factors that influence the performance of these weld metals.

Key words: Ultra Super Critical (USC), T/P92 steels, welding, weld metal, Creep

1．Introduction

Fossil fuels are currently the main means of obtaining electric power, about 40% of electricity we consume is still supplied by thermal power plants. However, the operation of conventional coal fired power plant releases more harmful gases, such as CO_2, NO_x and SO_x, than other power generation technology. Finding an effective solution to reduce the emissions of harmful gases has been the major challenge for the power generation industry as well as alloy material developers. Ultra Super Critical (USC) technology allows power plant to work at higher steam temperatures and pressures, hence significantly increasing the efficiency of thermal power plant, reducing fuel consumption and lowering emissions of harmful green house gases. When USC plant was introduced in the late 90s, the 9%Cr ferritic creep resistant alloy specified for the main steam pipe and other critical components was T/P91 steel. The T/P91 alloy allowed typical operating parameters up to 290bar pressure, main steam temperature 580°C and re-heat steam temperature 580°C [1]. As development has progressed, the new generation Cr-Mo alloys, T/P92, has replaced T/P91 alloy for USC unit. Compared to T/P91 steel, T/P92 steel has 25%-30% higher creep strength. The maximum design parameters of an USC unit have increased to 300bar/610°C/620°C -630°C [2-4]; the efficiency of USC plant is now approaching 50%.

In recent years, as one of the most important steels for USC plant, T/P92 steel has found more and more widespread use. To enable the full exploitation of T/P92 base material and increase its range of applications the development of matching consumables has been necessary. These matching consumables have been used for the fabrication and site erection of USC units using T/P92 steel. The present paper discusses the design philosophy of matching welding consumables; the relevant phase transformation temperatures, such as austenitisation temperatures during heating (Ac1), martensite transformation temperatures (Ms/Mf) during continuous cooling and effect of alloying elements on these temperatures. Based on the examination of these transformation temperatures, recommendations are made on welding parameters and postweld heat treatment (PWHT) procedures. Previous papers by the same authors provide additional background on the general tensile properties of T/P92 weld metals and also the effect of welding process on mechanical properties [5,6].

Using shielded metal arc welding (SMAW) and submerged arc welding (SAW) processes, investigations were carried out to evaluate the effect of welding and PWHT procedures on the ambient temperature toughness of T/P92 weld metals. According to the latest stress rupture results and field experience reports and newly revised base material creep data, further evaluation of creep properties of the weld metals is also made.

2．Design of matching welding consumables and alloy design

Presently, there are no national specifications for T/P92 steel welding consumables in either ASME/AWS or BS EN standards. Therefore, the design of the matching weld metal was based on the T/P92 base material composition and reference to the current international specifications for T/P91 welding consumables. The deposit composition is carefully balanced to obtain a fully martensitic microstructure with little or no δ ferrite, so that the best combination of high temperature creep properties and ambient toughness is achieved. Typical T/P92 weld metal analyses are give in Table 1.

Nb: work on both T/P91 and T/P92 consumables has shown that reducing the niobium towards the lower end of the parent alloy specification ranges has a beneficial effect on toughness. For this reason, most weld deposits have niobium levels of 0.04% or 0.05%. One exception is T/P92 solid wire, with typically 0.06%Nb. The GTAW process, with its inherently good toughness at ambient temperature, can tolerate a higher Nb level and when used with the submerged arc process, the deposit chemistry is lower in Nb than the original wire analysis.

Ni: Is beneficial in improving toughness for two reasons;**-** it lowers the Ac1 temperature and this improves the response to tempering and nickel also reduces the tendency for the formation of undesirable δ ferrite phase. However, excessive nickel (>1%) is detrimental in that it can reduce the Ac1 to below the PWHT temperature and so result in the formation of fresh untempered martensite on cooling to room temperature. Excessive nickel may result in reduced creep properties. Nickel is therefore controlled at about the 0.5% level.

Co: Test results have indicated that additions of cobalt play a similar role to nickel and helps achieve stable ambient impact toughness. Some reports also claim that Co, unlike Ni, has no effect on Ac1 temperature but this will be discussed in more detail in section 3.1 of this paper.

Mn: Is generally controlled to a higher level than in the patent alloy to promote sufficient deoxidation and ensure a sound weld deposit. However, it is important that the combination of manganese and nickel is not so high that the Ac1 temperature is reduced excessively, hence causing a risk of austenite reformation at higher PWHT temperatures. It is possible that some future specifications may limit to Ni+Mn to 1.5% or less as is the case with T/P91 welding consumable specifications.

Si: 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 generally have silicon levels in the range 0.2% to 0.3%.

