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. Two new steels are P92, a modification of the now very well established P91, and T23. Effective exploitation of these steels is 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.

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 an 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 design stress of almost twice that of T22 at 550°C can be exploited; but it 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, and then presents all-weld metal property data for both the P92 and T23 consumables. It is not reported here but in an earlier paper the same authors presented information on preheat and PWHT requirements which showed that P92 could be treated in a similar manner to P91, while T23 actually had some weldability advantages over T22 [4]. 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 EN or AWS) for matching welding consumables. As far as possible, weld metal compositions are kept within limits similar to the base material, but some variations are inevitable, either owing to deoxidation requirements or to optimise 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 for manual-GTAW root runs, for example in P92 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 wire. Although weld tests from T23 solid wire are not included in the present paper, such wire generally matches base material composition [5,6] or may contain a small addition of Ni. Filler wire for P92 also is usually modified for reasons explained later.

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* P92 and T23 are strictly ASTM-ASME designations for pipe and tube respectively of alloy grades 92 and 23, which are currently the forms most widely used. However, in this paper P92 and T23 are also convenient names for the materials, without restriction to the particular product form. Proprietary names are also used where appropriate.

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, often with a specified limit of 0.15% moisture in the flux covering. They are designed for all-positional welding of fixed pipework, and satisfy the 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 discussed 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 [7]. To achieve these benefits it is necessary to use a rutile-based flux system that 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 achievable weld metal properties, toughness in particular. Nevertheless, this process is now successfully used for welding P11, P22 and P91 creep resisting steels [7,8,9]. 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 [7,10]. Data for FCAW consumables in the present paper are for development products which are now near commercial production.

2.4 SAW

SAW is the most economic and productive process for joining larger diameter and thick section components that are being welded in the workshop and can be suitably positioned or rotated. The properties of SAW girth welds in thick section HCM2S pipe have been reported [3] and interest in welding thick material is growing [2]. However, the SAW process is unlikely to be required in the short-term for this alloy. The construction of membrane waterwalls may use SAW for welding the alloy strips to T23 tubing [6], but wire to match T23 is not necessary here. Some applications for P92 will be suitable for the SAW process, using a wire composition similar to GTAW.

3.0 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 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 within a preheat-interpass range of 200-250°C while welding with the P92 consumables, and 150-200°C for the T23 consumables. The groove was filled using two beads per layer. When PWHT was applied, test coupons were furnace cooled. Mechanical tests included ambient and elevated temperature tensile, hardness, and Charpy impact tests. Stress-rupture tests are not reported here.

3.1 P92 weld metals

All-weld metal tests were carried out for the GTAW, SMAW, FCAW and SAW 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.

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 wire (GTAW/SAW)	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
9CrWV (GTAW deposit)	0.10	0.74	0.23	0.006	0.007	8.5	0.49	0.39	1.66	0.17	0.05	0.03	15	<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
9CrWV+LA491 (SAW deposit)	0.09	0.76	0.29	0.005	0.011	8.3	0.48	0.39	1.66	0.16	0.04	0.04	9	0.015

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

As with weld metals for P91, Ni helps to ensure optimum toughness. Early workers on the development of weld metals for NF616 [11] reported that autogenous GTA welds had very poor toughness, due to the presence of delta ferrite. Parent material is austenitised to produce a fully martensitic transformation, but the rapid solidification and cooling rate of welding can result in retained ferrite in weld metal of equivalent composition [11]. Such ferrite was effectively suppressed by adding a little Ni, and it was shown that 0.36%Ni could increase impact energy of GTA welds by almost 200J. The SMAW and SAW compositions evaluated by these authors [11] had above 2% Mn+Ni, and although both Mn and Ni help to suppress ferrite, they also depress Ac_1 and the Ms-Mf range. This may help to explain why toughness values below 27J were reported. To avoid excessive misalignment of the transformation temperatures between weld and base material, current specifiers may prefer the total Mn+Ni restricted to 1.5% maximum [12,13].

