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WELDING CONSUMABLES FOR P92 AND T23 CREEP RESISTING STEELS

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Abstract

There is continuing effort to increase the energy conversion efficiency of fossil-fired power plants, for which enhanced creep resisting steels are essential to withstand more advanced steam conditions. Following the widespread and successful application of P91, newer steel developments have encouraged the realisation of plant with progressively improved generating efficiencies. Two such new steels are P92, a modification of the now very well established P91 with an addition of about 2% tungsten replacing most of the molybdenum, and T23 which is essentially a low carbon 2.4%Cr steel modified with tungsten, vanadium and niobium. Although P92 is primarily a piping material, and T23 is aimed at tubing, there is also interest in the potential use of 'P23' as a stronger alternative to P22 for piping. Effective exploitation of these steels is critically dependent upon the ability to fabricate a range of components and systems for the different types of fossil fuelled power plants. In turn, fabrication depends upon the availability of suitable welding consumables for the main arc welding processes commonly used for both new fabrications and upgrade/repair. In practice, this means that consumables for shielded metal arc welding (SMAW), flux cored arc welding (FCAW), gas tungsten arc welding (GTAW), and submerged arc welding (SAW), all need to be available, tried and tested. This paper examines recent developments and progress in consumable design for both P92 and T23 steels, as reflected in all-weld metal properties. Preliminary data are presented together with a selective review of the literature, which should help both users and fabricators to make informed decisions as to the correct selection of consumables, welding processes and procedures.

1.0 Introduction

The growth in world population and living standards continues to make increasing demands on energy supplies, particularly electricity. There is some growth in the use of renewable sources, such as wind power, and a new interest in nuclear power in some countries. However, for the foreseeable future, there will be major reliance on electricity generated from the burning of fossil fuels. The challenge is to produce this power with maximum efficiency and minimum environmental damage.

The use of new creep resisting alloy steels, particularly the modified 9%CrMo grade P91 developed in the USA some 20 years ago by ORNL and Combustion Engineering, has made a major contribution to improving the design and operating efficiency of fossil fuelled power plants. More recently, initial exploitation of subsequently developed steels with enhanced creep properties indicates that further improvements in efficiency are achievable, since these newer steels allow more advanced operating temperatures and pressures [1]. Introduction of the most advanced generating plants has been gradual, so current experience with the new alloys is at a historically early phase.

Two of the candidate steels important for improving power generating efficiency are P92 and T23*. The Japanese proprietary designation for P92 is NF616 (Nippon Steel) and for T23 is HCM2S (Sumitomo, co-developed with MHI). P92 is a modification of P91 with 2%W replacing most of the Mo, and T23 is a low carbon 2.4%Cr steel alloyed with W, V and Nb. Microalloying with up to 0.006% (60ppm) boron is also important for both alloys (specifications are tabled later with weld metals). P92 is primarily designed as a piping material for advanced steam conditions and is seen as a major improvement on P91, with a rupture strength advantage of about 30% at 600°C. T23 is aimed at tubing applications welded without post-weld heat treatment (PWHT), where its allowable stress of almost twice that of T22 at 550°C can be exploited, but is also being investigated for heavy wall piping as a cost-competitive alternative to P22 and/or P91 [2,3], and for retrofit applications [2].

To exploit fully the benefits that P92 and T23 offer, it is necessary to be able to fabricate them successfully, which in turn depends on the availability of suitable welding consumables. This paper first looks at the applicable arc welding processes and consumable design, reviews some aspects concerning weldability and PWHT, then presents all-weld metal property data for both the P92 and T23 consumables. The data are not exhaustive, but provide reassurance that suitable welding consumables are available and that there are no unfamiliar challenges involved in fabricating these new creep resisting steels.

2.0 Welding Processes

Traditionally GTAW, SMAW, FCAW and SAW are the most widely used arc welding processes and all of these could be applicable to P92 and T23. Although there are ASME Code Case specifications for both P92 and T23, there are not yet any national specifications (eg AWS) for matching welding consumables. As far as possible, weld metal compositions are kept within

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* P92 and T23 are strictly ASTM-ASME pipe and tube respectively of alloy grades 92 and 23, which are currently the most widely recognized forms. However, throughout this paper P92 and T23 are often convenient vernacular names, not restricted to the particular product form unless obvious from the context. Proprietary names are also used where appropriate.

limits similar to the base material, but some variations are inevitable, either owing to deoxidation requirements or to optimize mechanical properties, and some of these issues are discussed later. The following sections briefly review the four relevant arc welding processes.

2.1 GTAW (TIG)

This process is used commonly for manual GTAW root runs in thicker section pipe joints and for either manual or auto-GTAW welding of small diameter thin wall tubing, for example orbital welding of T23 waterwall tubes using 0.8mm (0.031in) wire [4]. Although weld tests are not included in the present paper, wire for T23 generally matches base material composition [4] or may contain a small addition of Ni. Filler wire for P92 is usually modified for reasons explained later.

2.2 SMAW (MMA)

Owing to its adaptability, the SMAW process is still widely used for both new fabrications and upgrades or repairs. The electrodes used for welding CrMo creep resisting steels such as P92 and T23 employ low hydrogen basic flux systems (equivalent to EXX15/16-G, and often with a specified limit of 0.15% moisture in the flux covering). These are designed to satisfy demanding all-positional operability for fixed pipework welding and excellent metallurgical integrity required for critical applications. The all-weld metal composition closely matches the major alloying of the relevant base materials although there are usually some minor variations to optimize weld metal properties. The modifications in analysis will be given in more detail later, but the main reason is to optimize the weld metal impact properties.