Table 1. Typical T/P92 weld metal deposit compositions (wt%) [5]

Element	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
GTAW/SAW wire[a]	0.11	0.71	0.29	0.008	0.009	9.0	0.5	0.5	1.7	0.06	0.20	0.05	<0.01	0.003
GTAW deposit	0.10	0.70	0.23	0.006	0.007	9.0	0.5	0.5	1.7	0.05	0.17	0.04	<0.01	0.002
SMAW deposit[b]	0.11	0.60	0.25	0.008	0.008	9.0	0.6	0.5	1.7	0.05	0.20	0.05	<0.01	0.003
FCAW deposit[c]	0.11	0.80	0.29	0.006	0.017	9.0	0.5	0.5	1.7	0.04	0.20	0.04	<0.01	0.003
SAW deposit[d]	0.10	0.76	0.29	0.005	0.010	8.8	0.5	0.5	1.7	0.04	0.17	0.04	0.015	0.001

Notes:

[a]: Analysis of GTAW/SAW solid wires;
[b]: Analysis of undiluted weld deposit from SMAW electrode;
[c]: Analysis of undiluted weld deposit from FCAW; Shielding gas: Ar + 20%CO_2;
[d]: Analysis of undiluted weld deposit from SAW.

3. P92 weld metal phase transformation temperatures

Under controlled heating and cooling conditions, the relevant phase transformation temperatures of T/P92 base material are typically: reaustenitisation temperature (Ac1) = 840°C-845°C, martensite start temperature (Ms) = 400°C, martensite finish temperature (Mf) = 200°C [3,7]. For the optimum balance of creep properties and toughness, the weld metal compositions differ slightly from the parent steel. In order to provide correct guidance for appropriate welding procedures, it is necessary to understand the phase transformation characteristics of the deposited weld metals. Using a dilatometry technique, Ac1, Ms and Mf temperatures of undiluted SMAW, SAW and FCAW P92 weld deposits were measured. The specimens were re-austenitised at 1100°C with a heating rate of 2°C/min. The specimen was held at the austenitisation temperature for two minutes to ensure a uniform full austenitic microstructure before cooling. The Ms and Mf temperatures were assessed at two different 800°C-500°C cooling rates, 20°C/sec and 50°C/sec, which were selected to represent the range of typical weld cooling rates.

3.1. Weld metal Ac1 temperature and effect of alloying elements

The measurement results of Ac1 temperature are plotted in Figure 1. Data for both T/P91 and T/P92 are shown; the base material values are taken from published data [3, 8]. It can be seen that the typical Ac1 temperature of P92 weld metal with the range of compositions given in Table 1 is between 800°C – 815°C. In the cases of base steels, the Ac1 temperature of T/P92 is higher than that of T/P91. The measured Ac1 values of P92 weld metals followed the same trend. With a similar level of Ni+Mn, the Ac1 temperature of P92 weld deposit is 10°C to 15°C higher than that of P91 weld deposits. This agrees with the results from thermal dynamic calculations [9].

As the Ni+Mn content increases, the Ac1 temperature is reduced; at 1.5% Ni+Mn the Ac1 temperature is ~790°C. Beyond this level, the Ac1 temperature continues to drop and the relationship gradually becomes non-linear. By the time the Ni+Mn is increased to ~2% the Ac1 temperature is reduced to ~735°C in T/P92 weld deposits; this indicates the importance of strictly controlling the Ni+Mn content in the P92 weld metals. Many T/P91 weld metal specifications have a maximum Ni+Mn of 1.5% and if this is applied to T/P92 then with an Ac1 temperature of ~790°C and a safety margin of 15°C, it would dictate a maximum PWHT temperature of ~775°C. This is higher than the figure of 760°C normally specified as the maximum for T/P91 weld metals with up to 1.5% Ni+Mn.

Due to the strong effect of nickel on Ac1 temperature, cobalt is also added to some P92 weld metals to partially, or even completely replace Ni to achieve stable ambient toughness. In the current work, the effect of cobalt on the Ac1 temperature was also assessed. Despite there being some reports that believed that Co has negligible effect on the Ac1 temperature the results in Figure 2 clearly show that although not as dramatic as Ni and Mn, Co does reduce the Ac1 temperature of T/P92 weld metals. There is some other evidence that Co reduces the Ac1 temperature based on predictive work carried out by ORNL on a 12%Cr alloy. This work indicated that for a 1%Co addition in a 12%Cr alloy there would be a reduction in the Ac1 temperature of ~7°C [10].

When the data is plotted as shown in Figure 3, it can be seen that Co also reduces the Ac1 temperature. The strength of its effect is about 40% of that Ni and Mn have on the Ac1 temperature of T/P92 weld metals. These results indicate that when using Co to replace Ni in P92 weld metal, the addition of the element should also be controlled. The recommendation is that, for a Ac1>790°C, the overall content of Ni+Mn+0.4Co should be limited to 1.5% maximum. This level should be further controlled to less than 1.4% if a Ac1 temperature of

800°C is required.

3.2. Weld metal Ms and Mf temperatures

According to the data from base material manufacturers on continuous cooling after austenitisation at 1050°C-1070°C, the temperature for martensitic transformation (Ms) of T/P92 is ~400°C, and the martensite completion temperature (Mf) is about 200°C [3, 7]. Table 2 shows the results for both P91 and P92 weld metals from processes of SMAW, FCAW and SAW. For T/P92 weld metals the Ms temperatures were all in the range 370°C -390°C and the Mf temperatures 105°C -150°C; the Mf temperatures being 20°C -40°C lower at the faster cooling rate of 50°C/sec. Generally the Ms and Mf temperatures for P92 were lower than for P91 weld metal deposits.