3.1.1 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 1 by the relationship between strength and hardness taken at the mid-section of weld slices. Ultimate tensile strength results are plotted against temperature in Figure 2, showing that all three processes are similar, with some convergence towards base material strength at the highest temperatures. Hot tensile test specimens had a gauge diameter of 5mm and there is some evidence that strength values may be conservative when compared to results from specimens with larger gauge diameter. The hot strength values are comparable to P91 weld metals previously reported [7], and interestingly, comparisons between P91 and P92 parent materials also show relatively little difference between the reported hot tensile properties for the two alloys [11,12,14], despite the significantly greater creep rupture strength of P92. Weld metal creep tests are not reported in the present paper.

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
		600	299	407	20	75	/
	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	/
9CrWV+LA491 (SAW)	760°C/2h	20	/	/	/	/	259
	760°C/4h	20	/	/	/	/	240

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

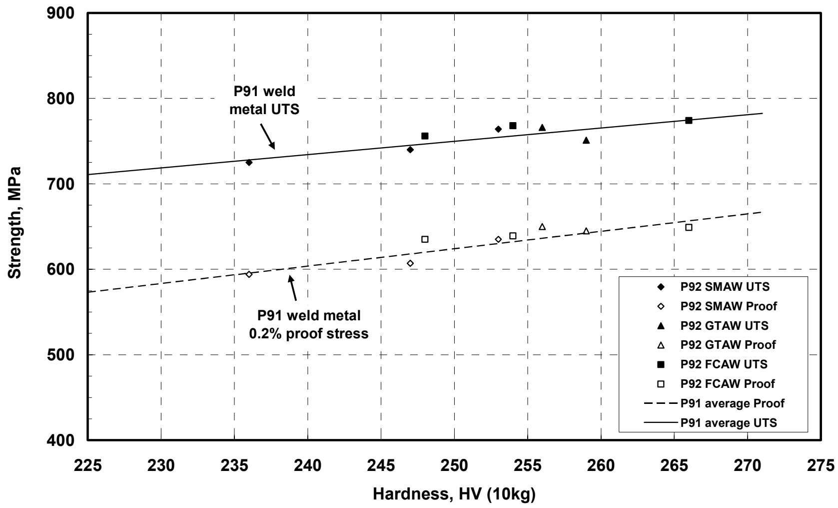

Figure 1. Relation between hardness and tensile properties of P92 weld metals, compared with average trends for P91 weld metals.

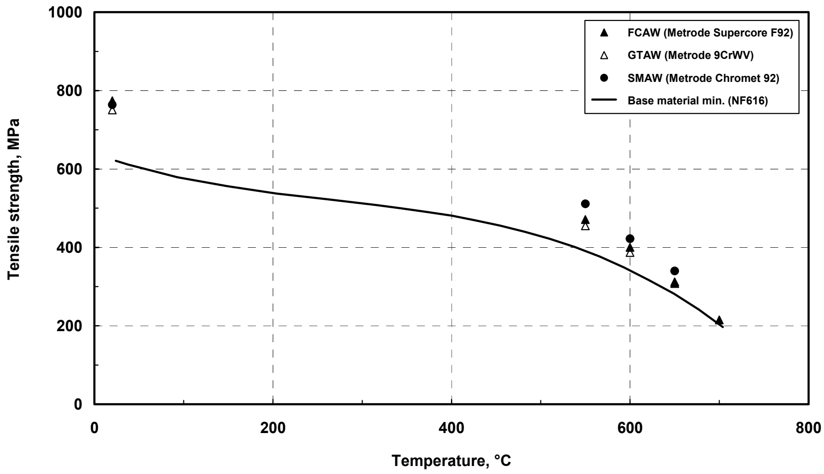

Figure 2. UTS of P92 weld metals at elevated temperatures, compared with parent material minimum values.