2.3 FCAW

The FCAW process has considerable advantages over the SMAW process in terms of its potential productivity; in some applications, the time saving can be as much as 40% compared to SMAW [5]. To achieve these benefits, it is necessary to use a rutile-based flux system which combines excellent operability with the all-positional capability necessary for welding fixed pipework. The use of a rutile flux system does impose certain limitations on the acheivable weld metal properties, toughness in particular. Nevertheless, tubular flux cored wires are now successfully used for welding P11, P22 and P91 creep resisting steels [5,6,7]. With specific reference to P91, but equally relevant to P92, some of the perceived limitations of flux cored wires and how they are addressed have been discussed in more detail elsewhere [5,8]. Data for FCAW consumables in the present paper are for products near commercial production and are believed to be the first in the open literature.

2.4 SAW

For joining larger diameter and thick section components that are being welded in the workshop and can be suitably positioned or rotated, SAW is the most economic and productive welding process. Although properties and application of SAW butt welds in thick section HCM2S have been reported [3], owing to the current applications of T23, the process is unlikely to be required in the short-term for this alloy. SAW may be used for welding lower alloy strips to T23 tube in waterwall fabrication [4], but wire to match T23 is not necessary here. Some of the proposed applications of P92 will be suitable for the SAW process. There are no test data on the SAW process for P92 or T23 presented in this paper.

3.0 Weldability – preheat and PWHT

The required preheat-interpass temperature to prevent hydrogen-assisted cold cracking in base material HAZ and/or weld metal is a particular concern for welding high strength steels. The necessary disciplines for welding P22 are well known, and current fabrication experience with P91 is also satisfactory. Recognising that consumables will have equivalent low hydrogen potential, it is logical to review P92 and T23 in relation to reported weldability tests and the conditions used for all-weld metal coupon tests presented in this paper. Some of the issues concerning PWHT will also be reviewed in the light of reported practice.

Incidentally, no evidence has been reported that specification levels of boron in P92 and T23 pose any problems, although it has been stated that boron leads to increased hot cracking sensitivity [13], but without supporting evidence for these alloys. However, potential successor steels to P92 are under development which typically contain much more boron, so the question might be relevant at a later date.

3.1 Preheat requirements

The Japanese developers of NF616 (P92) and HCM2S (T23) have presented [9,10] the results of Y-groove tests[11], which provide a useful index of susceptibility to cold cracking (including quench-transformation cracking and possibly hot cracking) in relation to preheat temperature. The technique is generally considered to be a severe test of the appropriate base material plus weld metal, and consists of a highly restrained assembly with a root notch, into which (typically) a SMAW weld bead is deposited at a chosen preheat temperature. The test results for these materials, with comparisons including P22 and P91 are shown in Figures 1 and 2.

On this evidence the behaviour of P92 is practically the same as P91, and 200°C (390°F) is sufficient to suppress cracking. However, other Japanese workers at the same time [14] reported a Y-groove cracking threshold at 250°C (480°F), and more recently a preheat-interpass range of 250-350°C (480-660°F) has also been proposed by European workers [13]. Despite this, the lower preheat was used successfully for welding 50mm (2in) wall NF616 pipe by SMAW and SAW processes [9,14], and 150°C (300°F) for GTAW which no doubt reflects the particularly low hydrogen potential of this process. These conditions agree with the recommendations of Europe's principal T/P92 tube and pipe producer [12]. In addition, according to continuous cooling transformation (CCT) data [12,15] and considering factors such as carbon content, as-quenched hardness and martensite transformation temperature, the preheat requirements for P92 are expected to be equivalent to that of P91. A preheat-interpass temperature range of 200-250°C (390-480°F) was therefore used for the P92 weld metal tests reported in the present paper.

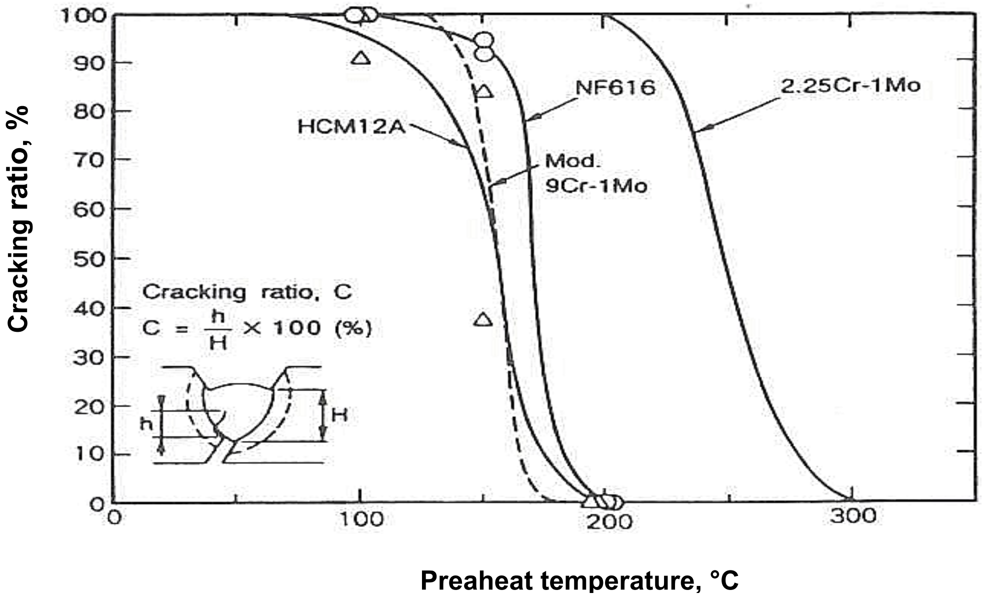

Figure 1. Relation between Y-groove weld cracking ratio and preheat temperature of P92 (NF616) welds compared with others including P91 (Mod.9CrMo) and P22 (2.25Cr-1Mo) [9].