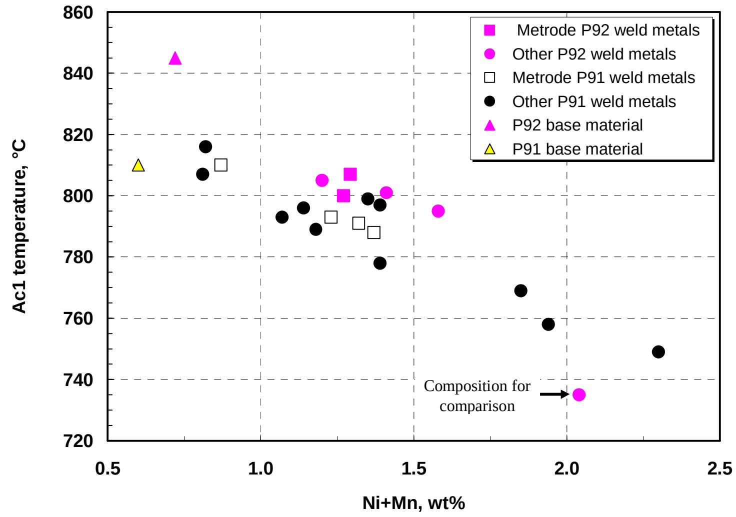


Figure 1. Ac1 temperatures of P92 and P91weld metals and the effect of Ni+Mn content

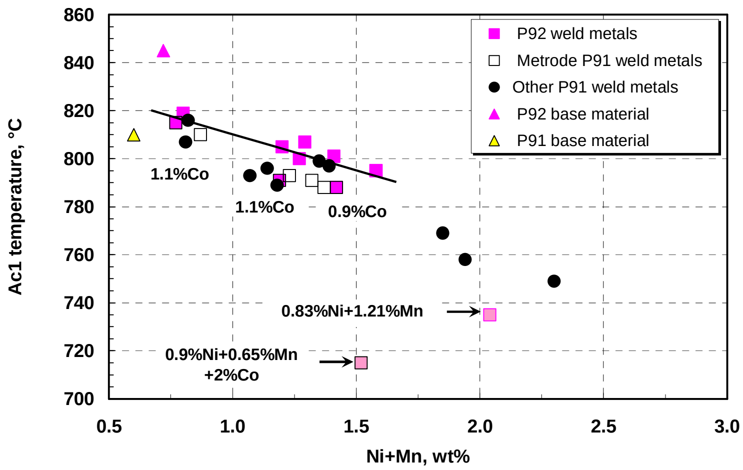


Figure 2. Effect of Ni and Mn on Ac1 temperature of P92 weld metals

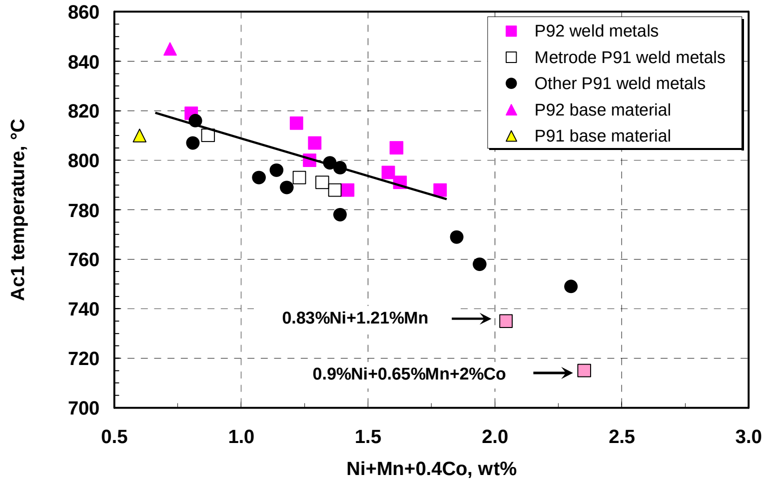


Figure 3. Effect of Ni ,Mn and Co on Ac1 temperature of P92 weld metals

Table 2. Martensitic transformation temperatures (Ms and Mf) of P91and P92weld metals

Alloy	Welding process	Cooling Rate = 20°C/s		Cooling Rate = 50°C/s	
		Ms, °C	Mf, °C	Ms, °C	Mf, °C
P91	SMAW	402	167	407	128
	SAW	419	200	426	136
	FCAW	381	157	385	107
P92	SMAW	383	151	382	117
	SAW	385	147	388	105
	FCAW	382	127	371	105

4. Selection of welding parameters

4.1 . Preheat and inter-pass temperatures

The welding of T/P92 steel 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) steel 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 4 [10]. 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 / inter-pass temperature range.

A preheat of 200°C is standard irrespective of material thickness except for some GTAW applications. The preheat can be relaxed to about 100°C -150°C for GTAW welding which has a very low diffusible hydrogen potential. Maximum inter-pass temperature is usually restricted to about 300°C to ensure that each weld bead substantially transforms to martensite which will be partially tempered by subsequent beads. An inter-pass temperature of 300°C keeps the weld metal within the Ms-Mf temperature range of 105-390°C and therefore ensures that at least substantial proportion of martensite transformation occurs for each weld bead that is deposited.

