Properties of T/P92 weld metals for ultra super critical (USC) power plant

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Abstract: The introduction of new power generation technologies, such as ultra super critical (USC) plant, has resulted in the development and application of a series of advanced Cr-Mo creep resistant steels. Among these new alloys, T/P92 steel has creep strength 25%–30% higher than the currently widely used T/P91 steel and it has become one of the major alloys for the construction of USC plant. In order to obtain a good understanding of the microstructural characteristics and properties of the T/P92 weld metals, investigation was conducted to welds from SMAW, SAW and FCAW processes using matching filler metals. The important phase transformation temperatures, Ac1, Ms and Mf, were measured. The mechanical properties at ambient temperature and creep properties of the weld metals were evaluated. Procedural factors that influence the performance of T/P92 weld metals were discussed and recommendations for suitable practical welding and post-weld heat treatment procedures were presented.

Keywords: ultra super critical; USC; T/P92 steels; welding; weld metal; creep; properties.

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1 Introduction

Fossil fuels are still the current main means of obtaining electric power, and about 40% of electricity we consume is 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 technologies. Finding an effective solution to reduce the emissions of harmful gases from thermal power plant 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 environmentally damaging gases. These have directly resulted in the development and application of a series of new generation advanced Cr-Mo creep resistant steels in the past two and a half decades. When USC plant was introduced in the late 90s, the 9% Cr-Mo ferritic creep resistant alloy specified for the main steam pipe and other critical components was modified 9% Cr–1% Mo steel T/P91. The T/P91 alloy allowed typical operating parameters up to 290 bar pressure, main steam temperature 580°C and re-heat steam temperature 580°C (Blum and Hald, 1997). As the progress of material development, a new generation 9% Cr–Mo alloy, T/P92, has started replacing T/P91 alloy for USC units. Compared to T/P91 steel, T/P92 steel has 25%–30% higher creep strength. The maximum design parameters of USC units fabricated with T/P92 alloy have increased to 300 bar/610°C/620°C–625°C (Bendick et al., 1998; Richardot et al., 2000; Arbab et al., 2001); and the efficiency of USC plant is now approaching 50%.

In the recent few 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, meeting the requirements of new power plant construction and increase the material's application range, the development of matching welding consumables has been necessary. These matching consumables have been used for the fabrication and site erection of USC units in which large numbers of components have been made with T/P92 steel.

The current paper presents the design philosophy of the matching welding consumables for T/P92 steel. Using all-weld metals made with shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux cored arc welding (FCAW) processes, the relevant phase transformation temperatures, such as austenitisation temperatures during heating (Ac1), martensite transformation starting (Ms) and finishing (Mf) temperatures during continuous cooling at cooling rates typical to welding were measured. The effect of alloying elements on these temperatures was evaluated. Based on the examination of these transformation temperatures, recommendations are made for suitable practical welding parameters and post-weld heat treatment (PWHT) procedures. Stress rupture test was conducted to examine the creep properties of these weld metals. According to the results from the current study and field experience reports together with newly revised base material creep data, a detailed evaluation of creep performance of the T/P92 weld metals was made. The latest all-weld metal data were also examined and compared with the creep properties of the transverse weld joint specimens.

Two earlier publications by the same authors provided test results of the general impact toughness and tensile properties of T/P92 weld metals and the effect of welding process on mechanical properties (Zhang et al., 2009; Marshall and Zhang, 2003). With weld metals of SMAW and SAW processes, current work further investigated the effect of welding parameters and PWHT procedures on the ambient temperature toughness of T/P92 weld metals.

2 Test weld metal preparation and testing methods

Using SMAW, SAW and FCAW processes, all-weld metal samples were prepared with 19 mm thick plates. The joint geometry followed relevant requirements of AWS A5.5 and A5.23 specifications. For samples for phase transformation temperature measurement and stress rupture test, weld bead arrangement conformed to the specifications. Different weld bead arrangements were also used for a selected group of SMAW welds to examine the effect on the weld metal mechanical properties (and in these cases, 12.5 mm thick plates were employed). The joint groove and backing bar were buttered with the same T/P92 SAMW electrode to eliminate the possible effect of dilution. The welding was carried out with a preheat temperature 200°C and inter-pass temperature 250°C. The welded coupons were cooled down in air to room temperature before being subjected to PWHT.

After PWHT, different all-weld metal specimens were then extracted from the weld coupons for various tests.

High speed dilatometry technique was used to measure the phase transformation temperatures. The cylindrical all-deposit specimens were extracted from the centre regions of the welds and along the longitudinal direction of welding. These specimens were machined into dimensions of 10.0 mm long with ∅4.0 mm diameter. The shielding gas was pure argon. During the test, the specimens were re-austenitised at 1100°C with a constant heating rate of 2°C/min and then were held at the austenitisation temperature for two minutes to ensure a uniform full austenitic microstructure before cooling down continuously. The Ms and Mf temperatures were assessed at two different 800°C to 500°C cooling rates, 20°C/sec and 50°C/sec, which were selected to represent the range of typical weld cooling rates. Dilation curves were recorded for each specimen for entire cycle of heating and cooling, and relevant transformation temperatures were then determined from the dilation curves.

