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Pipe steels for modern high-output power plants

METALLURGICAL PRINCIPLES – LONG-TERM PROPERTIES – RECOMMENDATIONS FOR USE
FILLER METALS AND THEIR USE IN WELDING

Part 1: Metallurgical principles - Long-term properties - Recommendations for use

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This article examines martensitic and bainitic materials which will, in future, permit steam temperatures of up to 625 °C in fossil-fuelled power-generating plants. Re-evaluation of the creep rupture strength data for E911 and P92 provide designers with reliable characteristics data for calculation. A new 12 % chromium steel (VM12-SHC) closes the gap between the 9 % chromium steels E911 / P92 and austenitic pipe steels for the heated boiler-tube zone in a temperature field up to 620 °C.

Development of the welding filler materials examined here must be accomplished virtually simultaneously with the development of each respective parent material. The strength data determined for the weld in creep rupture testing is needed by the designer to assure safe design of components continuously exposed to high pressure and temperature. The development for high-temperature steels of welding filler materials which, on the one hand, meet the strength and corrosion standards of the parent materials and, on the other hand, assure good weldability and adequate toughness, remains a demanding task. Part 2 of the article (Page 12) reports on this.

1. Introduction

The projects currently in service or under preparation at both national and international levels prove that, despite major efforts and advances in the utilization of alternative energy sources, fossil energy sources will continue to serve as the basis for power generation worldwide for some years to come. Tighter economic constraints and the requirements of environmental protection call for more cost-effective and ecologically more acceptable energy supplies than in the past. This can only be achieved by using less fuel, i.e. reducing the specific fuel-energy consumption per kilowatt-hour produced. The key to all this must therefore be a further increase in the efficiency of the new power stations compared with the modern plants brought on-stream in Germany between 1992 and 2002. New design and process solutions represent only part of the whole spectrum of possibilities. The main factors influencing a rise in efficiency are the steam parameters, i.e. pressure and temperature, which need to be pushed up yet further. Besides the demand for high creep rupture strength, the use of the currently available martensitic 9-12 % Cr steels is limited by their insufficient resistance to high-temperature corrosion. In 2005, the creep rupture strength of the steels E911 (X11CrMoWVNb9-1-1) and T/P92 (X10CrWMoVNb9-2) was reassessed for Europe by the European Creep Collaborative Committee (ECCC), and this has put a stop for the time being to further raising steam temperatures to above 625 °C [1]. Properties, application limits and processing conditions therefore constitute the main focus of this paper. A brief outline of the development status of a new 12 % Cr steel with improved resistance to high-temperature corrosion may serve as a pointer to the direction of future work.

Another factor is that a further raising of the steam parameters for the new generation of power plants to around 600/625 °C pushed to their limits the strength reserves of the steels previously used for water wall panels, such as 16Mo3 and 13CrMo4-5. As a result, new water wall panel steels were urgently required, and this led to the development of the steels T/P23 and T/P24 (7CrMoVTiB10-10). Here, therefore, the main focus will be on these low-alloy steels, indicating the wide range of possible applications as well as their technical and economic potential, not just for the new generation of power plants, but also for upgrading and modernizing projects in existing power stations which are still technically and economically viable and important.

2. Properties of martensitic 9-12 % Cr steels and recommendations for their use

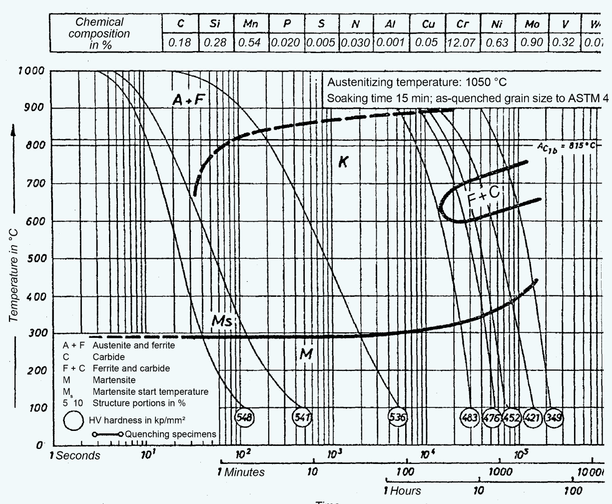
2.1 General material properties of 9 % Cr steels

The development of the steels T/P91 (X10CrMoVNb9-1), E911 (X11CrMoWVNb9-1-1) and T/P92 (X10CrWMoVNb9-2) started off from the martensitic 9 % Cr steel T/P9 (see **Table 1**). The German steel X20CrMoV11-1, which belongs to this group of materials, has also been included in the considerations for the purpose of comparison.