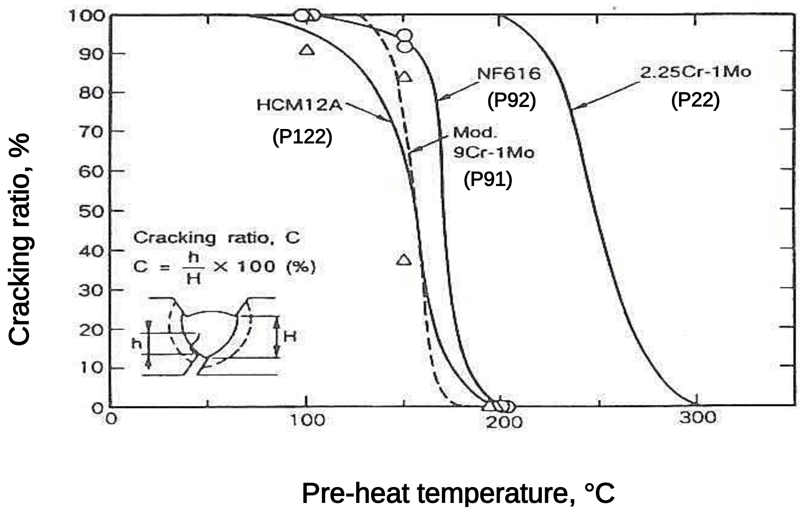


Figure 4. Y-groove test result of P92 weld metal and comparison with other Cr-Mo steels, including P91, P22 and P122 [11]

4.2．Control of the cooling after welding

As was seen in section 3.2, at a relatively fast cooling rate, the martensite finish temperature (Mf) of P92 weld metal can be as low as 105°C. This means that in order to ensure full martensite transformation the welded joint must be cooled to below 100°C before PWHT is carried out. If the weld metal is not allowed to fully transform before PWHT is conducted then any retained austenite will transform to untempered martensite on cooling to room temperature after PWHT.

Post-heat is a term used to describe the practice of maintaining the preheat temperature, ~200°C, 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 (<100°C) would be necessary before applying the post-heat 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 (or P91) and in practice, welds less than 50mm 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 the current recommendation is to cool no lower than 80°C [3].

5. Selection of PWHT procedure and the significance of Ac1 temperature

At normal welding cooling condition, the hardness of as-transformed martensitic T/P92 weld metal and coarse-grained HAZ is similar to T/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 before full PWHT; this ensures that the martensite transformation is completed prior to PWHT and resultant tempering (see section 4.2).

There are certain constraints placed on the selection of a suitable PWHT temperature. The minimum temperature should not be less than the 730°C 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. When Ni+Mn is controlled to <1.5%, as indicated in Figure 1, the Ac1 of P92 weld metal is typically in the range of 800°C-815°C. Therefore the maximum allowed PWHT temperature is slightly higher than that of P91 weld. One base material manufacturer tempers base material in the range 750-780°C [3]. Some specifications give a maximum temperature but in any case PWHT should not exceed the Ac1 temperature since this will result in the formation of fresh austenite and therefore untempered martensite on subsequent cool-out. The data presented in section 3.1 indicates that ~775°C is the suggested maximum PWHT temperature for a weld with Ni+Mn = 1.5%. This results in a rather narrow allowable PWHT temperature range and 760°C is the most frequently selected PWHT temperature; although as will be shown in section 6 temperatures up to 780°C have been used and good impact properties achieved, which would indicate that the Ac1 temperature had not been exceeded. In practice, there have been reports that, when welding thick-section P92 main steam pipes, major boiler fabricators have been using PWHT at 770°C and holding for 6-8 hours, which produced satisfactory weld metal properties.

6. Weld metal toughness

It can be argued that the ambient temperature toughness of P92 weld metal, which is designed to operate in the temperature range 500°C-625°C, 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 pressurised or loaded structurally at ambient temperatures during testing or construction. One example is hydro-testing, which depending on code requirements, may be carried out at a temperature between 0°C and +30°C. ASME guidelines recommend a minimum hydro-test temperature of +20°C.

To cater for these situations, it is considered by some authorities that the weld metal should exceed a minimum toughness at +20°C. There are as yet no national specifications for T/P92 welding consumables but the non-mandatory appendix to A5.5 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 and a minimum single value of 38J at +20°C for T/P91 SMAW weld metal. It is possible that future specified values for T/P92 will be of a similar magnitude but reference to data published by the same authors [5] 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 report [5] are both greater than those used for P91 and reflect the higher tempering resistance of P92 weld metal. As was stated before, the PWHT temperature is limited by the Ac1 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 average and 22J minimum single value at +20°C.