3.1.2 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, FCAW and SAW [15]. 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 [7]. 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 [7,10].

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	50	0.80
	760°C/4h	0	37	0.61
		20	70	1.10
Supercore F92 (FCAW)	760°C/4h	20	26	0.39
		70	60	0.94
	760°C/8h	20	29	0.41
9CrWV+LA491 (SAW)	760°C/2h	20	35	0.52
	760°C/4h	20	37	0.54

Table 3. Impact toughness of P92 weld metals.

Finally, an overview of the relationships found between Charpy absorbed energy and lateral expansion is shown in Figure 3. This log-log plot includes the results of tests at 0°C and 20°C and additional statistics from development data. Lateral expansion is not usually invoked as a notch ductility criterion for power plant materials or welds, but here it seems that when compared to the average trend for P91 weld metal, P92 welds may have a little more notch ductility.

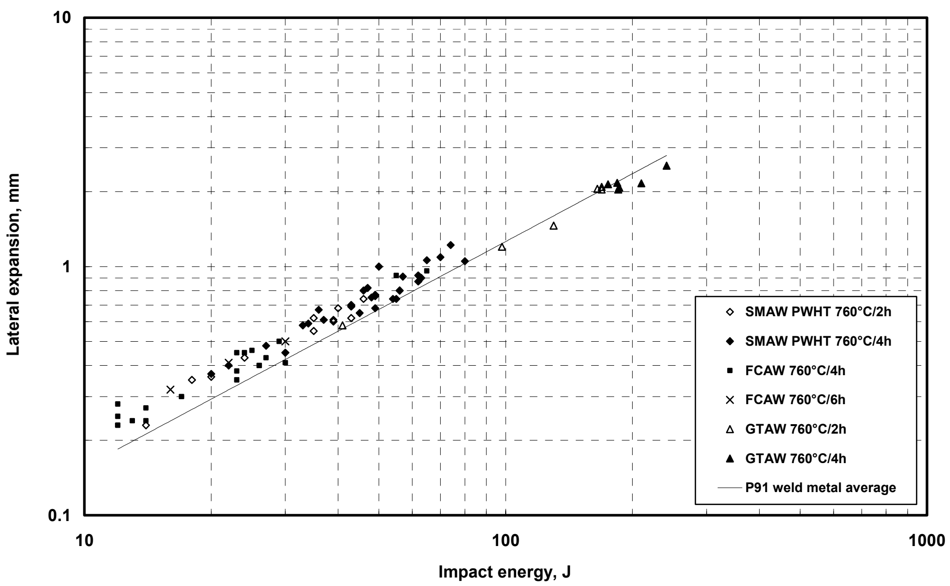

Figure 3. Relation between Charpy impact energy and lateral expansion of P92 weld metals, compared with average trend of P91 weld metals.

3.2 T23 weld metals

Table 4 gives representative all-weld metal compositions for two variants of SMAW electrodes and two flux cored wires (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. The flux cored wires are similar with one being nickel-free and the other having a deliberate nickel addition. In the course of development many other experimental batches of SMAW electrodes with minor variations were tested and the results are included to illustrate trends graphically.

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
FCAW (no Ni addition)	0.04	0.6	0.3	0.01	0.02	2.2	0.03	0.1	1.5	0.21	0.02	<0.02	20	0.003
FCAW (with Ni)	0.05	0.5	0.2	0.01	0.02	2.1	0.60	0.1	1.5	0.21	0.03	<0.02	26	0.003

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

3.2.1 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 for 2 hours. Hot tensile tests up to 550°C were also carried out on FCAW weld metal, and strength exceeded parent material minimum at all temperatures.

During SMAW development work, a slice from every all-weld test piece (most were for impact tests) was surveyed for hardness at the 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. Hardness below 350HV was considered desirable, but a number of tests exceeded this. However, there were underlying trends related to changing composition, as seen in Figure 4, 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.