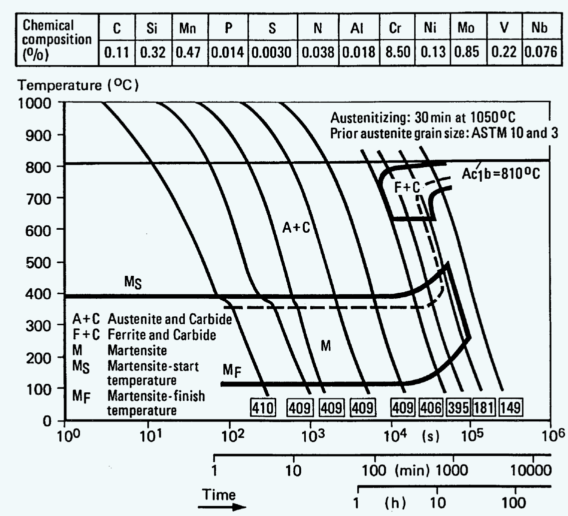
The higher creep rupture strength of X20CrMoV11-1 steel compared with T/P9 is essentially due to the complex effect of the Cr content in conjunction with Mo and V and the resultant martensitic structure, which is stabilized through the precipitation of $M_{23}C_6$ carbides. With P91 steel, a further increase in strength through precipitation hardening has been achieved via finely dispersed V/Nb carbonitrides of the MX type. Yet a further increase in strength was attained in the steels E911 and T/P92 by alloying with tungsten. The beneficial effect of tungsten on the creep rupture strength characteristics is highly complex and has still not been clarified in every detail. For example, the Laves phase Fe_2 (Mo, W) is precipitated even after thermal loads. This precipitation of coarse Laves phase counteracts the original solid-solution hardening effect, which in fact means that an extended exposure to thermal stress may be followed by a drop in creep rupture strength, as will be shown.

	T/P9	T/P91 X10CrMoVNb9-1	E911 X11CrMoWVNb9-1-1	T/P92 X10CrWMoVNb9-2	X20CrMoV11-1
C	max. 0.15	0.08 - 0.12	0.09 - 0.13	0.07 - 0.13	0.17 - 0.23
Si	0.25 - 1.00	0.20 - 0.50	0.10 - 0.50	max. 0.50	0.15 - 0.50
Mn	0.30 - 0.60	0.30 - 0.60	0.30 - 0.60	0.30 - 0.60	max. 1.00
P	max. 0.025	max. 0.020	max. 0.020	max. 0.020	max. 0.025
S	max. 0.020	max. 0.010	max. 0.010	max. 0.010	max. 0.020
Al	max. 0.040	max. 0.040	max. 0.040	max. 0.040	max. 0.040
Cr	8.00 - 10.00	8.00 - 9.50	8.50 - 9.50	8.50 - 9.50	10.0 - 12.50
Ni	-	max. 0.040	0.10 - 0.40	max. 0.040	0.30 - 0.80
Mo	0.9 - 1.10	0.85 - 1.05	0.90 - 1.10	0.30 - 0.60	0.80 - 1.20
W	-	-	0.90 - 1.10	1.50 - 2.00	-
V	-	0.18 - 0.25	0.18 - 0.25	0.15 - 0.25	0.25 - 0.35
Nb	-	0.06 - 0.10	0.06 - 0.10	0.04 - 0.09	-
B	-	-	0.0005 - 0.0050	0.0010 - 0.0060	-
N	-	0.030 - 0.070	0.050 - 0.090	0.030 - 0.070	-
Cu	max. 0.30	max. 0.30	-	-	max. 0.30

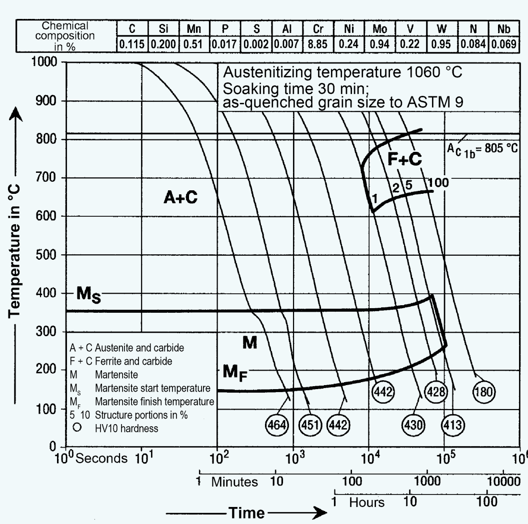
> Table 1 - Comparison of the chemical compositions of steels T/P9, T/P91, E911, T/P92 and X20CrMoV11-1 according to EN10216-2