6.1. Effect of welding procedure and PWHT on weld metal toughness

Although T/P92 consumables are not covered by AWS specifications, the basis of the welding procedures used in AWS A5.5 / A5.23 have been used to assess the effect of welding procedure and PWHT on the impact properties of both MMA and SAW deposits. Four welds were made with 3.2mm diameter SMAW electrodes (identified as welds A to D) and were all PWHT at 760°C for 5 hours, the details of the welds are given in Table 3. There were also three submerged are welds made with 2.4mm diameter wire using different welding parameters (identified as welds E to G) which were subjected to different PWHT, the details of the welds are given in Table 4.

From the data presented in Table 3, it can be seen that there is some variation in the toughness achieved with the different welding procedures although not as much as might be expected. The AWS type procedure, weld A, and the thick full width weave, weld C, gave the lowest toughness. The AWS procedure is often expected to achieve the best toughness because the Charpy specimen is notched in the weld bead overlap region where maximum refinement is expected. In this instance the AWS procedure (weld A) is probably not achieving as consistent weld bead refinement as procedures B and D, because in procedure D the very thin layers allow almost complete and uniform refinement of the previous weld beads and in weld B although the layer thickness is greater than weld A (2.1mm compared to 1.8mm) there are more beads and probably greater overall refinement. In reality the stringer beads used in weld B are easier to control than the thin layers used in weld D so from a practical viewpoint the stringer bead approach is far easier to use.

To provide an indication of the effect of PWHT on the toughness of SMAW weld metal. Two welds were made and PWHT at 760°C for 2 hours and 5 hours. The average Charpy energy at +20°C was 69J after 2 hours and 93J after 5 hours. In summary, it should be pointed out that all welds tested produced satisfactory toughness much above the requirements for T/P91 SMAW weld metal in BS EN 1599. This indicates the sophistication of the latest design of P92 SMAW electrode.

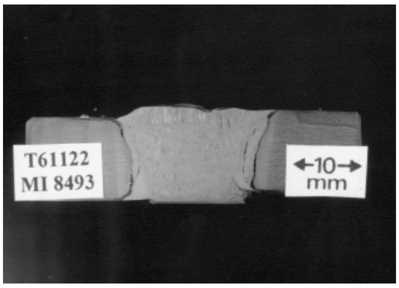
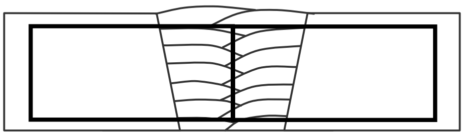
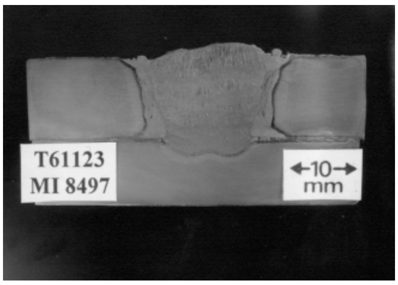
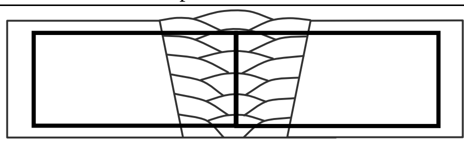
The data on the SAW weld metal in Table 4 does not show quite such a clear trend. The lowest heat input parameter, weld E, gave the lowest toughness; and the highest heat input (weld G) was not significantly different to the intermediate heat input joint (weld F). With the lowest heat input (weld E) although the weld metal was tempered, indicated by the lower hardness, the PWHT time and temperature had minimal effect on the toughness. It is difficult to draw definite conclusions from this data but generally the higher temperature and longer time do provide additional tempering, lowering the hardness; and in most cases also improving the toughness

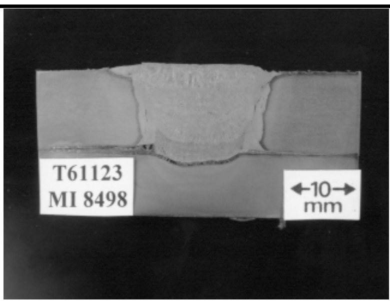
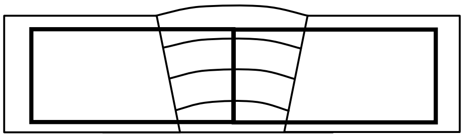
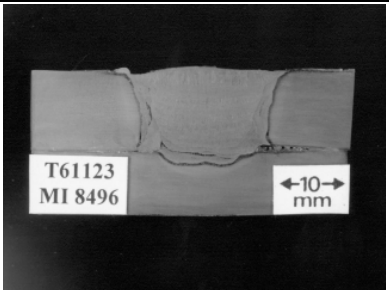
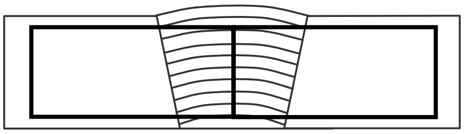
7. Weld metal creep properties and interpretation of test data

7.1. All weld metal creep properties and weld joint creep rupture

For an alloy designed to be used at 500-625°C, the high temperature properties of T/P92 weld metal are of considerable importance. Stress rupture tests on all-weld metal were carried out at temperatures 600°C -650°C. Figure 5 shows the creep properties of P92 weld deposit and base material (for the convenience of comparison with base material, the constant C=36 was used in the Larson-Miller index). The weld deposit data are from specimens from representative GTAW, SMAW, FCAW and SAW processes. Results indicate that weld metal properties are within the parent material average envelope (±20% mean) and generally at or above the parent material average.