Stress rupture test was conducted to evaluate the creep properties of the weld metals. The specimens were extracted from the weld coupons longitudinally to the welding direction and the type was modified TR22 (stress to rupture) with a total length of 75 mm. The parallel gauge length was 24 mm with ∅8.0 mm in diameter. The test parameters, load and temperature, were selected with reference to the data of T/P92 base alloy (Richardot et al., 2000). The test procedure followed BS EN 10291:2000 specification. The test results were assessed using Larson-Miller plot with different values of the constant C in the equation, and compared with the performance of T/P92 base metal.

3 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 EN ISO 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 full 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 given in Table 1.

Nb: Work on both T/P91 and T/P92 consumables has shown that reducing the niobium content towards the lower end of the parent alloy specification ranges has a beneficial effect on toughness. For this reason, most weld deposits have Nb level of 0.04% or 0.05%. One exception is the T/P92 solid welding 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 SAW 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 also 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 4.1 of this paper.

Mn: Is generally controlled to a higher level than in the parent 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 the 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%)

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]GTAW: gas tungsten arc welding; GTAW/SAW solid wire: 9CrWV/ER90S-G(92)
[b]SMAW electrode: Chromet 92/E9015-G(92)
[c]FCAW wire: Supercore F92/E91T1-G (92), shielding gas: Ar + 20%CO_2
[d]SAW wire and flux combination: 9CrWV/EG(92) + flux LA491

Source: Zhang et al. (2009)

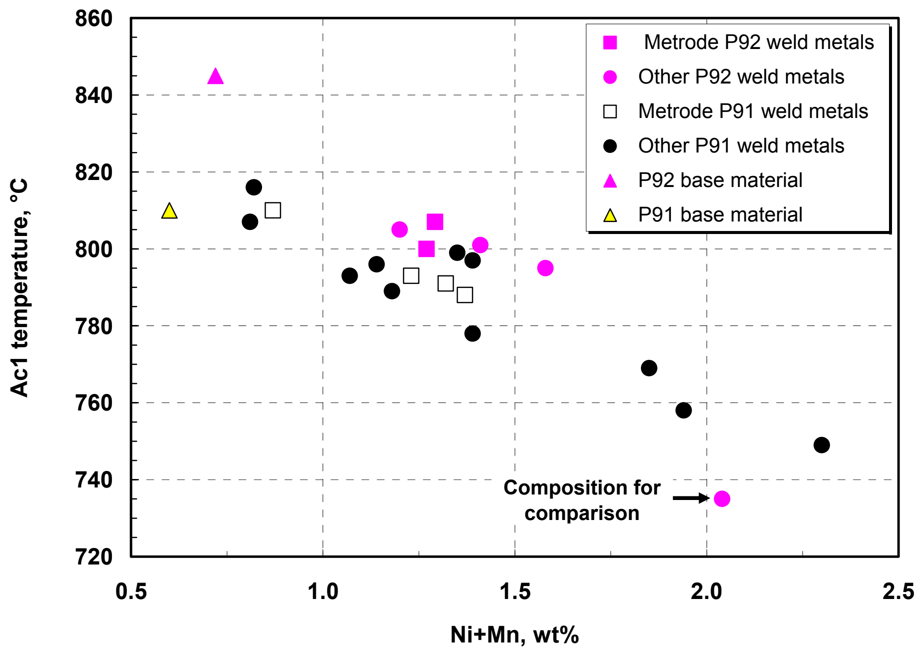
4 P92 weld metal phase transformation temperatures

Under controlled heating and cooling conditions, the relevant phase transformation temperatures of T/P92 base material are typically: reaustenitisation temperature (Ac1) = 840°C to 845°C, martensite start temperature (Ms) = 400°C, martensite finish temperature (Mf) = 200°C (Richardot et al., 2000; Naoi et al., 1995). 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 T/P92 weld deposits were measured.

4.1 Weld metal Ac1 temperature and effect of alloying elements

The measurement results of Ac1 temperature are plotted in Figure 1. In the figure, data for both T/P91 and T/P92 are shown and the base metal values are taken from published data (Richardot et al., 2000; Harrmann et al., 2002). It can be seen that the typical Ac1 temperature of T/P92 weld metal with the compositions given in Table 1 is between 800°C to 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 welds followed the same trend. With a similar level of Ni + Mn, the Ac1 temperature of T/P92 weld deposits are 10°C to 15°C higher than T/P91 weld metals. This agrees with the results from thermal dynamic calculations (Masuyama et al., 1989).

