ALLOY DESIGN FOR SIMILAR AND DISSIMILAR WELDING AND THEIR BEHAVIOURS

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ABSTRACT

The need for higher thermal efficiencies necessitates the use of new materials in boiler and steam lines of future fossil-fired power stations. To meet these requirements, new ferritic - bainitic materials like grade P23 and grade P24 and new martensitic steels like P92, E911 have been developed. These steels have high economic importance both for the refurbishment of existing power stations and for new constructions with conventional steam parameters. A new martensitic 12 % Cr steel (VM 12) with increased scaling resistance is under intensive investigation. The development of matching filler metals for all mentioned above base materials is running parallel. The aim of this paper is to summarize the development of these new creep resistant filler metals. The authors will demonstrate the importance and advantages of the new welding consumables both for boiler construction (welding of tubes without PWHT) and for joining heavy-wall components in steam lines, making similar and dissimilar joints.

KEYWORDS

Creep resistant ferritic and martensitic filler metals, P23, P24, P92, E911, VM 12, similar and dissimilar joints, all weld metal properties, alloy design.

INTRODUCTION

It is the endeavour of operators of fossil fuel fired power stations to increase the efficiency of their installations through an increase of steam pressure and temperature in order to assure supply of electricity on a low cost level and with reduced CO_2 emission. Increase of service parameter requires adequate materials with sufficient creep strength. This is true for both base materials and welding consumables. All over the world numerous research projects are running to gain this aim. In Europe, one important research project concentrates in the COST Program, where turbine- and boiler makers, steel makers, producer of filler metals, research and university institutes and finally operating companies of fossil fuel fired power plants work together to improve material properties. At present time COST 536 is running, starting in summer 2004. Within this project about 50 partners of more than 15 European countries joined together in five different work packages: Alloy design, modelling, turbine group, boiler group and welding group. It is their aim to develop and to qualify creep resistant ferritic and martensitic materials for the use up to 650 °C steam temperature. The main focus of this contribution is with new welding consumables matching these new creep resistant filler metals, with special attention to alloy design.

1. NEW CREEP RESISTANT BASE MATERIALS

The demand for higher efficiency in fossil fired power plants lead to the development of new creep resistant materials during the last decades. They made it possible to increase the steam temperature up to the range of 625 °C for permanent service, using ferritic and martensitic materials.

Concerning martensitic steels, special attention was turned to the improvement of the 9 - 10 % Cr-steels. These grades had their basis in the well known grade T/P9 (X11CrMo9-1). As the next step forward, T/P91 (X10CrMoVNb9-1) was developed in the 1980th. To enhance its creep-rupture strength, the elements V, Nb and N were added to the alloy of T/P9. Following P91, two new grades have been developed nearly simultaneously: P92 which is a Japanese development and steel E 911 (X11CrMoWVNb9-1-1), which has been developed during the European Cost activities. The higher creep strength in comparison to P 91 was made possible by the addition of tungsten. E 911 is alloyed with approximately 1% W. P 92 has a higher W-content of 1.7 % [e.g. 1-4]. At the same time the Mo-content is reduced down to 0.5 %, to suppress the formation of δ-ferrite.]. The service temperature of these two grades is in the range of about 585 to 625 °C. At present time this is the upper possible temperature for the use of martensitic steels. For this temperature range both grades have sufficient creep strength. But with respect to scaling resistance both grades are worse than the well known and old steel X20CrMoV12-1 (X20), which is higher in Cr. As a consequence of such material behaviour life time of components at these high temperature will depend in future not only on creep strength properties, but even more on scaling resistance. [5]. During the actual running research program of Cost 536 the new grade VM 12 (X12CrCoW 12 2 2) from Vallourec & Mannesmann is under investigation. VM 12 was especially designed for the use up to 650 °C. This grade with a Cr content of 12 % Cr has a much better scaling resistance than P92 or E911 and comparable creep properties.

Striving for higher steam parameters has also led to increased requirements for the tube steels of water walls, which than can no longer be fulfilled with the previously used steels 13CrMo4-4 or T11/T12. In addition to higher creep-rupture strength, the construction of water walls also requires welding consumables without the need for a post weld heat treatment (PHWT). This new requirement profile leads to the development of the T/P23 steel (HCM2S) in Japan and T/P24 (7CrMoVTiB 10-10) by Vallourec & Mannesmann [6], which both not only prove suitable for being used as boiler tubes but also offer a favourable alternative to P 91 in the sector of heavy-wall high-pressure piping systems at temperatures from 500 to 570 °C. The advantages of these new steels are therefore not only important for power plants with high steam parameters, but also for new facilities with conventional parameters and for the refurbishment of existing facilities. **Table 1** will summarize the chemical composition of important new and already well approved - ferritic – bainitic and martensitic steels. For comparison and completeness materials like P 22 (11CrMo9-10), X20 (X20CrMoVW12-1) and P91 (X10CrMoVNb9-1) are mentioned, too. For all these materials, matching filler metals are available.

2. DEVELOPMENT OF NEW CREEP RESISTANT FERRITIC AND MARTENSITIC FILLER METALS

During development of new base materials it is of great importance, that corresponding filler metals with matching creep strength properties will be developed simultaneously. Concerning the alloy concept, it is the easiest way that the chemical composition is identical to those of the base material. That is true for a great number of filler metals, but not for all. Additional micro alloying elements and specialities concerning improvement of weldability and handling are the detailed knowledgement of the individual development departments. In the following matching filler metals for the two new ferritic bainitic steels T/P23 and T/P24 and for martensitic steels like P911, P92 and VM 12 will be introduced. For all of these grades Böhler Thyssen Welding has developed matching filler metals for common used welding processes like GTAW, SMAW and SAW. All filler metals mentioned in this paper base on solid wires and the chemical composition of these wires are matching the corresponding base metal. That means, all alloying elements are already in the wire.

In **table 2** the corresponding filler metals matching the steels mentioned in **table 1** are listed with their chemical composition and mechanical properties.