Table 3. Effect of welding parameters and weld bead arrangement on toughness of P92 SMAW weld metal

Weld macro	Welding parameters and weld bead arrangement	Charpy V impact energy and lateral expansion[a]	
		20°C	0°C
	 Weld A : Average weave, two passes per layer Total 14 passes Average layer thickness ~1.8mm Heat input 1.2kJ/mm	64 (58) J 0.99(0.74)mm	33 (28) J 0.60(0.50) mm
	 Weld B : Small weave, three passes per layer Total 18passes Average layer thickness ~2.1mm Heat input 1.0kJ/mm	77 (66) J 1.19(1.04)mm	48 (41) J 0.75(0.70) mm

 	 Weld C： Full width weave, 1 pass per layer Total 4 passes Average layer thickness ~3.2mm Heat input 2.0kJ/mm	63 (56) J 1.02(0.93)mm	43 (36) J 0.68(0.58) mm
 	 Weld D： Full width weave, 1 pass per layer Total 10 passes Average layer thickness ~1.2mm Heat input 1.3kJ/mm	71 (64) J 1.10(1.07)mm	46 (42) J 0.75(0.67) mm

Note:
[a]: Average Charpy energy and lateral expansion are given with the minimum value in brackets.

In reality for a 9%Cr creep resistant alloy, the creep failure of a welded joint will normally occur in the HAZ of the base material (type IV zone). Figure 6 shows data for all-weld metal tests and for transverse weld joint tests in T/P92. It can be seen that as tests become more representative of longer term tests the transverse welded joint rupture stresses start to fall below both base material and weld metal values. The same trend has been demonstrated with weld joints of other 9%Cr Cr-Mo steels, such as P91 and E911; on a Larson-Miller plot if the weld metal data falls within a band of ±20% of the base material average then the weld metal will be strong enough that failure will occur in the type IV in the HAZ (Figure 7). At lower Larson-Miller parameters the transverse joints fail at the fusion line but as the tests become longer and more representative of service conditions the failure starts to occur in the type IV zone. As failure occurs in the type IV zone, the data crosses the base material average -20% line. This provides a good indication that as long as the weld metal strength falls within a band ±20% of the average base material creep strength then it will be acceptable.

Table 4. Effect of welding parameters, weld bead arrangement and PWHT on impact toughness and hardness of P92 SAW weld metal

Welding parameters[a]	PWHT and tempering parameters{b} Charpy V impact energy at +20°C, average (minimum) and average hardness			
	760°C/4h (P=21.29)	770°C/4h (P=21.49)	780°C/4h (P=21.70)	760°C/10h (P=21.70)
Weld E：21 passes Heat input=1.1kJ/mm[a] Average layer thickness ~2.9mm;	31（27）J 243HV	26（22）J 235HV	28（24）J 238HV	34（29）J 222HV
Weld E：17 passes Heat input=1.8kJ/mm[a] Average layer thickness ~2.5mm;	76（69）J 241HV	52（42）J 238HV	74（62）J 233HV	62（56）J 219HV
Weld G：11 passes Heat input=2.5kJ/mm[a] Average layer thickness ~3.6mm;	51（34）J 231HV	52（46）J 241HV	86（71）J 228HV	73（49）J 222HV

Note：
[a]: Weld E: Current 350A; voltage 30V; travel speed 600mm/min;
Weld F: Current 450A; voltage 30V; travel speed 450mm/min;

Weld G: Current 550A; voltage 30V; travel speed 390mm/min;

[b]: P is the Larson-Miller Parameter, $P = K(20 + \log t)10^{-3}$ where K = temperature in K and t = time in hours.

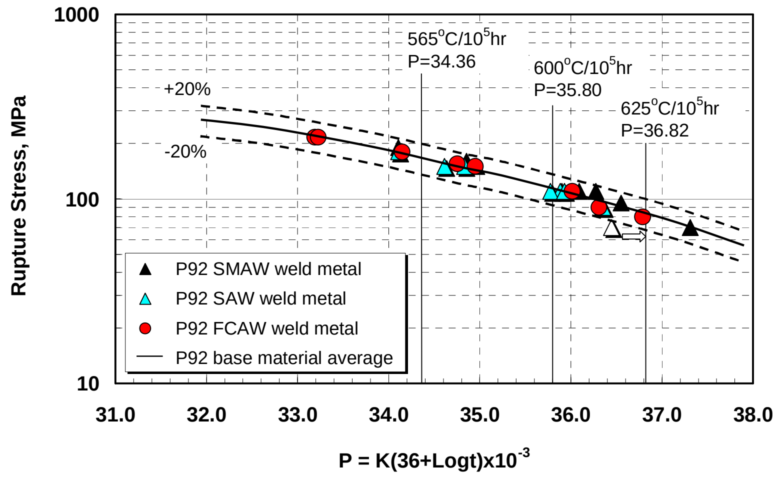


Figure 5. Larson-Miller plot of P92 base metal and weld metals with C=36

7.2. Interpretation and understanding of creep data of P92 steel and weld metal

Because of its superior creep properties, the application of T/P92 steel has made it possible for USC units to operate at temperatures up to 600°C-630°C and pressures of 300bar. In the past 3-4 years, with the building of a considerable number of 1000MW USC units, the usage of T/P92 steel has increased substantially. However, it should be pointed out that, as a newly developed alloy, exploitation of T/P92 steel is still relatively limited. Further confidence and experience in the alloy, particularly its performance after long term operation at high