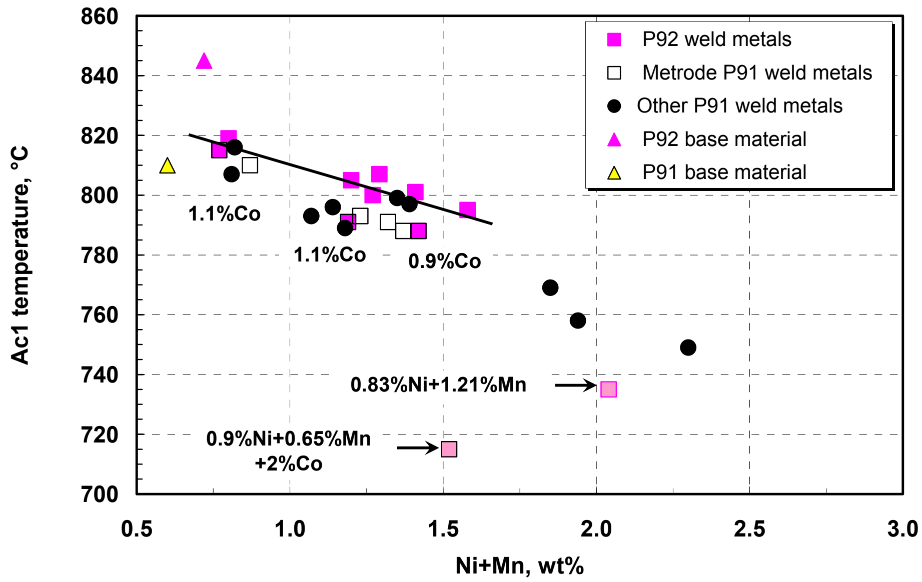
Figure 1 Ac1 temperatures of P92 and P91weld metals and the effect of Ni + Mn content (see online version for colours)



As the Ni + Mn content increases, the Ac1 temperature is reduced; at 1.5% Ni + Mn the Ac1 temperature is ~795°C. Beyond this level, the Ac1 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 T/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 ~795°C and a safety margin of 15°C, it would dictate a maximum PWHT temperature of ~780°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.

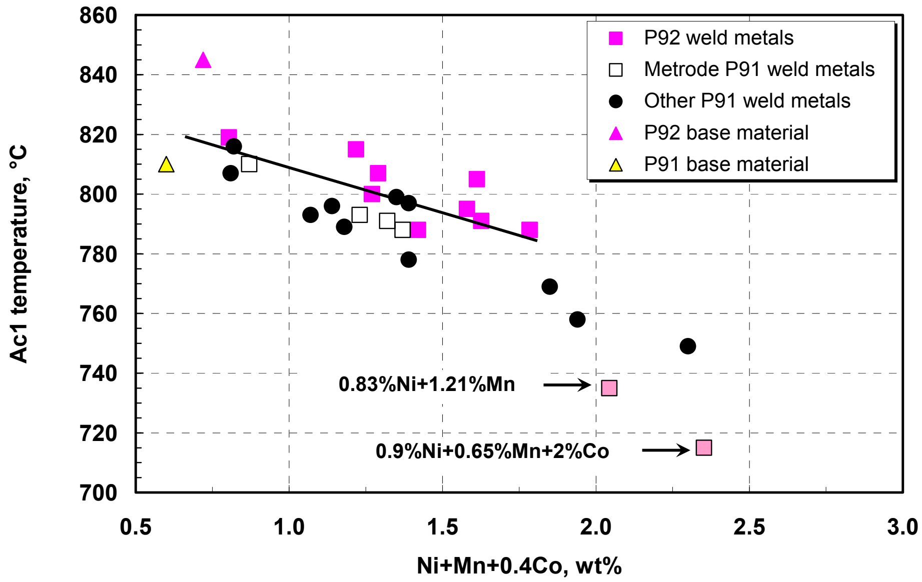
Due to the strong effect of nickel on Ac1 temperature, cobalt is sometimes also added to some T/P92 weld metals to partially, or even completely replace Ni to achieve a stable ambient toughness. In the current work, the effect of cobalt on the Ac1 temperature was also assessed. Despite there being some 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 (Shingledecker, 2007).

Figure 2 Effect of Ni and Mn on Ac1 temperature of P92 weld metals (see online version for colours)



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 T/P92 weld metal, the addition of the element should also be controlled. The recommendation is that, for an Ac1 > 795°C, the overall content of Ni + Mn + 0.4 Co should be limited to 1.5% maximum. This level should be further controlled to less than 1.4% if an Ac1 temperature of 800°C is required.