Table 1. Chemical composition of ferritic - bainitic and martensitic base materials including well approved grades like P22, X20 and P91

Grade	Weight-%										Service temp. °C 1)
	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	and	
Bainitic ferritic steels											
10 CrMo 9-10 (P22)	≤ 0,15	≤ 0,50	0,30 – 0,60	1,90 – 2,60	-	0,87 – 1,13					
HCM2S (T/P23)	0,04 - 0,10	≤ 0,50	0,30-0,60	1,90-2,60	-	≤ 0,30	0,20-0,30	1,45-1,75	0,02-0,08	N ≤ 0,010	≤ 550
7CrMoVTiB10-10 (T/P24) 1.7378	0,05 -0,095	0,15-0,45	0,30-0,70	2,20-2,60	-	0,90-1,10	0,20-0,30	-	-	N ≤ 0,010 B 0,0015-0,0070 Ti 0,05-0,10	≤ 550
Martensitic steels *(9 - 12 % Cr-)*											
X20CrMoV12-1 1.4922	0,17-0,23	< 0,50	< 1,0	10,0-12,5	0,30-0,80	0,80-1,20	0,25-0,35	-	-	-	≤ 575
X10CrMoVNb9-1 (P91) 1.4903	0,08-0,12	0,20-0,50	0,30-0,60	8,0-9,5	< 0,40	0,85-1,05	0,18-0,25	-	0,06-0,10	N 0,03-0,07	≤ 585
X11CrMoWVNb9-1-1 (E911) 1.4905	0,09-0,13	0,10-0,50	0,30-0,60	8,50-9,50	0,10-0,40	0,90-1,10	0,18-0,25	0,90-1,10	0,06-0,10	N 0,05-0,09	≤ 630
P92 (Nf616)	0,07-0,13	< 0,5	0,30-0,60	8,5-9,5	< 0,40	0,30-0,60	0,15-0,25	1,5-2,0	0,04-0,09	N 0,03-0,07 B 0,001-0,006	≤ 630
VM 12 (values of a real heat [7])	0,11	0,45	0,2	11,5	0,23	0,28	0,24	1,40	0,06	Co 1,6 N 0,056 B 0,003	≤ 650

1) constructive obvious working temperature limitation in power station service

Table 2. chemical composition of ferritic - bainitic and martensitic filler metals corresponding to steels mentioned in **table 1**

	base material	filler metal acc. DIN EN 1599/1600	filler metal composition											mech. properties all weld at RT			
														PWHT	YS	TS	toughness
			C	Si	Mn	Cr	Mo	Ni	Nb	V	W	Co	N	°C / h*	(MPa)	(MPa)	(J)
ferritic - bainitic	10 CrMo 9-10	E CrMo 2 B 42	0,07	0,25	0,70	2,20	0,90	-	-	-	-		-	690 / ≥ 2	510	620	180
	HCM2S (T 23)	EZ C2WV B 42	0,06	0,26	0,52	2,1	0,08	0,05	0,03	0,21	1,65		-	740/2	880	1000	16
	7 CrMoVTiB 10-10 (T24)	EZ CrMo 2VNb B 42	0,09	0,3	0,5	2,7	1,0	-	-	0,25	-		-	740/2	> 500	> 800	45
martensitic	X 20 CrMoWV 12-1	E CrMoWV 12 B 42	0,18	0,25	0,5	11,5	1,0	0,6	-	0,3	0,5		-	760 / ≥ 4	600	750	40
	X 10 CrMoVNb 9-1 (P 91)	E CrMo 9 B 42	0,09	0,22	0,65	9,0	1,1	0,80	0,05	0,20	-		0,04	760 / ≥ 2	600	750	50
	E 911	EZ CrMoWV 9 11 B 42	0,09	0,20	0,57	8,85	0,92	0,83	0,047	0,21	1,01		0,05	760 / ≥ 2	600	750	50
	P 92 (Nf 616)	EZ CrMoWV 9 0,5 2 B 42	0,098	0,23	0,66	9,23	0,53	0,66	0,037	0,20	1,62		0,06	760 / ≥ 2	600	750	45
	VM 12	EZ CrMoWV 9 0,5 2 B 42	0,11	0,5	0,6	11,2	0,3	0,7	0,06	0,25	1,5	1,6	0,05	770 / ≥ 2	600	750	> 27

3.1 MATCHING FILLER METALS FOR WELDING T/P24 (7CRMOVTIB10-10; 1.7378)

If you compare the chemical composition of steel P22 with P24, the close correlation is obvious. Carbon in P24 is reduced to max 0,095 % which improves the weldability. Creep properties have been strengthened by the addition of V, Ti and B. Finally N was limited to a low level of max 0,010 % in order to avoid the formation of Ti-nitrides. Alloying the base material with B and more especially with Ti was a problem for welding. Due to the large affinity of Ti to Oxygen there is a

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clear burn off of these elements during welding. This is true for all welding processes including GTAW, where the arc is protected in an optimum way by an inert shielding gas. But the loss of Ti is more severe for SMAW and SAW [8,9,10,11]. Up to a certain degree it is possible to compensate this (at least for SMAW and SAW process) by adding Ti bearing components to the coating or flux. Nevertheless such a high Ti content as required for the base material (0,05-0,1 %) can not be guaranteed for the weld. This lack has consequences on creep properties of welded joints and for the all weld metal.

Early tests of filler metals with Ti-matching chemical composition showed, that all required properties have been successfully achieved, except those for the creep strength. Investigations in different research projects showed, that, caused by the uncontrollable burn off of Ti, the HAZ in a P24 joint was no longer the weak point, but it was the weld itself with clearly differing Ti contents. Only under carefully controlled welding conditions inside a welding laboratory it seems to be possible to transfer enough Ti from the filler metal into the weld pool. Under field welding conditions that can not be guaranteed. Tests have shown, that depending on welding parameter and welding position clearly different Ti contents will result in the weld metal. Such a behaviour was very unsatisfactory and it could only be solved by exchanging Ti to another creep strength supporting element with lower affinity to oxygen. Therefore Ti was substituted successfully by Nb [12, 13]. **Table 3** shows the chemical composition and the mechanical properties of these T/P24 filler metals.