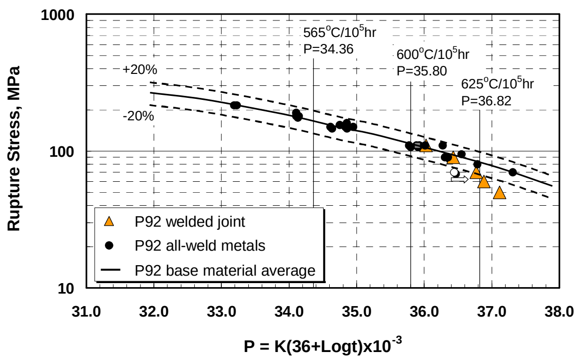


Figure 6 – P92 transverse joint tests in comparison with all-weld metal and base material (C=36）

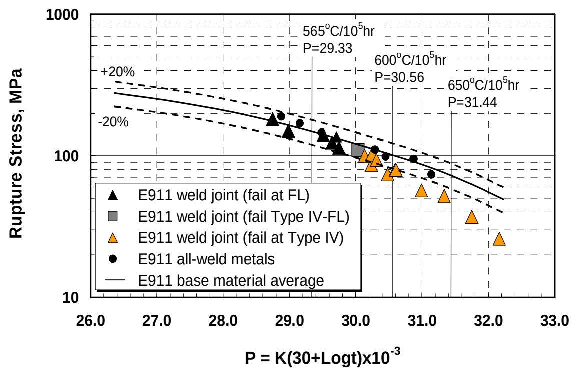


Figure 7. E911 transverse joint tests in comparison with all-weld metal and base material (C=30)

temperatures and pressures has yet to be established; therefore, appropriate interpretation of currently available data is essential for the successful application of this important alloy. Over the years since T/P92 was first introduced in mid 1990s [17], the allowable stresses and creep rupture strength have been re-evaluated as new test data becomes available. For example, in 1999 the European Creep Collaborative Commission (ECCC) published a data sheet on P92 which showed a 100,000 hour creep rupture stress at 600°C of 123MPa [18], a reduction of 8MPa from the original 131MPa. In 2005 a new data sheet was published for P92 by the ECCC [19] which further modified the 100,000 hour creep rupture stress at 600°C downwards to 113MPa. This is a total reduction of ~14% from the originally extrapolation value. The ASME code case 2179-6 (2006) [20] has also modified the allowable design stresses for P92 downwards compared to the 1994 code case. For example, the 593°C allowable design stress was reduced from 94MPa to 83MPa.

A convenient means of displaying the creep data is to use a Larson-Miller plot. This allows tests carried out at different temperatures to be displayed on the same plot, providing the appropriate constant is used.

In evaluating P92 creep data, for quite some time, constant C = 32.6-36 have been commonly used [3, 7, 11, 21]. Based on recent test results and actual operation experience of T/P92 and T/P122 steels, it has been mentioned that with a Larson-Miller constant of 36, the longer term extrapolations may over estimate the potential creep performance of the alloy. Figure 8 illustrates the estimated duration to soften as the increase of C for creep resistant alloys [13,14]. Examination believes that the creep softening rates of T/P92 and T/P122 steels are very likely faster than the estimation using C=30-36. A constant less than 30 has therefore been recommended. The two consecutive revisions of the creep strength to T/P92 alloy in the past 8 years reflected the timely correction to the earlier over-estimated performance. In fact, in the current COST 522 and 536 projects, a Larson-Miller constant of C=25 has been used to evaluate the data for the next generation 9-15%Cr ferritic creep resistant alloys, such as C(F)B2 alloy [22]. Without doubt, this development improved our understanding of the performance of this new advanced alloy and produced more realistic creep strength predictions. However, the price paid is that some recently built USC power plants now have to be operated at reduced parameters than they were originally designed for; and some other units under fabrication required modifications to their designs, e.g. increase the thickness of some critical components to suit the specified operating temperature and pressure.

Using a constant of 30 and 25, the base material and weld metal creep data are re-plotted, Figure 9 and 10. When compared to Figure 5, it can be seen that when C=25, which would provide a pessimistic evaluation of the data (Figure 10), the weld metal data tends to fall in the lower band of the base material range but still above -20% line whereas with C=36 (Figure 5) the weld metal data falls on or above the base material average line. This helps provide some reassurance that even when using a pessimistic extrapolation the weld metal still provides satisfactory creep performance compared to the base material.