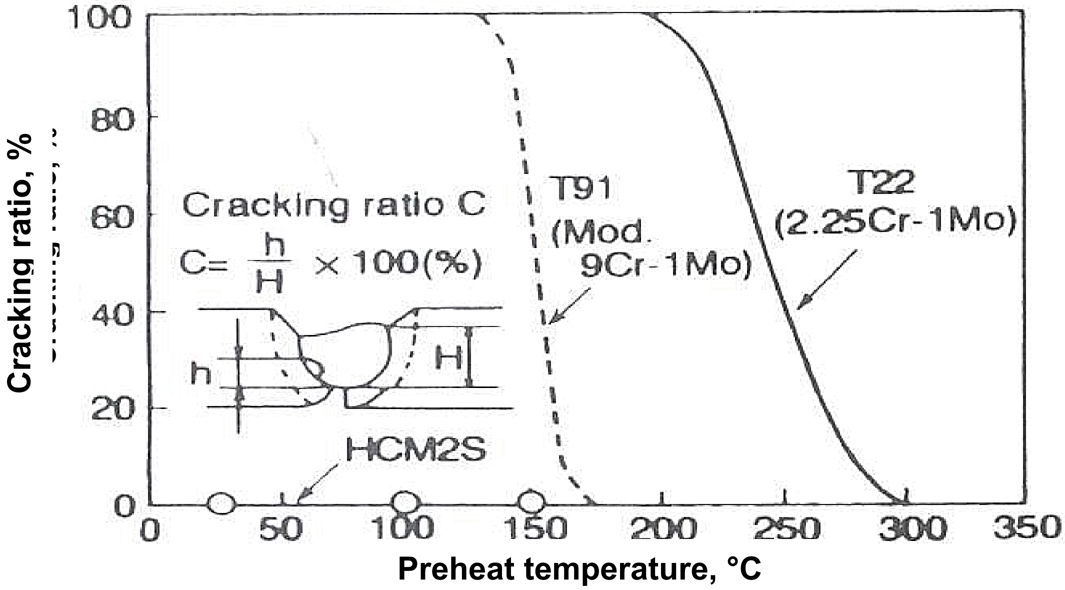

Figure 2. Relation between Y-groove weld cracking ratio and preheat temperature of T23 (HCM2S) compared with T22 (2.25Cr-1Mo) and T91 (Mod.9Cr-Mo) [10].

Like P91, the welding interpass temperature for P92 is within the martensite transformation range, and cooling to below 100°C (212°F) is necessary to encourage complete transformation before PWHT [12]. For sections above 50mm (2in) the current recommendation is to cool no lower than 80°C (176°F), but cool-out to ambient is acceptable below this thickness [12].

Although the untempered weld zone will be relatively brittle at this stage, local residual stresses should not be high because they are offset by the expansion accompanying transformation around interpass temperature [16], with continued transformation followed by more-or-less homogenous contraction of the preheated zone during (slow) cool-out.

In contrast to P92 (and P22), the Y-groove tests for the lower carbon bainitic type T23 (HCM2S) imply that it is immune to cold cracking when welded without preheat, and this benefit, coupled with avoidance of PWHT, is exploited successfully for welding boiler waterwalls (where PWHT is essentially impractical) and for superheater tubes where thin sections prevail [4].

However, preheating is applied when welding heavier wall pipe (and in this case weldments are also given PWHT). For welding 350mm (14in) diameter 50mm (2in) wall HCM2S pipe, Japanese workers [3] used a minimum preheat of 150°C (300°F) for the SMAW and SAW processes, and 100°C (212°F) for the GMAW process. A similar preheat-interpass range of 150-200°C (300-390°F) was used for welding the SMAW and FCAW coupons for which all-weld tests are reported in the present paper.

At usual cooling rates, the as-transformed hardness of T23 is expected to be 300-360HV, and preheat has little apparent effect on hardness [4]. According to CCT data, the bainite transformation temperature for T23 is up to 100°C (180°F) higher than T/P22 [4,17,18]. This might promote more auto-tempering during welding, but may be less desirable with respect to residual stress, which is roughly proportional to the interval between transformation and interpass temperature, and is possibly amplified by the alloy's high bainitic yield strength [16]. Aside from particular code requirements, this argument points to the general benefit of preheating for most thicknesses, despite the remarkable resilience indicated by Y-groove tests. A threshold thickness above which preheat should be applied is not yet clear, and is probably process-dependant too: for example, up to 6-8mm (0.25-0.31in) wall tube welds are likely to be all-GTAW without preheat, while pipe welds above this thickness may use SMAW with preheat.

3.2 Post weld heat treatment

The as-transformed martensite hardness of P92 weld metal and HAZ is similar to P91 at around 400-450HV under all normal cooling conditions, so that PWHT is viewed as mandatory, irrespective of section thickness. At this hardness, there is some concern about potential susceptibility to stress corrosion cracking if untempered welds are exposed to humid conditions, so PWHT of welds cooled to ambient should probably not be delayed too long after welding.