Table 3. Chemical composition and mechanical properties of all weld metal of filler metals matching T/P24

Chemical composition of different filler metals (weight %)

	C	Si	Mn	Cr	Mo	V	Ti	Nb	N	B
wire	0,061	0,24	0,53	2,39	1,01	0,24	0,073	0,008	0,016	0,0037
GTAW	0,061	0,23	0,49	2,29	1,00	0,24	0,034	0,007	0,014	0,0020
SMAW	0,064	0,47	0,56	2,38	0,97	0,24	0,043	0,008	0,022	0,0030
SMAW Nb-mod.	0,091	0,25	0,55	2,51	1,03	0,22	-	0,046	0,013	0,0011
SAW	0,050	0,20	0,72	2,26	0,98	0,22	0,015	0,007	0,009	0,0010

Typical mechanical properties of above mentioned filler metals

Welding process	**Ø (mm)**	**Test-temp. (°C)**	**PWHT (°C/h)**	**YS (MPa)**	**TS (MPa)**	**Elong. (%)**	**Toughness ISO-V (J)**	**Hardness (HV10)**
GTAW	2,4	+20	---	664	803	19,1	298 298 298	322
		+20	740/2	595	699	20,3	264 280 292	230
SMAW Ti modification	4,0	+20	740/2	507	626	21,9	155 163 166	233
		+600	740/2	306	366	25,6	---	192
Nb-modification	4,0	+ 20	740/2	577	689	18,1	154 152 148	221
SAW	4,0	+20	740/2	495	600	23,8	260 267 282	206

When welding thin walled tubes of water walls with the GTAW process, the PHWT can be waived, as the low carbon content of filler and base material prevent a hardness increase with values in excess of 350 HV 10 both in the weld metal and in the HAZ. Even without a PWHT highest toughness properties can be achieved. Also longitudinal SAW welding of water wall panels with matching filler metals is possible without PWHT. Using P24 filler metals for the welding of thick walled components (≥ 10 mm wall thickness), a PWHT is necessary for achieving a sufficient toughness level in the weld. For the post weld heat treatment, a temperature of 740 °C for at least 2 h for SMAW (4 h for SAW) is recommended.

Table 4 shows results of a welding test during qualification work. A heavy-walled P24-joint was welded using GTAW, SMAW and SAW. The root was GTA-welded as a single pass, followed by 2 passes with the stick electrode, and SAW filler passes of the remaining seam. The transverse tensile specimen fractured in the base metal. After PWHT at 740°C/2 h the weld metal toughness with values about 260 J is at a level comparable to that of the all weld metal. At a bending angle of 180°, the bending specimen did not produce any defects; the hardness value was less than 250 HV 10.

Table 4. Mechanical properties of a joint of P24 with matching filler metal Thermanit P 24

Pipe: 159 x 20 mm
Filler metal: root, GTAW: Ø 2,4 mm
2 fills: SMAW: Ø 2,5 and 3,2 mm
7 fills and cap: SAW: wire-Ø 3,0 mm
T preheat: 240 °C; T interpass: ≤ 320 °C
SAW: Is 420 A (=/+), Us: 27 V, travelspeed: 50 cm/min., heat input: 12,9 kJ/cm

PWHT °C/h	**Test temp. °C**	**TS (MPa)**	**Fracture location**	**Bending angle**	**Toughness (ISO-V) J**		**Hardness HV10**
					weld	HAZ	
740/2	+20	557	GW	180°	237 247 293	239 281 300	< 250
740/2	+600	348	GW	---	---	---	---

3.2 MATCHING FILLER METALS FOR WELDING T/P 23

HCM 2 S or T/P23 is a Japanese development. This grade found it´s origin in P22, too. The chemical composition of the steel is given in **table 1**.

Also for this grade, a filler metal for GTAW has been developed for the welding of water walls at first. As with P24, a PWHT can be waived, as the low carbon content prevents a hardness increase with values in excess of 350 HV 10. This is true both in the weld metal and the HAZ. It could be proved that this material is also well suited for heavy-wall components, so that in addition to the GTAW-process also stick electrodes and SAW filler metals are required. In this case, a PWHT is essential for achieving a sufficient toughness in the weld metal [8, 9, 10, 11]. **Table 5** shows the chemical composition of matching filler metals and gives the mechanical properties for various welding processes. For GTA-weld metal, the toughness is high with and without PWHT (740 °C) and can be above 200 J, depending on diameter and welding parameters. Hardness values amount to approx. 270 HV 10 without PWHT and to 250 HV 10 after PWHT. Slag producing welding processes like SMAW and SAW must be followed by a PWHT at 740 °C, as otherwise the toughness will only reach a level of about 20 J.

As steel P23 shows a susceptibility to stress relieve cracking [14] PWHT has to be carried out under careful consideration of the full construction. “Thin” walled components (10 – about 25 mm) and joints of pipes with consistent wall thicknesses can be cooled down to temperatures below 250 °C after welding. Thicker walled components or especially joints with major differences in wall thicknesses on both sides should be heated by an intermediate temperature in a range of 500 – 550 °C directly after welding (**fig. 1**). This treatment should than be followed by the standard PWHT at 740 °C. Such a kind of modified PWHT should help to avoid stress relief cracking for which P23 base material is sensitive [12, 15].