Figure 3 Effect of Ni, Mn and Co on Ac1 temperature of P92 weld metals (see online version for colours)



4.2 *Weld metal Ms and Mf temperatures*

According to the data from base material manufacturers on continuous cooling after austenitisation at 1,050°C to 1,070°C, the starting temperature for martensitic transformation (Ms) of T/P92 steel is ~400°C, and the martensite finishing temperature (Mf) is about 200°C (Richardot et al., 2000; Naoi et al., 1995). Table 2 shows the results for both T/P91 and T/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 to 390°C and the Mf temperatures 105°C to 150°C; the Mf temperatures being 20°C to 40°C lower at the faster cooling rate of 50°C/sec. Generally the Ms and Mf temperatures for T/P92 were lower than for T/P91 weld metal deposits.

Table 2 Martensitic transformation temperatures (Ms and Mf) of T/P91and T/P92 weld metals

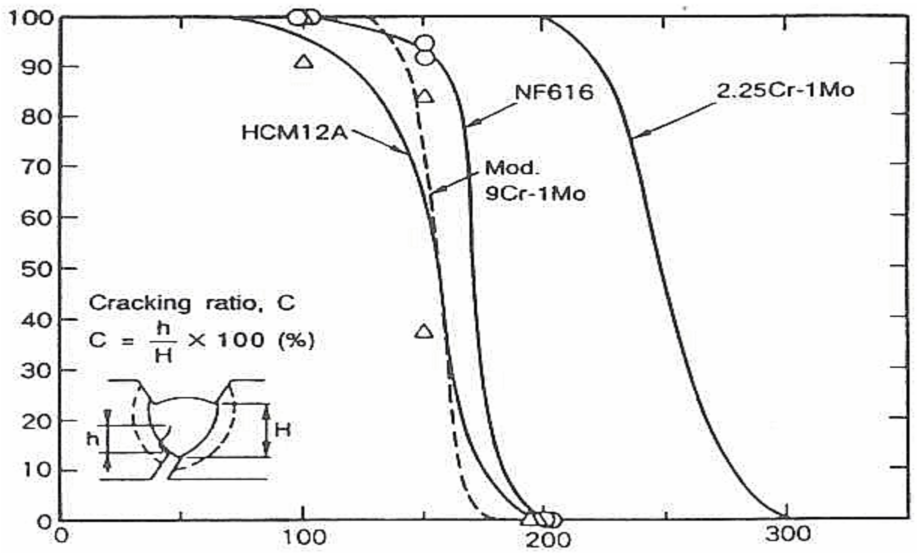
Alloy	*Welding process*	*Cooling rate = 20°C/s*		*Cooling rate = 50°C/s*	
		Ms, °C	*Mf, °C*	*Ms, °C*	*Mf, °C*
P91	SMAW	402	167	407	128
	SAW	419	200	426	136
	FCAW	381	157	385	107
P92	SMAW	383	151	382	117
	SAW	385	147	388	105
	FCAW	382	127	371	105

5 Selection of welding parameters

5.1 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 (Masuyama and Yokoyama, 1995). 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.

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



Source: Masuyama nd Yokoyama (1995)

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 to 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 about 250°C keeps the weld metal within the Ms-Mf temperature range of 105°C to 390°C and therefore ensures that at least a substantial proportion of martensite transformation occurs for each weld bead that is deposited.

5.2 Control of the cooling after welding

As was seen in Section 4.2, at a relatively fast cooling rate, the martensite finish temperature (Mf) of T/P92 weld metal can be as low as 105°C. This means that in order to ensure a full martensite transformation, the welded joint must be cooled down to below 100°C before PWHT is carried out. If the austenite of the weld metal is not allowed to fully transform before PWHT is conducted then any retained austenite will transform to untempered fresh martensite on cooling to room temperature after PWHT.

Post-weld hydrogen diffusion anneal is a term used to describe the practice of maintaining the preheat temperature, ~200°C, for two to four 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 T/P92, partial cool-out below the preheat temperature (<100°C) would be necessary before applying the post-weld hydrogen diffusion anneal to eliminate untransformed austenite before reheating to the intended temperature, because hydrogen that is trapped in the austenite diffuses out of it far slower than from martensite.

Fortunately, unlike the earlier higher carbon alloy X20 (12%CrMoV), post-heat is not considered to be necessary with T/P92 (or T/P91) and in practice, weldment less than 50 mm 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 with a thickness above 50 mm the current recommendation is to cool no lower than 80°C (Richardot et al., 2000).

6 Selection of PWHT procedure and the significance of Ac1 temperature

Under normal welding cooling conditions, the hardness of as-transformed martensitic T/P92 weld metal and coarse-grained HAZ is similar to T/P91 at around 400–450 HV 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 5.2).

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 T/P92 weld metal is typically in the range of 800°C to 815°C. Therefore the maximum allowed PWHT temperature is slightly higher than that of T/P91 welds. One base material manufacturer tempers base metal in the range 750°C to 780°C (Richardot et al., 2000). 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 4.1 indicates that ~780°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 7 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 six to eight hours, which produced satisfactory weld metal properties.