PWHT temperature for P92 is generally similar to P91, usually 750-760°C (1380-1400°F), but response to tempering is such that a minimum of 2 hours is advisable, and even 4 hours [12] is preferable for improved toughness in welds other than GTAW. Shorter durations may be appropriate for thinner wall tube welds (0.5hour has been applied to P91), but it should be recognized that tempering (hence hardness, toughness) is temperature-time dependant.

Like weldments in P91, maximum PWHT temperature is restricted somewhat compared to base material because weld metals typically have higher Mn+Ni, which reduces the Ac1 temperature. However, the Ac1 of P92 appears to be higher than P91 [12,14], so there may be some additional headroom allowing higher temperature PWHT of shorter duration. For the tests reported in the present paper, PWHT was 760°C (1400°F) for 2 or 4 hours.

For T23, the low carbon, predominantly bainitic, microstructure has a quenched or as-cooled hardness of around 300-360HV and pipework welds of relatively thin section do not require PWHT [4,10]. As will be dicussed later, as-welded toughness may be relatively low. Applications in thicker sections of P23 pipework are forthcoming, and PWHT is then applied for stress-relief and to improve properties. The thickness above which PWHT is governed by code requirements may not coincide with that necessary for this new material, and this subject is currently being investigated [2].

The PWHT conditions for SMAW, GMAW and SAW weldments reported in Japanese work [3] on 50mm (2in) wall HCM2S pipe were 715°C (1320°F) for 2 hours. The same temperature and some variations in duration were used for the tests reported in the present paper. Other workers have applied 690°C (1275°F) and 730°C (1345°F) for various durations to GTAW weld metal and pipe weldments [13]. This alloy responds much more readily to tempering than P92, and treatment like T/P22 may prove satisfactory.

4.0 All-weld metal tests: results and discussion

All-weld metal test coupons were prepared in general accordance with AWS-ASME procedures using low carbon steel plates of thickness 13 or 19mm (½ or ¾ in) as appropriate to the welding process or electrode size, with 10-degree bevelled edges buttered with two layers of the test weld metal. Each strongbacked assembly with backing strip was held at a preheat-interpass range of 200-250°C (390-480°F) while welding with the P92 consumables, and 150-200°C (300-390°F) for T23 consumables. The groove was filled using two beads per layer. When PWHT was applied, test coupons were furnace cooled. Tests included ambient and elevated temperature tensile, hardness, and Charpy impact tests. Stress-rupture tests are not reported here.

4.1 P92 weld metals

All-weld metal tests were carried out for the GTAW, SMAW and FCAW processes and Table 1 gives their typical undiluted compositions together with the parent material specification for comparison. Compositions are similar to parent material except that more Mn is allowed and some Ni is added as explained below.

As with weld metals for P91, Ni helps to ensure optimum toughness. In early work on the development of weld metals for NF616 [14], the authors reported that autogenous GTA welds had very poor toughness due to the presence of delta ferrite. The alloy solidifies as primary delta

Table 1. Specification limits for parent P92 and typical composition of undiluted weld metals

Parent material/Weld metals	**C**	**Mn**	**Si**	**S**	**P**	**Cr**	**Ni**	**Mo**	**W**	**V**	**Nb**	**N**	**B ppm**	**Al**
Parent P92 limits	0.07 0.13	0.30 0.60	- 0.50	- 0.010	- 0.020	8.50 9.50	- 0.40	0.30 0.60	1.50 2.00	0.15 0.25	0.04 0.09	0.030 0.070	10 60	- 0.040
9CrWV* (GTAW)	0.12	0.71	0.29	0.008	0.009	9.1	0.49	0.42	1.72	0.19	0.06	0.06	30	<0.01
Chromet 92 (SMAW)	0.11	0.60	0.25	0.011	0.008	9.0	0.61	0.45	1.80	0.20	0.05	0.05	30	0.005
Supercore F92 (FCAW)	0.10	0.70	0.29	0.006	0.018	9.0	0.40	0.50	1.70	0.21	0.03	0.04	30	0.005

* Wire analysis.

ferrite, but whereas parent material is fully austenitised isothermally at around 1050°C (1920°F), some ferrite may be retained in rapidly cooled weld metal of equivalent composition [14]. Thiswas effectively suppressed with a little added Ni, and for GTA welds these authors showed that 0.36%Ni could increase impact energy by almost 200J (147ft-lb). The SMAW and SAW compositions evaluated by these authors [14] had above 2% Mn+Ni. However, although both Mn and Ni help to suppress ferrite, they also depress Ms-Mf and Ac1, and for a robust procedural window which avoids excessive misalignment of transformation temperatures between weld and base material, total Mn+Ni are restricted to a total of 1.5% maximum [12,13].

Table 2. Tensile properties of P92 weld metals at ambient and elevated temperatures

Weld metal (Process)	**PWHT**	**Test temp. °C**	**0.2%Proof stress, MPa**	**Tensle strength, MPa**	**EL (4D), %**	**RA, %**	**Mid-section hardness, HV10**
9CrWV (GTAW)	760°C/2h	20	650	766	25	70	256
	760°C/4h	20	645	751	29	70	259
		550	374	455	25	82	/
		600	282	387	21	85	/
		650	200	312	28	89	/
Chromet 92 (SMAW)	760°C/2h	20	627	752	21	49	246
	760°C/4h	20	635	764	22	50	245
		550	419	511	15	64	/
		600	320	422	20	73	/
		650	229	340	20	80	/
Supercore F92 (FCAW)	760°C/4h	20	649	774	21	50	252
		550	385	471	19	68	/
		600	294	400	25	77	/
		650	194	308	27	81	/
		700	125	215	26	86	/