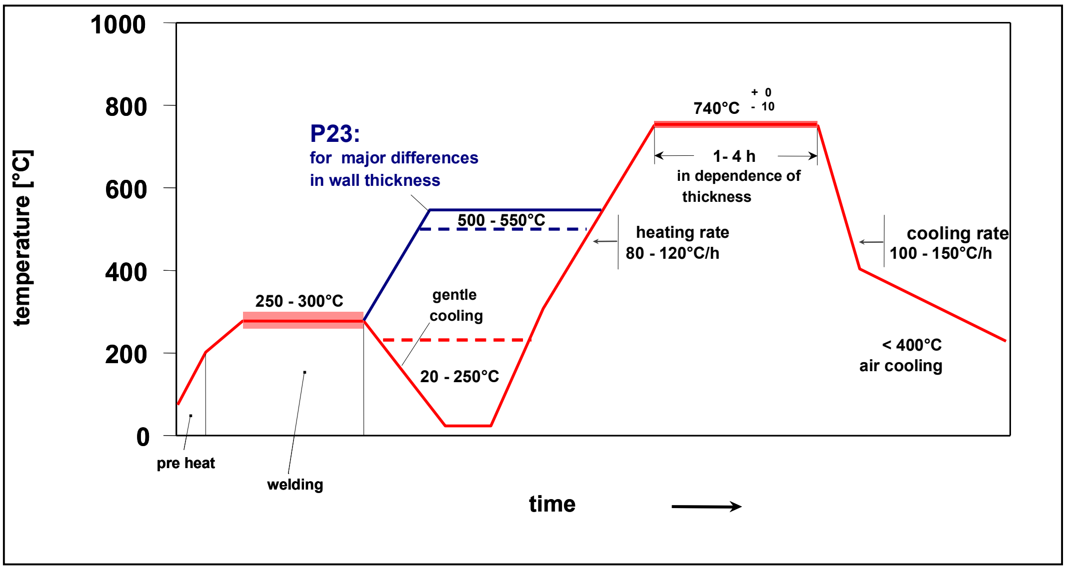

Fig. 1. Schematic temperature cycle during welding and PWHT of T/P23 ("modified black line") and T/P24

Table 5 summarizes the chemical composition and the mechanical properties of T/P 23 filler metals for all relevant welding processes. The mechanical properties of a heavy-wall butt weld of size OD 219.1 x 30 mm have been summarized in **Table 6**. The root was GTA-welded. The first and second filler passes were welded with stick electrodes of 2.5 and 3.2 mm in diameter, whilst the remaining 10 passes were welded by SAW process. PWHT for this wall thickness was performed at 740 °C for only 1 h. Even such a short PWHT resulted in a toughness level between 125 and 150 J. The transverse tensile specimen ruptured in the base metal. The hardness in the weld metal amounted to 250 HV 10 max. At a bending angle of 180°, the bend specimen did not show any defects.

Table 5. Chemical composition and the mechanical properties of T/P23 filler metals for all relevant welding processes

Chemical composition in weigth %

	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	N	B
wire	0,08	0,26	0,55	2,15	0,08	0,08	0,22	1,55	0,031	0,013	0,002
GTAW	0,08	0,27	0,54	2,14	0,04	0,08	0,21	1,58	0,031	0,011	0,002
SMAW	0,06	0,22	0,46	2,28	0,12	0,02	0,28	1,72	0,043	0,017	0,002
SAW	0,05	0,27	0,94	2,04	0,09	0,11	0,19	1,61	0,043	0,007	<0,001

Mechanical properties of all weld metal

Welding process	**Ø (mm)**	**Test-temp (°C)**	**PWHT (°C/h)**	**YS (MPa)**	**TS (MPa)**	**Elong. (%)**	**Toughness ISO-V (J)**	**Hardness (HV10)**
GTAW	2,4	+20	-	639	818	21,4	228 230 268	270
		+20	740/2	520	620	20,2	261 286 299	250
		+550	740/2	426	449	17,4	---	---
SMAW	4,0	+20	740/2	509	625	19	128 136 140	227
		+20	740/15	421	553	25	156 156 160	192
		+550	740/15	302	350	26,4	---	---
SAW	4,0	+20	740/2	615	702	18,1	187 204 208	237

Table 6 . Test results of a joint P23 with matching filler metal Thermanit P 23

Pipe: Ø 219 mm x 30 mm
filler: root: GTAW: Ø 2,4 mm
2 fills: SMAW: Ø 2,5 and 3,2 mm
10 fills: SAW; wire-Ø 3,0 mm
T preheat.: 250 °C; T. interpass: max. 300 °C.
UP: I_s = 450 A (=/+); U_s = 28 V; v_s = 52 cm/min.; E = 14,5 kJ/cm

PWHT °C/h	**Test temp. °C**	**TS (MPa)**	**Fracture location**	**Bending angle**	**Toughness (ISO-V) J**		**Hardness HV10**
					weld	HAZ	
740/1	+20	580	GW	180°	124 150 153	92 156 223	< 250
740/1	+600	333	GW	---	---	---	---

3.3 MATCHING FILLER METALS FOR MARTENSITIC GRADES LIKE E911 AND P92

The toughness level of martensitic weld deposit is generally on a lower level than in the ferritic ones [16]. The reasons for this are based in the martensitic structure and in alloying elements like C, Nb, N, B and W. These elements form creep strength supporting particles, grains and precipitations, but at the same time they decrease the general toughness level in the weld. Therefore the guaranteed minimum values for the all weld metal orientates itself at the minimum of the base metals, which is ≥ 41 J at room temperature.

There are some possibilities for the developing engineers of filler metals as well as for the welder, to react on this [17]. The negative toughness influence of these elements can partially be compensated by an increase of Ni. Whereas the Ni content in the steel grades P91, P92, E911 is limited to a maximum of 0.40 %, the upper limit of Ni in the weld metal is increased to ≤ 1 %. At the same time the Nb content in the weld metal is reduced (to min. 0,04 %) in comparison to the base metal (min. 0,06 % for P91 and E911). Both will increase toughness in the weld. In addition, Mn and Ni must be adjusted, too: “Mn + Ni ≤ 1.5 %” have to be maintained, because both decrease the lower transformation point Ac_{1b} [18]. **Figure 2** and **3** show as an example the influence of Ni and Nb on the toughness properties on grade P 91. These results can be related directly to P92 and E911. **Figure 4** shows the influence of B on toughness of P92 and E911.