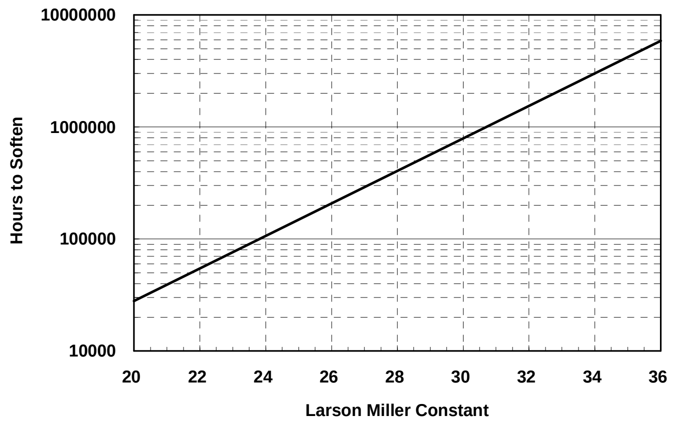


Figure 8. Estimated duration of alloy strength start softening vs Larson-Miller constant [13.14] (Operating temperature: 615°C; Tempering temperature: 760°C)

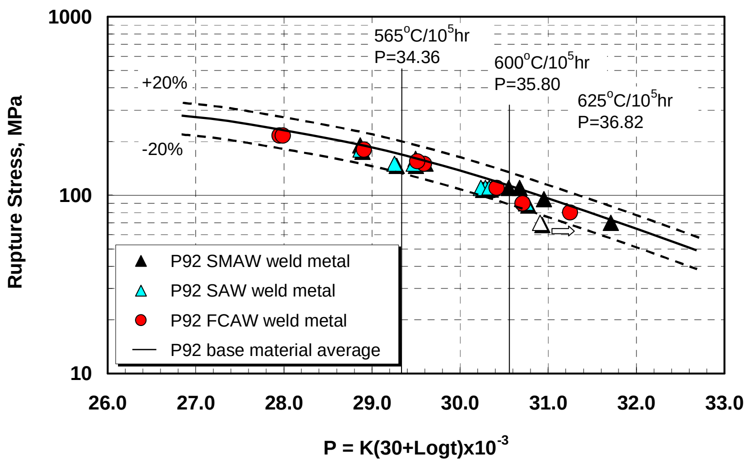


Figure 9. Larson-Miller plot of P92 base metal and weld metals with C=30

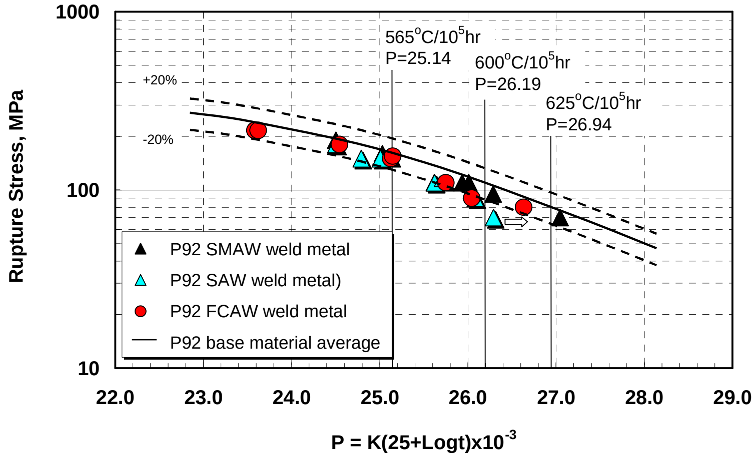


Figure 10. Larson-Miller plot of P92 base metal and weld metals with C=25

8. Conclusions

As one of the most important new base materials for USC power plant, T/P92 offers improved creep properties over other current Cr-Mo steels, and has been used on a considerable scale. Matching welding consumables have also been developed and used in the shop fabrication and site erection of USC units.

Actual measurements of the phase transformation temperatures were conducted on T/P92 all-weld deposits. The Ac1 temperature of the weld metals with optimised analyses is typically between 800°C-815°C. Ni, Mn and Co all reduce the Ac1 temperature of the P92 weld metal, with Co having ~40% the effect that Ni and Mn have. As long as Ni+Mn (or Ni+Mn+0.4Co) is controlled to 1.5% maximum, the Ac1 temperature of the weld deposit will be high enough to allow PWHT to be carried out at 760°C and tests using a PWHT temperature as high as 780°C have also proved to be satisfactory. However, a temperature above 780°C is not recommended.

The Ms temperature of P92 weld metals is in the range 370°C-390°C, while the minimum Mf temperature was measured at 105°C. These indicate that weld joints should be cooled below 100°C to allow a full martensite transformation before PWHT, and that the weld joint should be kept in the temperature range 200°C-300°C during the whole process of welding.

Both welding procedure and PWHT were shown to have an effect on weld metal ambient temperature toughness. There were some inconsistencies in the results but generally better and more uniform refinement of the weld metal and higher tempering parameters are beneficial in achieving higher toughness.

P92 welding consumables discussed in the current work demonstrated satisfactory creep properties. The weld metals were shown to have creep strength that was within a ±20% band of the base material average. Even when using a more pessimistic Larson-Miller constant (C=25), their creep performance matched that of T/P92 base alloy.

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