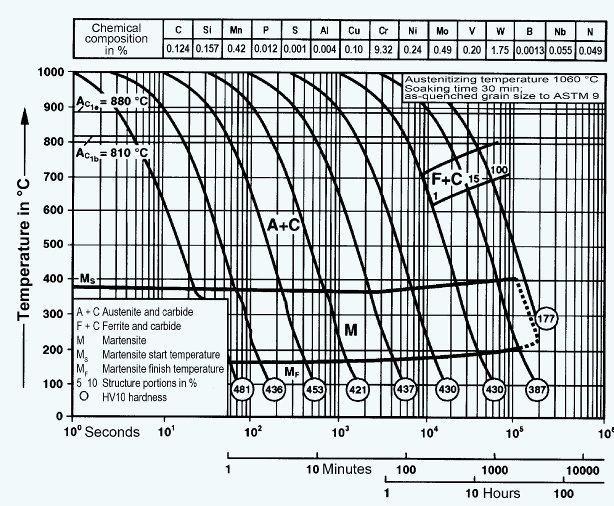
> Fig. 1 - CCT diagram for steel X20CrMoV11-1



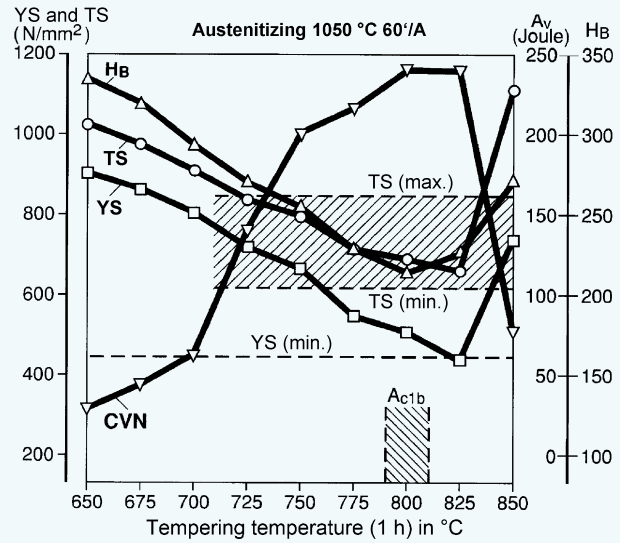
> Fig. 2 - CCT diagram for steel T/P91 (X10CrMoVNb9-1)



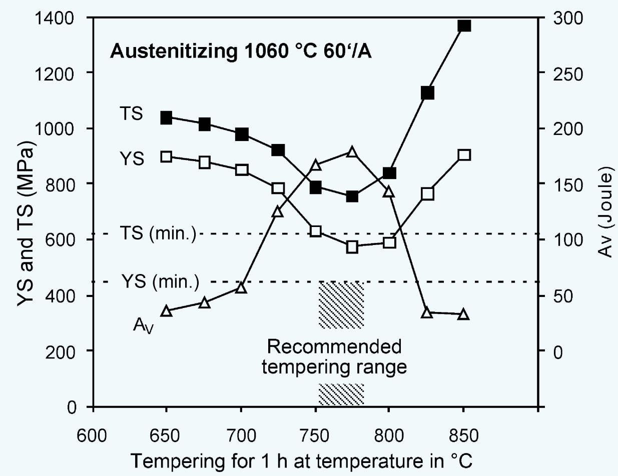
> Fig. 3 - CCT diagram for steel E911 (X11CrMoWVNb9-1-1)



> Fig. 4 - CCT diagram for steel T/P92 (X10CrWMoVNb9-2)



> Fig. 5 - Tempering behaviour of steel T/P91 (X10CrMoVNb9-1)



> Fig. 6 - Tempering behaviour of steel E911 (X11CrMoWVNb9-1-1)

All of the above mentioned martensitic Cr steels share the same transformation behaviour, as can be seen from a comparison of the CCT diagrams for the steels X20CrMoV11-1, P91, E911 and P92 in **Figures 1 to 4**. They also reveal a shift in the ferrite region towards long cooling times. Complete martensite transformation occurs even with relatively slow cooling. Due to the reduced carbon content compared with X20CrMoV12-1 steel, 9 % Cr steels form a martensite which is lower in carbon, and this leads to an approximately 100 °C higher martensite finish temperature. At the same time, the martensite hardness is reduced by about 150 HV units. These conditions have a positive effect on the processing behaviour (hot forming and welding).