The martensitic steels are welded in the “martensitic range”, this means preheat- and interpass temperatures are between 200 °C and 300 °C. Due to the martensitic structure and the required toughness, great care is necessary during welding, regarding thickness of individual weld layers, heat input and later with the post weld heat treatment. Pure martensitic transformation results from wall thickness’ up to about 80 mm followed by air cooling and begins at temperatures about 400 °C. With greater wall thickness ferrite and carbide will be formed due to the longer cooling periods. At these wall thickness’ accelerated cooling is necessary to maintain a pure martensitic structure. This is valid for P91, E911 and P92. After welding a PWHT is carried out at 760 °C. Here after hardness is approximately 250 HV 10. This low hardness in these steels is caused by the reduced C content in P91, P92 and E911 (compared to X20) and it makes further processing easier. Directly after welding, the hardness in the weld metal is with approximately 400 HV 10 about 100 units below the hardness of the weld metal for X20. Therefore the risk of cold cracking is reduced, so that after welding and before PWHT, cooling down to room temperature is possible [17, 19]. It is important that the weld cools completely below martensitic temperature before heat treatment. This is to achieve total post weld tempering of all martensite through the ensuing heat treatment. The martensitic finish temperature (m_f) of P91, E911 and P92 is in the range of 150 °C, so that cooling to at least 100 °C is required.

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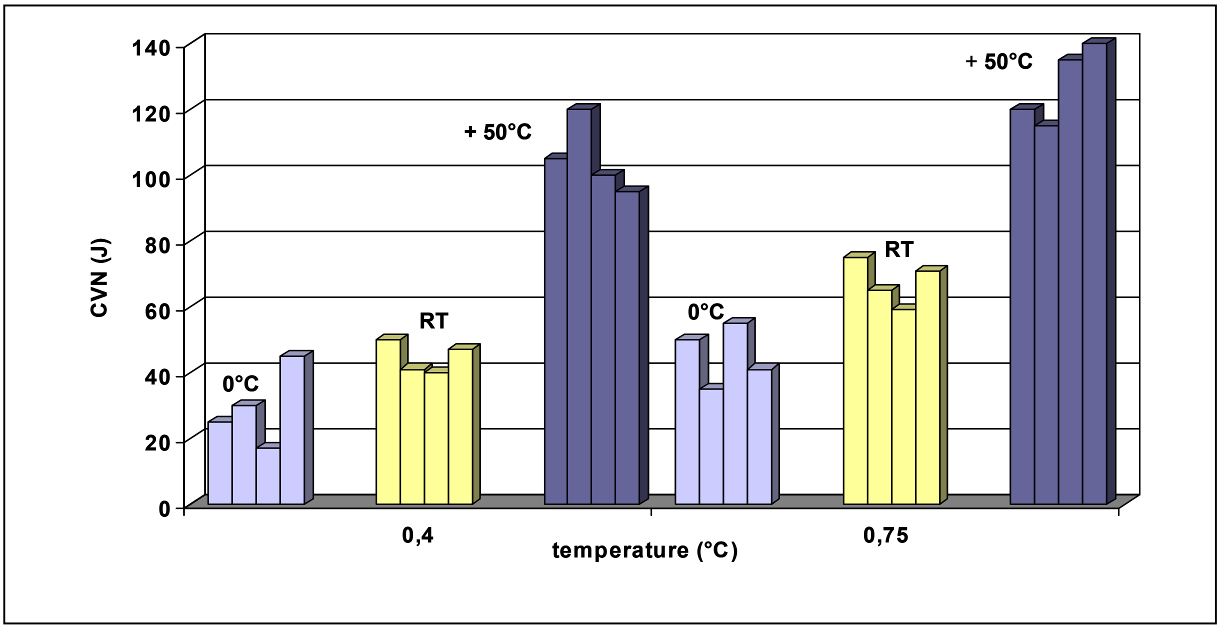

Fig 2. Influence of Ni on toughness of all weld matching to P91, different test temperatures

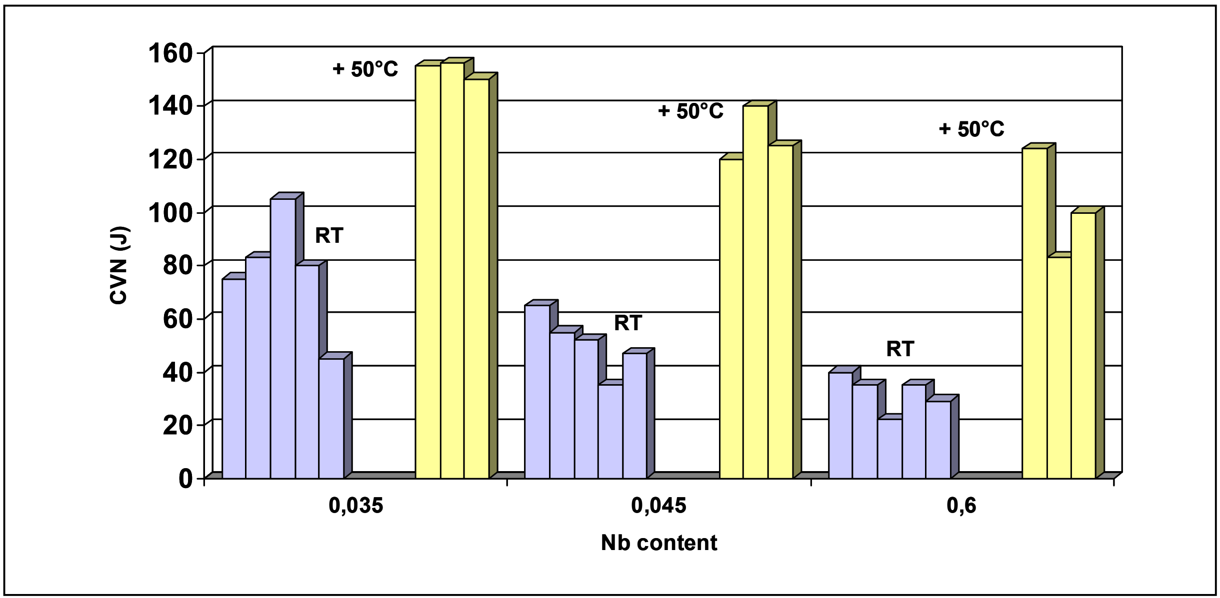

Fig. 3. Influence of Nb on toughness of all weld matching to P91, different test temperatures