Tensile properties and hardness. Table 2 gives representative results after PWHT for all-weld metal tensile tests at room and elevated temperatures, with typical hardness values. Room temperature strength after 2-4 hours PWHT comfortably exceeded P92 base material requirements, and except for GTAW having a small ductility advantage, there were no remarkable differences between processes. The general similarity to P91 weld metals is shown in Figure 3 by the relationship between strength and hardness taken at the mid-section of weld slices. Proof stress results are plotted against temperature in Figure 4, showing that all three

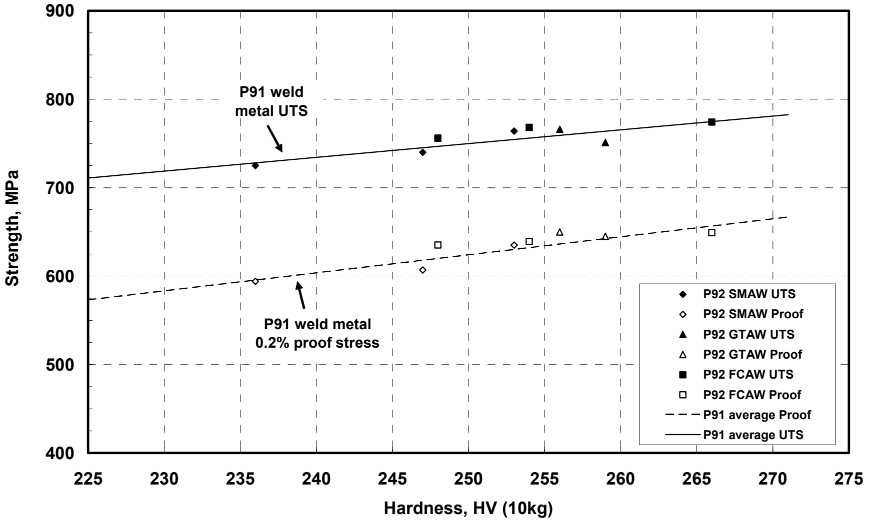

Figure 3. Relation between hardness and tensile properties of P92 weld metals, compared with average trends for P91 weld metals

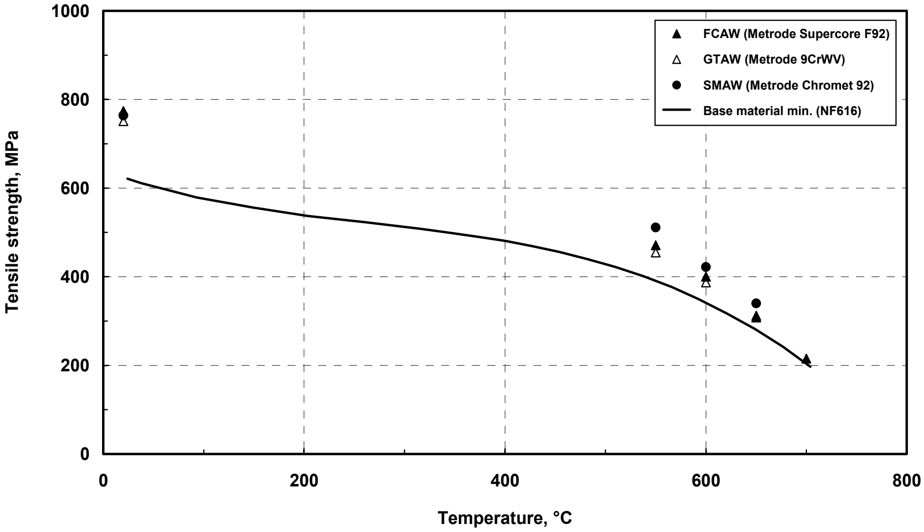

Figure 4. 0.2% proof strength of P92 weld metals at elevated temperatures, compared with parent material minimum values.

processes are similar, with some convergence to base material minimum towards 650-700°C (1200-1290°F). Hot tensile test specimens had a gauge diameter of 5mm (0.2in) and there is some evidence that strength values may be conservative when compared to results from specimens with larger guage diameter. The hot strength values are comparable to P91 weld metals previously reported [5], and interestingly, comparisons of minimum and typical hot tensile properties for P91 and P92 parent materials also show relatively little difference between the two alloys [12,14,15], despite the significantly greater creep rupture strength of P92. Weld metal creep tests are not reported in the present paper.

4.1.2 Impact properties. Representative results from all-weld metal Charpy impact tests are given in table 3. In the case of toughness, there was a noticeable benefit of increasing PWHT from 2 to 4 hours, and there were also differences between welding processes. As expected, GTAW weld metal was the toughest owing to its low oxygen (non-metallic inclusion) content compared to SMAW and FCAW [20]. However, a contributing factor to the lower FCAW toughness is believed to be residual Ti arising from rutile, which is an essential component of the flux system [5]. The longer PWHT duration of 4h is therefore considered most prudent for FCAW welds. Toughness may be a particular concern with respect to hydrotesting, and these issues have been addressed from a fitness-for-purpose perspective in previous papers [5,8].