7 Weld metal toughness

7.1 Toughness requirement of T/P92 weld metal

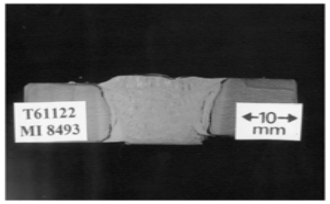
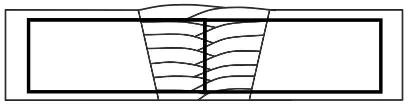
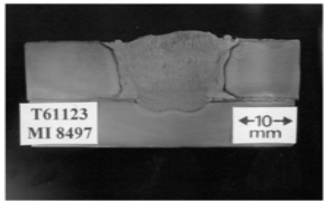
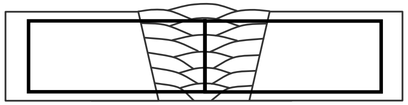
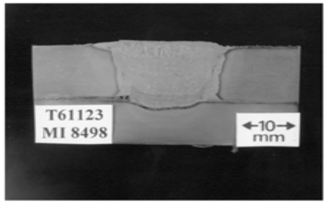
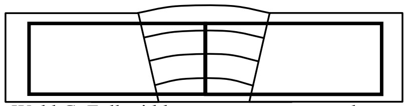
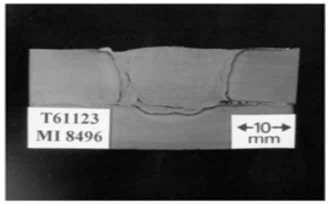
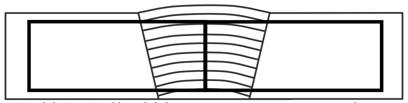
It can be argued that the ambient temperature toughness of T/P92 weld metal, which is designed to operate in the temperature range 500°C to 625°C, is an irrelevant consideration since this is far above the temperature where there is any risk of fast brittle fracture. However, there are situations where 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 +7°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 EN ISO 3580-A:2008 requires a minimum average value of 47 J and a minimum single value of 38 J 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 (Zhang et al., 2009) 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 (Zhang et al., 2009) are both greater than those used for T/P91 and reflect the higher tempering resistance of T/P92 welds 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 EN ISO standard for the filler metal of X20 (12%CrMoV) steel, a well-established weld metal with a requirement of 34 J average and 27 J minimum single value at +20°C.

7.2 Effect of welding procedure and PWHT on weld metal toughness

Although T/P92 consumables are not yet covered by relevant 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 SMAW and SAW deposits. Four welds were made with 3.2 mm diameter SMAW electrodes (identified as welds A to D) and were all PWHT at 760°C for five hours. The details of the welds are given in Table 3. There were also three submerged are welds made with 2.4 mm 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.

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

Weld macro		*Welding parameters and weld bead arrangement*	*Charpy impact energy and lateral expansion*[a]	
			20°C	*0°C*
		Weld A: Average weave, two passes per layer Total 14 passes Average layer thickness ~1.8 mm Heat input 1.2 kJ/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 18 passes Average layer thickness ~2.1 mm Heat input 1.0 kJ/mm	77 (66) J 1.19(1.04) mm	48 (41) J 0.75(0.70) mm
		Weld C: Full width weave, one pass per layer Total 4 passes Average layer thickness ~3.2 mm Heat input 2.0 kJ/mm	63 (56) J 1.02(0.93) mm	43 (36) J 0.68(0.58) mm
		Weld D: Full width weave, one pass per layer Total 10 passes Average layer thickness ~1.2 mm Heat input 1.3 kJ/mm	71 (64) J 1.10(1.07) mm	46 (42) J 0.75(0.67) mm

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

Table 4 Effect of welding parameters, weld bead arrangement and PWHT on impact

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

Notes: [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.

From the data presented in Table 3, it can be seen that there is some variations 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. Generally, 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) was probably not achieving as consistent weld bead refinement as procedures B and D, because in procedure D the very thin layers allowed almost complete and uniform refinement of the previous weld beads and in weld B although the layer thickness was greater than weld A (2.1 mm compared to 1.8 mm) there were more beads and probably greater overall refinement. In reality the stringer beads used in weld B are expectedly 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 two hours and five hours. The average Charpy energy at +20°C was 69 J after two hours and 93 J after five 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 EN ISO 3580-A. This indicates the sophistication of the latest design of T/P92 SMAW electrode.