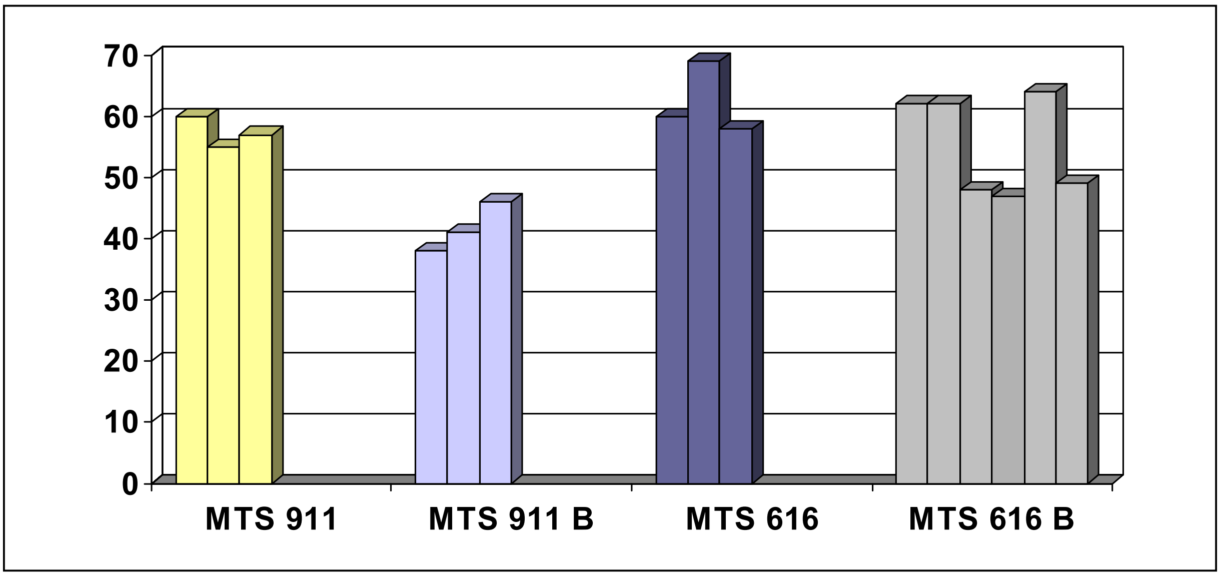

Fig. 4. Influence of B on toughness of martensitic filler metals matching P92 and E911

In dependence of the temperature during PWHT the toughness level can be influenced as a function of the holding time. The recommended temperature for these grades is 760 °C, but under certain conditions, e. g. for dissimilar joints, a lower temperature could be necessary. In this case a longer holding time will compensate the lower temperature. **Figure 5** shows this behaviour for all weld metal of the electrode Thermanit MTS 616.

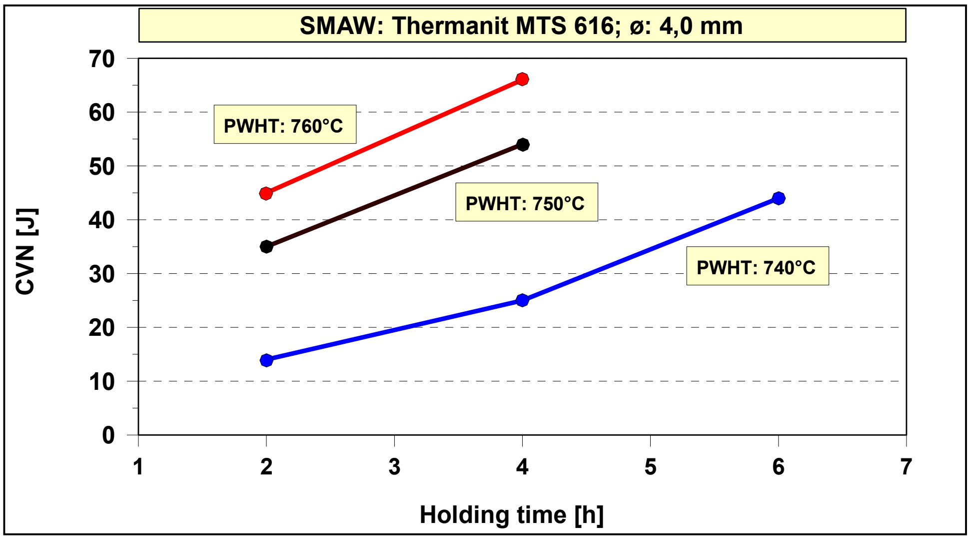

Fig. 5. Influence of temperature and holding time on toughness for all weld metal matching to P92

During qualification tests several thick walled pipe joints of E911 and P92 have been welded, using different welding processes. After welding the joints cooled down carefully to RT, and PWHT was carried out at 760 °C. **Table 7** and **8** list the results for these joints, showing SAW data.

All test results meet the requirements (**table 2**) not only at room temperature but also at elevated temperatures (600°C). In **Table 7** and **8** one can also see the influence of a too short PWHT. In both cases toughness in the all weld metal is not sufficient after a heat treatment of only 2 hrs at 760 °C.

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However after heat treatment with recommended duration (4 hrs for SAW), the required toughness values of ≥ 41 J are clearly exceeded.