Table 3. Impact toughness of P92 weld metals

Weld metals (Process)	PWHT	Test temperature, °C	Absorbed energy, J	Lateral expansion, mm
9CrWV (GTAW)	760°C/2h	0	90	1.08
		20	168	2.06
	760°C/4h	0	182	2.13
		20	212	2.25
Chromet 92 (SMAW)	760°C/2h	20	48	0.75
	760°C/4h	0	37	0.61
		20	62	1.03
Supercore F92 (FCAW)	760°C/4h	20	26	0.39
		70	60	0.94

Finally, an overview of the relationships found between Charpy absorbed energy and lateral expansion is shown in Figure 5. This log-log plot should not be over-interpreted, since it includes additional statistics from development data, as well as tests at 0°C and 20°C (32 and 68°F). Lateral expansion is not 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.

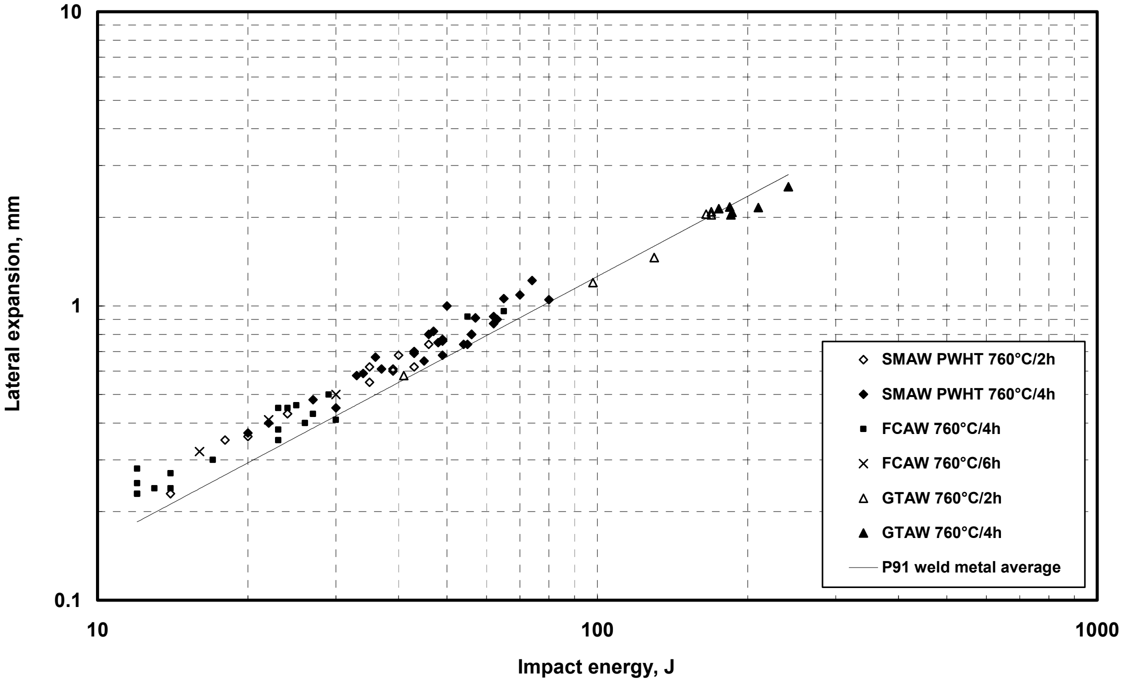

Figure 5. Relation between Charpy impact energy and lateral expansion of P92 weld metals, compared with average trend of P91 weld metals.

4.2 T23 weld metals

Table 4 gives representative all-weld metal compositions for the two variants of SMAW electrodes and one batch of FCAW (product still under development) for which mechanical properties are tabled in the following sections. One of the electrodes (Chromet 23L) has a low carbon level around 0.05% and a deliberate nickel addition, aimed to optimise as-welded toughness. The other (Chromet 23H, not currently a production variant) is closer to base material composition, with no nickel and a little more carbon, possibly more appropriate where heat treatment will be applied. In the course of development many other experimental batches of SMAW electrodes with minor variations were tested and the results are used to illustrate trends graphically.

Table 4. Specification limits for parent T23 and typical composition of undiluted weld metals

Parent/ Weld metal	C	Mn	Si	S	P	Cr	Ni	Mo	W	V	Nb	N	B, ppm	Al
Parent material limits	0.04 0.10	0.10 0.60	- 0.50	- 0.010	- 0.030	1.9 2.6	- -	0.05 0.30	1.45 1.75	0.20 0.30	0.02 0.08	- 0.030	5 60	- 0.030
Chromet 23L (SMAW)	0.05	0.5	0.2	0.01	0.01	2.2	0.80	0.1	1.5	0.21	0.03	<0.02	10	0.005
Chromet 23H (SMAW)	0.07	0.5	0.2	0.01	0.01	2.2	0.03	0.1	1.5	0.21	0.05	<0.02	10	0.005
Cormet 23 (FCAW)	0.05	0.6	0.3	0.01	0.02	2.2	0.03	0.1	1.5	0.24	0.02	<0.02	20	0.003

Table 5. Tensile properties of T23 MMA and FCW weld metals at ambient and elevated temperatures

Weld metal (Process)	PWHT	Test temp, °C	0.2%Proof stress, MPa	Tensile strength, MPa	EL (4D), %	RA, %	Mid-section Hardness, HV10
Chromet 23L (SMAW)	As-welded	20	938	987	20	56	353
Chromet 23H (SMAW)	715°/2h	20	679	754	20	55	242
Cormet 23 (FCAW)	As-welded	20	772	837	18	48	292
	715°C/2h	20	583	657	23	65	240
		350	509	572	15	63	/
		450	458	529	10	39	/
		550	330	420	12	54	/

4.2.1 Tensile properties and hardness. Table 5 gives some representative all-weld metal tensile test results. In all cases the weld metals were sufficiently strong, and the very high strength without PWHT reflects as-welded hardness values of 290-350HV, which fell below 250HV after PWHT at 715°C (1320°F) for 2 hours. Hot tensile tests up to 550°C (1020°F) were also carried out on FCAW weld metal, and strength exceeded parent material minimum at all temperatures.