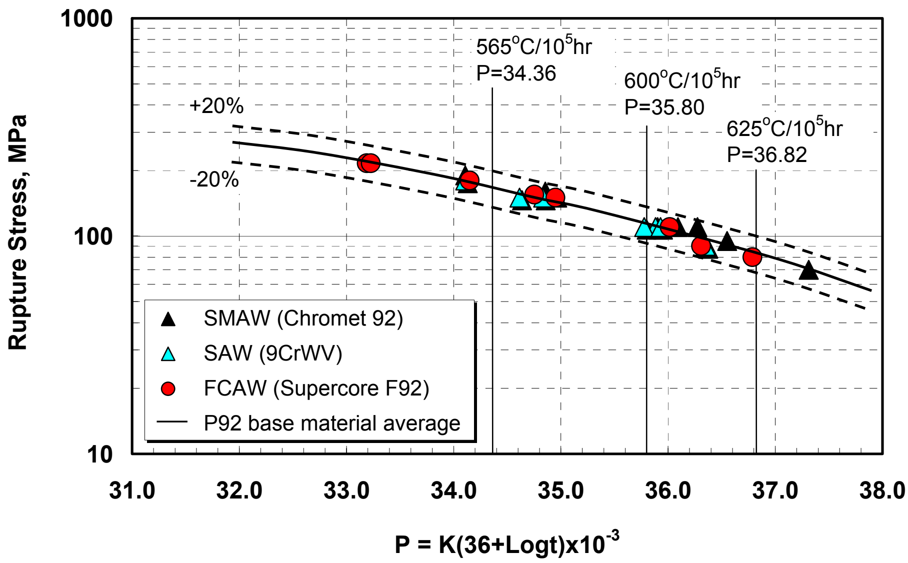
The data on the SAW weld metal in Table 4 does not show quite such a clear trend. The lowest heat input parameter, weld E, gave the lowest toughness; and the results of the highest heat input (weld G) was not significantly different to the intermediate heat input joint (weld F). With the lowest heat 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.

8 Weld metal creep properties and interpretation of test data

8.1 All weld metal creep properties and weld joint creep rupture

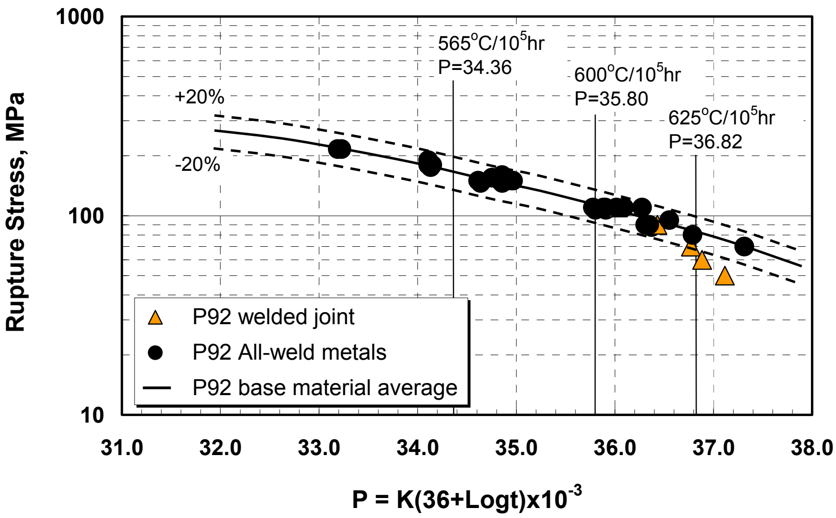
For an alloy designed to be used at 500°C to 625°C, the high temperature properties of T/P92 weld metal are of considerable importance. Stress rupture tests on all-weld metals were carried out at temperatures 600°C to 650°C. Figure 5 shows the Larson-Miller plot of the creep properties of T/P92 weld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

Figure 5 Larson-Miller plot of T/P92 weld metals and base metal with C = 36 (see online version for colours)



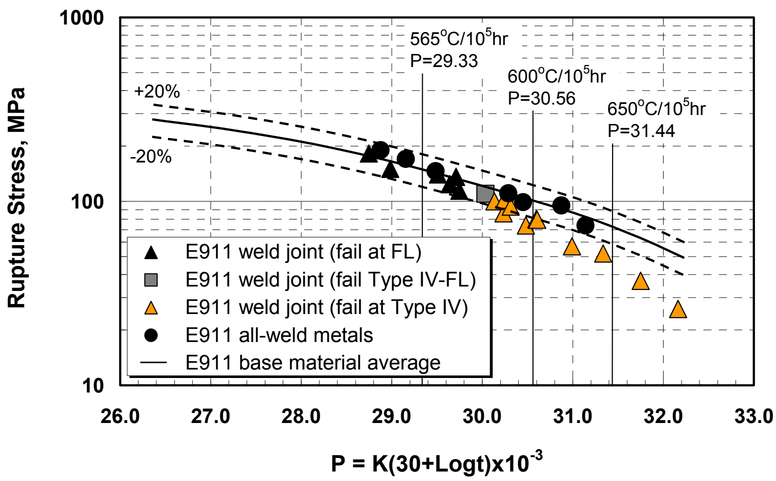
In reality, for a 9% Cr-Mo creep resistant alloy, the creep failure of a welded joint will normally occur in the soft zone in the HAZ of the base material (type IV zone). Figure 6 shows data from all-weld metal tests and transverse weld joint tests in T/P92 weldment (Abe, 2006). It can be seen that as tests become more representative of longer term tests, the rupture stress of the transverse weld joint test started to fall below both base material and weld metal values. The same trend has been demonstrated with weld joints of other types of 9% Cr-Mo steels, such as T/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 and failure will occur in the type IV zone in the HAZ (Figure 7). At lower Larson-Miller parameters the transverse joints fail at the fusion line but with tests at higher LMP values and lower stress which are more representative to the conditions of operation service 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.