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
	705°C/10h	20	577	660	22	68	225
Chromet 23H (SMAW)	715°C/2h	20	679	754	20	55	242
FCAW (no Ni addition)	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	/
	715°C/3h	20	/	/	/	/	211
FCAW (with Ni)	715°C/2h	20	649	713	14	26	251
		350	560	606	7	14	/
		450	517	576	7	32	/
		550	406	479	14	53	/

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

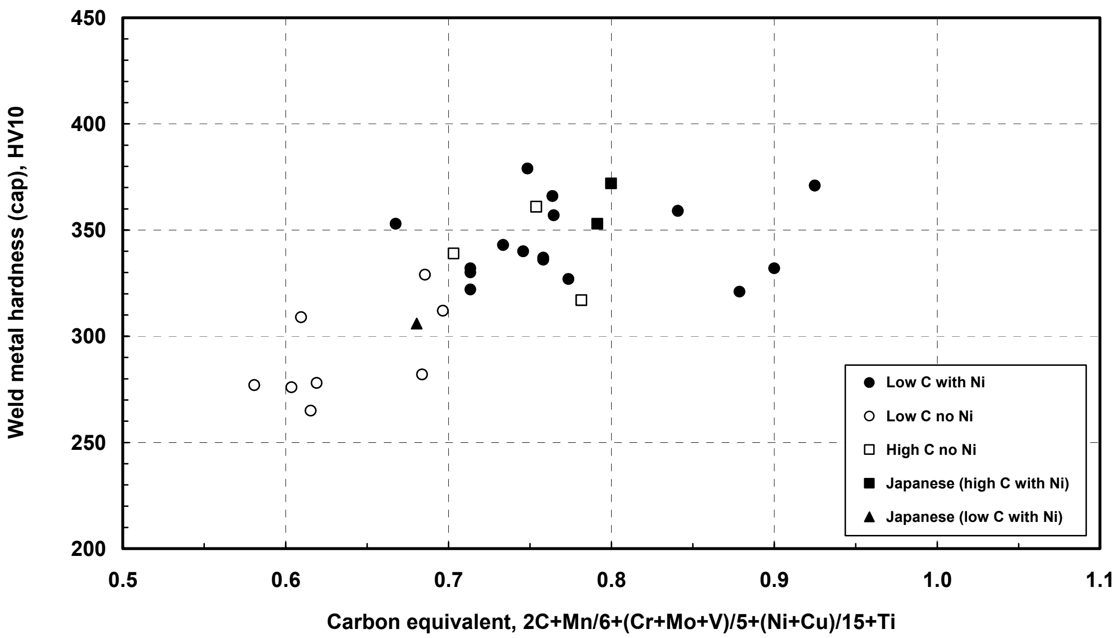

Figure 4. Relation of as-welded T23 SMAW weld cap hardness and carbon equivalent.

3.2.2 Impact properties.

Results of all-weld Charpy tests at 0°C and 20°C for representative batches of SMAW electrodes and flux cored wires are given in Table 6. Most testing was carried out on the Ni-bearing SMAW welds without PWHT. Before considering these, it is notable that the Ni-free SMAW and FCAW welds were satisfactory at 20°C after PWHT at 715°C, although at 0°C SMAW was distinctly higher in toughness after only 30 minutes PWHT than FCAW after 2-3hours PWHT. As-welded toughness of these Ni-free SMAW and FCAW welds was considered borderline at room temperature and unsatisfactory at 0°C.

Addition of Ni was found in general to improve as-welded toughness and also to raise lateral expansion relative to impact energy: Figure 5 shows these relationships for welds tested at 0°C, including Japanese examples. Welds with lower Nb 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 at ambient), and the toughest Japanese weld had 0.015%Nb.

The relatively low toughness found in welds without PWHT (below 27J at ambient, unless Nb is removed) is probably acceptable for applications in thin material or where impact testing is not specified. Optimization is currently aimed to ensure 15J at 20°C. After PWHT toughness can be greatly improved. The nickel containing welds equal or exceed the toughness of Ni-free welds and are therefore considered to be more versatile.