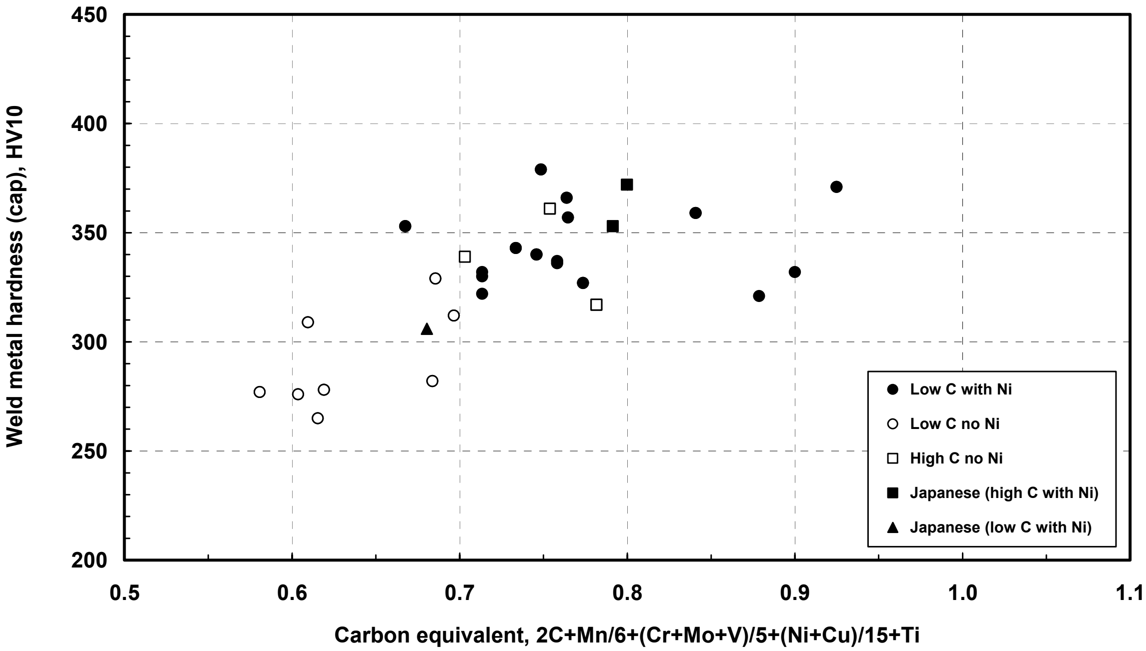

Figure 6. Relation of as-welded T23 SMAW weld cap hardness and carbon equivalent

During SMAW development work, a slice from every all-weld test piece (most were for impact tests) was surveyed for hardness at cap and mid-section. The grossed average as-welded hardness of cap and mid-section (25 batches) was 329HV, and although some of the highest individual values were found in the cap, about 60% of tests were slightly harder in mid-section. A hardness below 350HV was considered desirable but a number of tests exceeded this. However, these numbers conceal underlying trends related to changing composition, as seen in Figure 6, which shows how the weld cap hardness increases as a function of a 'carbon equivalent' parameter. Most of the harder welds, irrespective of carbon level, were those with Ni added, or those without Ni but higher carbon.

4.2.2 Impact properties. Results of all-weld Charpy tests at 0°C and 20°C (32 and 68°F) for representative batches of SMAW and one batch of FCAW are given in Table 6. Most testing was carried out on the Ni-bearing SMAW welds without PWHT. Before considering these, it is noteworthy that the Ni-free SMAW and FCAW welds were satisfactory at 20°C after PWHT at 715°C (1320°F), although at 0°C (32°F) FCAW was distinctly lower in toughness after 2-3hours PWHT than SMAW after only 30min. As-welded toughness of these Ni-free SMAW and FCAW welds was considered borderline at room temperature and unsatisfactory at 0°C (32°F).

Table 6. Impact properties of T23 weld metals

Weld metals (proceses)	PWHT	Test temp., °C	Absorbed energy, J	Lateral expansion, mm
Chromet 23L (SMAW)	As-welded	0	17	0.21
		20	22	0.39
Chromet 23H (SMAW)	As-welded	0	9	0.11
		20	14	0.20
	715°C/0.5h	0	38	0.48
		20	112	0.75
	715°C/2h	0	64	1.00
		20	84	1.36
Cormet 23 (FCAW)	As-welded	0	7	0.05
		20	15	0.16
	715°C/2h	0	16	0.22
		20	44	0.66
	715°C/3h	0	12	0.08
		20	122	1.49

Addition of Ni was found in general to improve not only as-welded toughness but also to raise lateral expansion relative to impact energy. Figure 7 shows these relationships for welds tested at 0°C (32°F), including Japanese examples. Welds with lower Nb(Cb) also tended to be tougher, and two welds with below the parent limit of 0.02%Nb are marked. The toughest Ni-free weld had no Nb (this gave 41J (30ft-lb) at ambient), and the toughest Japanese weld had 0.015%Nb. Overall optimization is currently aimed to ensure 15J (11ft-lb) at 20°C (68°F). After PWHT, these welds will inevitably equal or exceed the toughness of Ni-free welds and are therefore considered to be more versatile, so future modification to the FCAW composition is likely to follow this route.