Figure 6 Transverse joint tests of T/P92 steel weldment in comparison with all-weld metal and base material (C = 36) (see online version for colours)



Source: Data after Abe (2006)

Figure 7 Transverse joint tests of E911 steel weldment in comparison with all-weld metal and base material (C = 30) (see online version for colours)



Source: Data from the test results of Metrode Chromet 10MW SMAW electrode

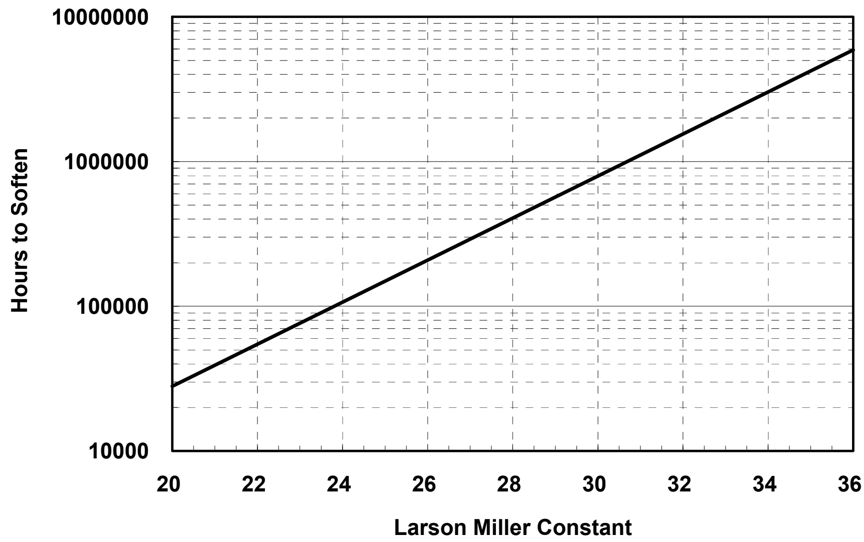
8.2 Interpretation and understanding of creep data of P92 steel and weld metal

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 to 625°C and pressures of 300 bar. In the past three to four years, with the building of a considerable number of USC units up to 1,000 MW, 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 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 (Cases for ASME Boiler and Pressure Vessel Code, 1994), 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 Committee (ECCC) published a data sheet on T/P92 steel which showed a 100,000 hour creep rupture stress at 600°C of 123 MPa (ECCC, WG3.2, 1999), an 8 MPa reduction from the original 131 MPa. In 2005, a new data sheet was published for P92 by the ECCC (ECCC, WG3A, 2005) which further modified the 100,000 hour creep rupture stress at 600°C downwards to 113 MPa. This is a total reduction of ~14% from the originally extrapolation value. The ASME code case 2179-6 (2006) (Cases for ASME Boiler and Pressure Vessel Code, 2006) has also modified the allowable design stresses for T/P92 downwards compared to the 1994 code case. For example, the allowable design stress at 593°C was reduced from 94 MPa to 83 MPa.

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 T/P92 creep data, for quite some time, constant C = 32.6–36 have been commonly used (Richardot et al., 2000; Naoi et al., 1995; Masuyama and Yokoyama, 1995; Masuyama, 1995). 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 with increase of C for creep resistant alloys (Kimura, 2005; Prager, 2006). Examination suggests 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 eight years reflected the timely correction to the earlier over-estimated performance. In fact, in the current European 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 (Staubli, 2003). 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 lower parameters than they were originally designed for; and some other units under fabrication have required modifications to their designs, e.g., increase the thickness of some critical components to suit the specified operating temperature and pressure.

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



Source: Kimura (2005) and Prager (2006)

Using a constant of 30 and 25, the base material and weld metal creep data are re-plotted in Figures 9 and 10.