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
	705°C/10h	0	108	1.53
		20	121	1.59
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
FCAW (no Ni addition)	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
FCAW (with Ni)	715°C/2h	0	26	0.38
		20	95	1.35

Table 6. Impact properties of T23 weld metals.

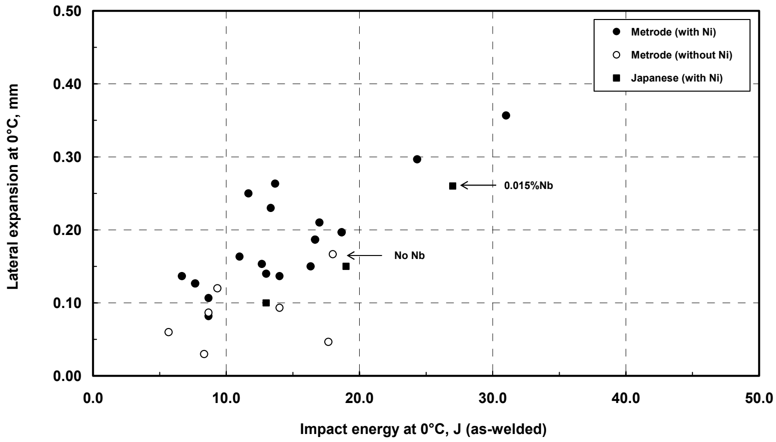

Figure 5. Relation between as-welded impact energy and lateral expansion at 0°C for T23 SMAW weld metals.

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 wall HCM2S pipe gave around 10-30J at 0°C (values derived from a graphical presentation and converted from J/cm^2) after PWHT at 715°C for 2 hours. The present Ni-free SMAW tests after equivalent PWHT gave higher values. The latter workers [3] also reported better toughness for GMAW and SAW pipe welds after PWHT, but most surprisingly found base material Charpy values scattered between 15J and 210J, whereas the lowest single HAZ value was around 67J, and HAZ values for each process formed a group with little scatter. Though not discussed by the authors, these observations might indicate a sensitivity to factors influencing the alloy's transformation behaviour (such as through-hardenability, as noted for thick 2¼Cr-1Mo [16,17]). Aside from such considerations, tests were reported [3] to show 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 welds in P91.

4.0 Conclusions

The merits of the common welding processes have been described with particular reference to the all-weld metal composition and properties of recently developed welding consumables for these materials. For P92 the welding processes were GTAW, SMAW, FCAW and SAW, 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. The following are some general conclusions:

P92 – Consumables which matched the base material analysis with the exception of a slightly higher Mn (~0.7%) and a deliberate Ni addition (~0.5%) have been shown to achieve satisfactory all-weld metal strength and toughness. Weld procedures the same as those proven for P91 produced satisfactory results although for optimum toughness the preferred PWHT was 760°C for a duration of 2 hours (possibly less) for GTAW, of 2-4 hours for SMAW and SAW, and of 4 hours for FCAW.

T23 – Consumables matching the base material analysis were only capable of achieveing toughness of 15-22J at +20°C which was considered borderline, but the toughness could be significantly improved by PWHT. SMAW consumables with an addition of ~0.7% Ni were capable of producing satisfactory as-welded properties, although peak hardness could exceed 350HV. After PWHT, SMAW and FCAW consumables with added Ni provided adequate strength, lower hardness, better ductility and significantly improved toughness, as appropriate for welding thicker material.

Overall it is concluded that the data presented provides confidence in the ability to weld the P92 and T23 alloys with the main arc welding processes (GTAW, SMAW, FCAW, SAW for P92 and SMAW, FCAW for T23) using procedures which have already been proven for existing CrMo base materials (eg. P91 and T22).

5.0 Acknowledgement

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