Table 7. Results of SAW pipe joint with E911 using Thermanit MTS 911 as matching filler metal

SAW wire /flux combination: Thermanit MTS 911 / Marathon 543
wire-Ø: 3,2 mm; Is: 380 - 420 A; Us: 28 - 30 V
travel speed: 500 - 600 mm/min.; T pre heat: 250 °C; T inter pass: 300 - 330 °C

Chemical composition of all weld metal and from the joint (weight %)

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**	**W**	**N**	**Nb**
all weld	0,10	0,38	0,59	0,016	0,004	8,99	0,89	0,74	0,18	0,90	0,063	0,045
joint	0,106	0,36	0,57	0,017	0,004	9,04	0,89	0,68	0,20	0,95	0,065	0,039

Mechanical properties of
a) all weld

Test temp. °C	**PWHT °C/h**	**YS MPa**	**TS MPa**	**Elong. %**	**Toughness (ISO-V) J**
+20	760/**2**	705	825	19,8	31 27 42
+20	760/**4**	685	798	20,6	63 41 56

b) joint: E911, pipe-Ø$_a$: 336 mm, wall thickness: 62 mm

Test temp. °C	**PWHT °C/h**	**YS MPa**	**TS MPa**	**Elong. %**	**Fracture location**	**Toughness (ISO-V) J**	**Hardness HV10**
+20	760/4	466	653	16,0	BM	50 60 56	247 - 253
600	760/4	284	344	17,5	BM	-	-

Table 8. Results of SAW pipe joint with P 92 using Thermanit MTS 616 as matching filler metal

SAW wire /flux combination: Thermanit MTS 616 / Marathon 543

wire-Ø: 3,2 mm; Is: 380 - 420 A; Us: 28 - 30 V
travel speed: 500 - 600 mm/min.; T preheat: 250 °C; T inter pass: 300 - 330 °C

Chemical composition (weight %)

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**	**W**	**N**	**Nb**
all weld	0,09	0,36	0,60	0,015	0,005	8,45	0,41	0,73	0,17	1,59	0,059	0,034
joint	0,097	0,34	0,60	0,016	0,004	9,14	0,43	0,66	0,17	1,63	0,047	0,034

Mechanical properties of
a) all weld

Test temp. °C	**PWHT °C/h**	**YS MPa**	**TS MPa**	**Elong. %**	**Toughness (ISO-V) J**
+20	760/**2**	678	789	19,8	27 37 41
+20	760/**4**	621	742	20,8	57 61 41

b) joint: P92, pipe-Ø$_a$: 300 mm, wall thickness: 40 mm

Test temp. °C	**PWHT °C/h**	**YS MPa**	**TS MPa**	**Elong. %**	**Fracture location**	**Toughness (ISO-V) J**	**Hardness HV10**
+20	760/4	502	678	15,0	GW	96 88 84	234 - 249
600	760/4	293	355	18,0	GW	-	-

In the datasheet of the base materials a PWHT of 730 to 780 °C is mentioned for P92 and E911. Generally it is to be noted, that the PWHT parameters: temperature and time, are critical for the required toughness and must be carried out exactly, whereby both must be brought into line. The recommended heat treatment temperature of 760 °C must be taken as a regulation figure, whereby a tolerance range of +0°C, -10°C is to be aimed for.

3.4 MATCHING FILLER METALS FOR WELDING MARTENSITIC THE NEW GRADE VM 12

During service, the before mentioned base materials E911 and P92 can be used up to max. 620 °C. At higher temperatures, scaling resistance is not sufficient any more. In this high temperature range material with higher Cr content is necessary. In the European research program COST 536 such a material developed by Vallourec & Mannesmann [7],– VM 12 (X12CrCoW12 2 2) and suitable up to 650 °C - is under investigation. Böhler Thyssen Welding has developed a matching filler metal to VM 12 [12,13]. In comparison to E911 or P92, this grade has a higher Cr content of about 11,5 %. As this will cause formation of ferrite, additional Co as an austenite stabilising element is used. Cobalt will act like Ni, but without influencing the A_{c1b} –temperature. The chemical composition of the filler metal matching to the new grade VM 12 is given in **table 9**.

Although the development of the base material and the consumables is not finished so far, main results are already available. The all weld metal can be characterized as high strength material with YS above 650 MPa and with TS above 750 MPa. Creep strength for base and filler materials is on the level of P92 or E911. Toughness properties of the filler metal at room temperature are about 40 J. This is a level clearly below P92 and E911 and similar to those of the old X20. Modifications of Ni in the filler metals, as it was carried out successfully with the Thermanit MTS 911 and MTS 616, seems not to be successful with the VM 12. Nevertheless the present toughness level is sufficient, as the minimum required values are given with ≥ 27 J according European regulations. On the other hand it is clear and necessary, to take outmost care during welding (limitation of heat input, correct choice of electrode Ø, welding thin layers with gentle weaving technique, etc). A PWHT is necessary for all welding processes at 770 °C. This is higher than with the other 9 % Cr steels, but with a PWHT at only 760 °C, sufficient toughness can not be guaranteed and values show a greater scatter band, too. A_{c1b}-temperature of the weld was determined at 800 °C. The following table shows the chemical composition and the mechanical properties of the all weld metal for Thermanit MTS 5 CoT.

Table 9. Chemical composition and mechanical properties of the all weld metal of Thermanit MTS 5 Co T

Chemical composition (weight %)

	C	Si	Mn	Cr	Ni	Mo	V	W	Co	Nb	B	N
GTAW	0,12	0,51	0,39	11,60	0,30	0,28	0,26	1,51	1,63	0,06	0,005	0,05
SMAW	0,11	0,45	0,65	11,15	0,70	0,30	0,25	1,50	1,60	0,06	0,003	0,05
SAW	0,10	0,50	0,60	11,30	0,65	0,29	0,23	1,50	1,60	0,04	0,003	0,06

Mechanical properties of all weld

	Test temp. °C	PWHT °C/h	YS MPa	TS MPa	Elong. %	Toughness (ISO-V) (RT) J	Toughness (ISO-V) (+50 °C) J
GTAW	+20	770/2	767	906	18	50 23 32	
SMAW	+20	770/2	694	835	16	46 34 42	57 66 58
	600	770/2	335	423	18		
SAW	+20	770/4	688	819	18	36 48 46	

Table 10 shows the results of a joint VM 12 welded with matching SAW filler metal Thermanit MTS 5 Co T.