Figure 9 Larson-Miller plot of P92 base metal and weld metals with C = 30 (see online version for colours)

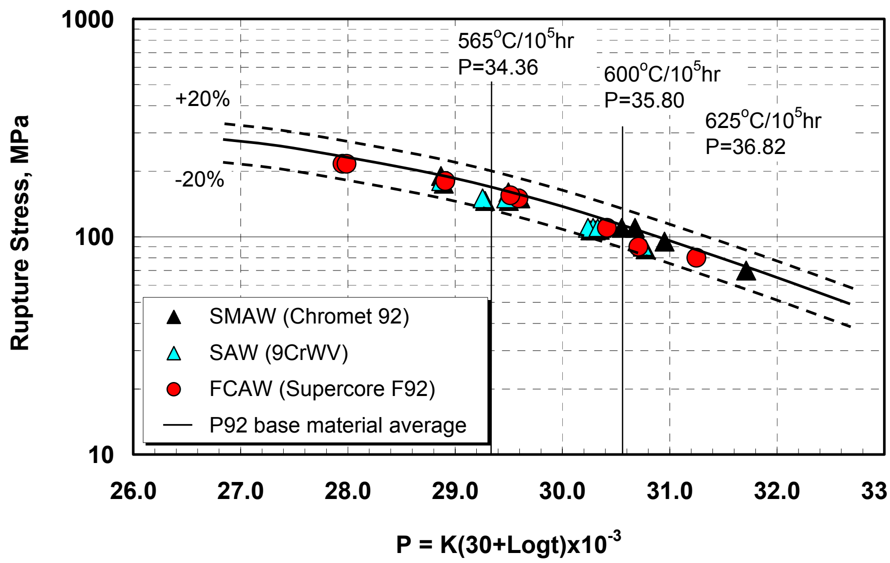
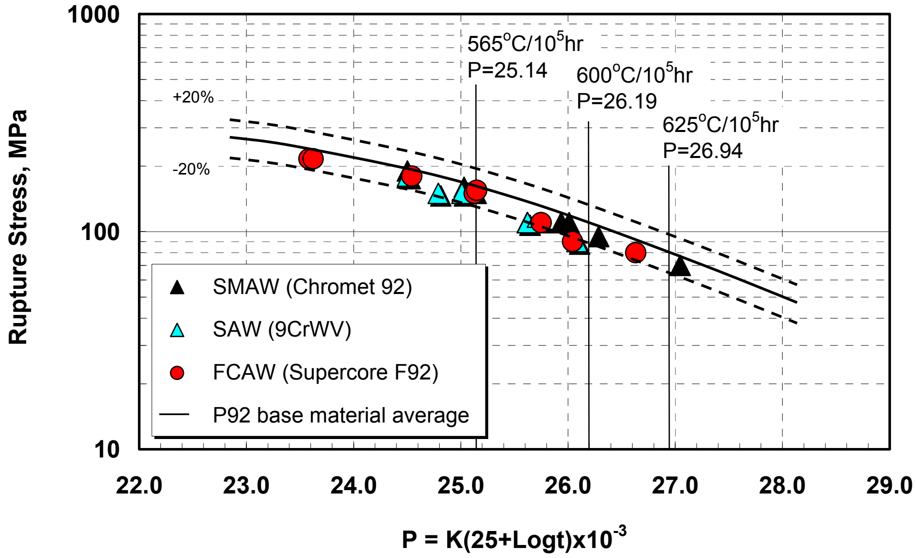


Figure 10 Larson-Miller plot of P92 base metal and weld metals with C = 25 (see online version for colours)



When compared to Figure 5, it can be seen that when C = 25, which would provide a more conservative 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 conservative extrapolation the weld metal tests still show a satisfactory creep performance compared to the base material.

9 Conclusions

As one of the most important new base materials for USC power plant, T/P92 steel offers improved creep properties over other current Cr-Mo creep resistant 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. From the current investigation, the following results and conclusions are obtained:

1. Actual measurements of the phase transformation temperatures were conducted on T/P92 all-weld deposits. The Ac1 temperature of the weld metals with optimised chemical composition is typically between 800°C to 815°C.
2. Ni, Mn and Co all reduce the Ac1 temperature of the T/P92 weld metal, with Co having ~40% the effect that Ni and Mn have.
3. It is necessary to control the content of Ni + Mn to 1.5wt% maximum. This will enable the Ac1 temperature of the weld deposit >795°C. In the case Cobalt is added as an alloying element, level of Ni + Mn + 0.4 Co should be kept to 1.5wt% maximum. This level should be further controlled to less than 1.4% if an Ac1 temperature of 800°C is required. These levels of Ac1 temperature would be high

enough to allow PWHT of the T/P92 weldment 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.

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

5 Both welding procedure and PWHT were showing to have 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 ambient toughness.

6 Matching welding consumables for T/P92 steel discussed in the current work demonstrated adequate creep properties matching the base material. The weld metals from SMAW, SAW and FCAW processes all demonstrated satisfactory creep strength and the creep data plotted in the Larson-Miller graph were 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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