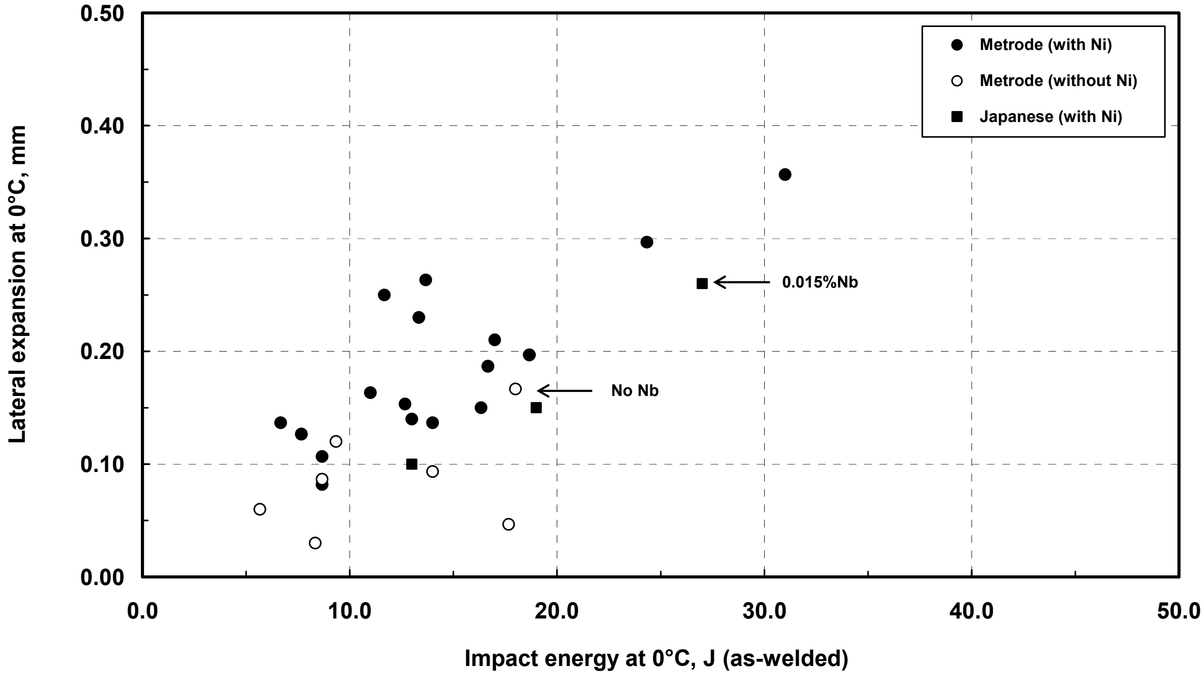

Figure 7. Relation between as-welded impact energy and lateral expansion at 0°C for T23 weld metals

The as-welded SMAW impact values at room temperature reported here are actually similar to some examples reported for all-weld GTAW tests using matching (Ni-free) filler wire [13]. In another example [3], a 'matching' SMAW weld (no details were given) in 50mm (2in) wall HCM2S pipe gave around 10-30J* (7-22ft-lb) at 0°C (32°F) after PWHT at 715°C (1320°F) for 2 hours. The present Ni-free SMAW tests after equivalent PWHT gave higher values. The latter workers also reported [3] better toughness for GMAW and SAW pipe welds after PWHT, but most surprisingly found base material Charpy values between 15 and 210J (11 to 155ft-lb), whereas the lowest single HAZ value was around 67J (49ft-lb), and HAZ values for each process formed a group with little scatter. Though not discussed by the authors, these observations might indicate somewhat greater sensitivity to factors influencing the alloy's transformation behaviour (ie. through-hardenability, as noted for thick 2¼Cr-1Mo [17,21]) than is apparent from the current literature. Aside from such considerations, the weldments were reported [3] to have good cross-weld creep properties, with longer-term failure in the weakened HAZ (type IV zone) as usual, and an estimated rupture stress reduction ratio similar to P91.

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* Given impact values are derived from a graphical presentation and converted from J/cm^2.

5.0 Conclusions

The merits of the common welding processes have been described, and the weldability of P92 (NF616) and T23 (HCM2S) in relation to preheat and PWHT practice has been assessed from the literature, and with particular reference to the all-weld metal composition and properties of recently developed welding consumables for these materials. For P92, welding processes were GTAW, SMAW and FCAW, and for T23 SMAW and FCAW. The results of mechanical testing and the influence of PWHT are reported, including data which illustrate trends in properties obtained during consumable development. Although development of the FCAW consumables is still under review, the data presented are believed to be the first in the open literature. The following are some general conclusions:

P92 shows similar weldability to P91 and requires the same welding conditions. Satisfactory properties were obtained and no new challenges should be expected, except to recognise that longer PWHT may be necessary to meet a given toughness criterion. The preferred PWHT temperature is 760°C (1400°F), and duration for GTAW 2hours (possibly less), for SMAW 2-4hours, and for FCAW 4hours.

T23 evidently has advantages in weldability compared to T22, which also extend to thicker sections. However, the threshold thickness above which PWHT should be mandatory is not yet clear. Similar issues concern preheat, but the cost of precaution is less significant. Optimised SMAW electrodes modified with addition of Ni gave satisfactory as-welded properties, but hardness values below 350HV were not necessarily guaranteed. Based on testing of Ni-free welds (including FCAW), this alloy responds readily to PWHT, and 715°C (1320°F) for 0.5-2hours dramatically raised toughness and moderated hardness.

6.0 Acknowledgement

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