Table 10. Joint: VM12, pipe-$Ø_a$: 406 mm, wall thickness: 35 mm

wire-Ø: 3,2 mm; Is: 380 - 420 A; Us: 28 - 30 V
travel speed: 500 - 600 mm/min.; T pre heat: 250 °C; T inter pass: max. 300 °C

Test temp. °C	**PWHT °C/h**	**Ys MPa**	**Ts MPa**	**Fracture location**	**Toughness (ISO-V) J**	**Hardness HV10**
+20	770/4	576	765	GW	45 41 31	260
600	770/4	293	383	GW	-	-

4. DISSIMILAR JOINTS

Dissimilar joints between martensitic and low-alloy ferritic steels as well as with austenitic steels can be produced without problems. In general, the standard filler metals are used for such mismatching joints. Mismatching joints however demand certain compromises concerning welding technology and necessary PWHT. In principle there are three possibilities for choosing the best kind of filler metal:

- Matching to lower alloyed grade
- Matching to higher alloyed grade
- Mismatching to both sides

Figure 6 will give a schematic view about these possibilities. There are examples for three basic mismatching possibilities:

- Joint of two martensitic base metals, one is X 20
- Joint of ferritic to martensitic material
- Joint of martensitic to austenitic material

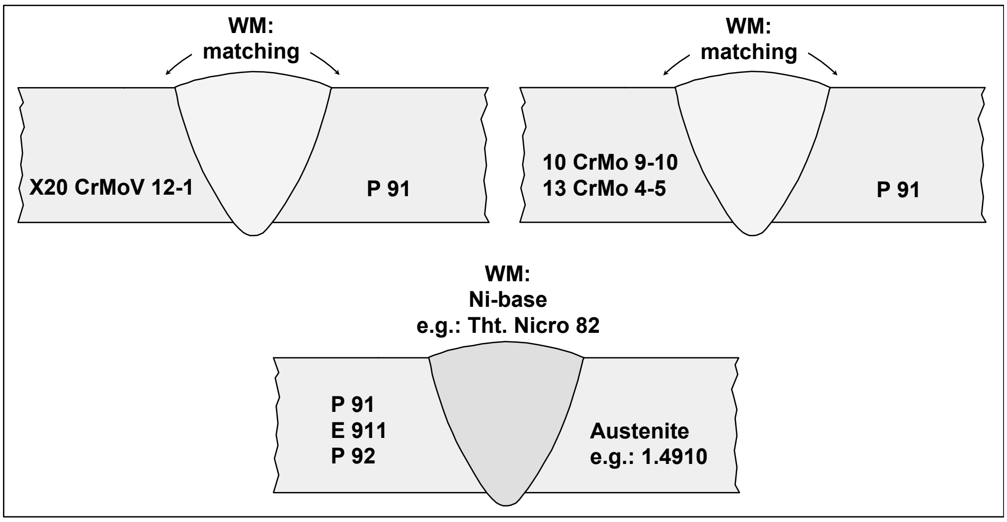

Fig. 6. Schematic demonstration of possible filler metal choice for dissimilar welds between

In dependence of the different chemistry of the involved partners of the joint one have to encounter the phenomenon of the so called "up–hill" diffusion of carbon in this kind of welds. Carbon diffusion will happen as a function of C - concentration, and temperature-/-time during PWHT. Due to the difference in Cr - content between the involved materials, Carbon moves during PWHT from the low Cr material into the neighboring high Cr - steel or weld metal. The resulting decarburized zone cannot be avoided, unless a nickel-base filler metal would be used. On the other side of the joint a high C - zone of Cr-carbides will cause a zone with increased hardness. These two micro structural changes have an effect on room temperature toughness. However, creep rupture strength of such a dissimilar weld usually is not affected. The fine grained intercritical HAZ of the low-alloy ferritic steel remains the weak zone during longtime service exposure.

Beside this phenomenon, another aspect for consideration can be seen in the different recommended PWHT of the involved two base materials. PWHT of the dissimilar joint has to be in accordance with the specifications of the low-alloy ferritic steel. As an example there is a trend, that more and more the filler metal matching to P91 is used for dissimilar weld P 91 to P 22/23/24 (**table 11**). In this case it is necessary to increase the PWHT time at the max. allowable temperature for P22, P23 and P24 to guarantee sufficient toughness in the weld.

Table 11. Mechanical properties of a dissimilar joint P23 to P91 welded with matching filler metal to P91

joint: P 23 – P 91, Ø 219 mm x 25 mm
filler: root: GTAW: Ø 2,4 mm, Thermanit MTS 3
all fills: SMAW: Ø 2,5 and 3,2 mm, Thermanit Chromo 9 V

T preheat.: 180 °C; T interpass: max. 250 °C. E = max. 12 kJ/cm
Welding pos.: PF
PWHT: 740°C / 2h

Test temp . °C	**Position of specimen**	**TS (MPa)**	**Fracture location**	**Bending angle**	**Toughness (ISO-V) J**		
					weld	HAZ (of P23)	HAZ (of P91)
20	12:00	565	P23	180°	106 136 119	235 212 231	150 135 165
20	06:00	563	P23	180°	100 81 86	189 199 212	112 125 140
550	12:00	367	P23	---	---	---	---

The best way to realize a joint between a martensitic (e. g. P91) and an austenitic steel is by making a buffer layer on the low alloyed side of the joint. At first a Ni-base weld metal is deposited on the T/P91 piece followed by a PWHT similar to T/P91 base material. This buffered pipe can than be joined to the austenitic partner by using a Ni-base filler (e. g. Thermanit Nicro 82) without PWHT. In order to reduce welding stresses, a multiple bead technique with low heat input should be used. In case of thin walled tubes, a transition between T91 and an austenitic steel is usually done by direct welding with a Ni-base filler followed by a PWHT at about 760 °C.

5. CONCLUSION

Thanks to their specific chemical composition and mechanical properties at room and elevated temperature, new ferritic and martensitic base materials like T/P23; T/P24 ; E911 and T/P92 fulfill all the requirements for a beneficial and safe use in new (Ultra) Super Critical Boiler plants. Matching filler metals for the above mentioned base materials have been developed and qualified for all commonly used welding processes. A new martensitic base material (VM 12) with improved scaling resistance and the corresponding filler metals are under intensive investigation. Testing has demonstrated that the filler metals fulfill all requirements of the base metal using the appropriate welding procedures and right temperature cycles. That is true both for similar and dissimilar joints. All materials are commercially available.

HOME

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