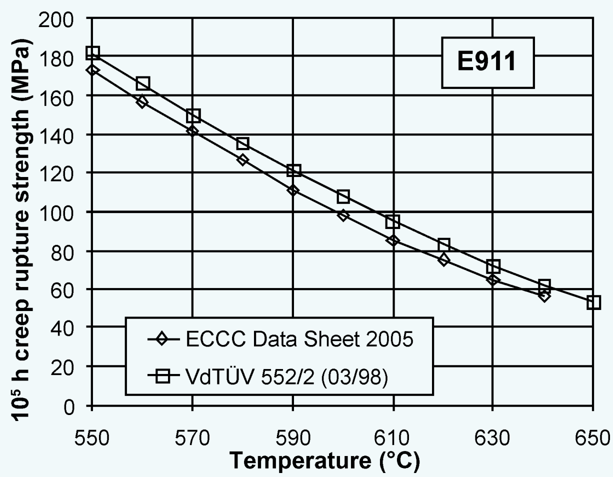
Generally, defined creep rupture strength properties for the above 9 % Cr steels can only be attained through a suitable heat treatment, i.e. cooling from the normalizing temperature must be at a fast enough speed for the cross section of the respective component. Decisively, the component must be cooled to below the martensite finish temperature to ensure complete martensite transformation and hence the presence of only tempered martensite after the subsequent temper treatment. Air cooling is sufficient for seamless pipes with large wall thicknesses of up to about 130 mm, as the extensive tests conducted at Vallourec have shown. Forgings with large heat treated cross sections, in particular, should be subjected to cooling in oil or a comparable emulsion in order to ensure martensite transformation through the entire cross section.

Figures 5 and 6 plot the effect of different tempering temperatures on the short-time strength characteristics of the steels T/P91 and E911. Optimum properties are achieved at tempering temperatures of between 750 and 780 °C. Steel T/P92 shows an analogous behaviour [2]. As is seen from **Table 2**, the heat treatment specifications are all the same for these steels, which makes for easy handling and fabrication. Another important advantage is the high tempering resistance of martensitic steels compared to the group of low-alloy CrMoV steels.

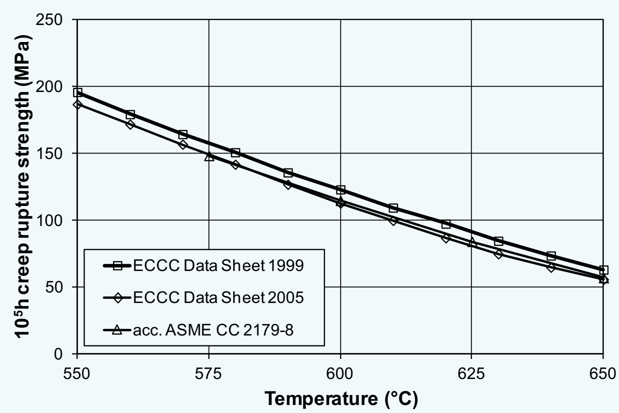
Steel grade	Normalizing temperature °C	Tempering temperature °C
X20CrMoV11-1	1020 to 1070	730 to 780
T/P91 (X10CrMoVNb9-1)	1040 to 1080	750 to 780
E911 (X11CrMoWVNb9-1-1)	1040 to 1080	750 to 780
T/P92 (X10CrWMoVNb9-2)	1040 to 1080	750 to 780

> Table 2 - Heat treatment parameters of 9 % Cr steels

The new 9 % Cr steels are superior to the well-established X20CrMoV11-1 steel, not only in terms of their creep rupture strength; they also show a significantly higher level of impact energy. Where the impact energy at room temperature of steel X20CrMoV11-1 in the initial condition reaches an average of 60 to 70 Joules, these are lower range values found with very large wall thicknesses and depending on the reduction ratio and shaping process. In actual fact, the average values are significantly above 100 Joule. This encouraging behaviour provides for reliable processing and fabrication, especially as regards heat treatment processes for dissimilar welds in low-alloy ferritic steels. The toughness of the heat affected zone in 9 % Cr steels is not a failure criterion for such dissimilar welded joints, provided that a low-alloy welding filler is used and the post-weld heat treatment is adjusted to the temperature of the low-alloy steel. In Germany, however, the implementation of these findings conflicts with the general technical rules laid down in an Association Agreement which, incomprehensibly, requires that the root pass in such dissimilar joints also be ground over [3].



> Fig. 7 - Comparison of the results of the 2005 ECCC creep rupture strength evaluation with the characteristic values specified in VdTÜV materials data sheet 522/2 for steel X11CrMoWVNb9-1-1



> Fig. 8 - Comparison of the results of 1999 and 2005 ECCC creep rupture strength evaluations with the characteristic values specified in ASME Code Case 2179 for steel T/P92

2.2 Creep rupture strength and corrosion behaviour

Fundamental to the construction of power plants with elevated steam parameters are reliable creep rupture strength values. To achieve this, the creep behaviour, especially of the new 9 % Cr steels, must be subjected to regular checks. This task has been undertaken for over 60 years by the Association for High-strength Steels and High-temperature Materials (*Arbeitsgemeinschaft für warmfeste Stähle und Hochtemperaturwerkstoffe*). The long-time creep rupture strength values specified in German technical rules are predominantly upheld by the evaluations carried out by this working group.

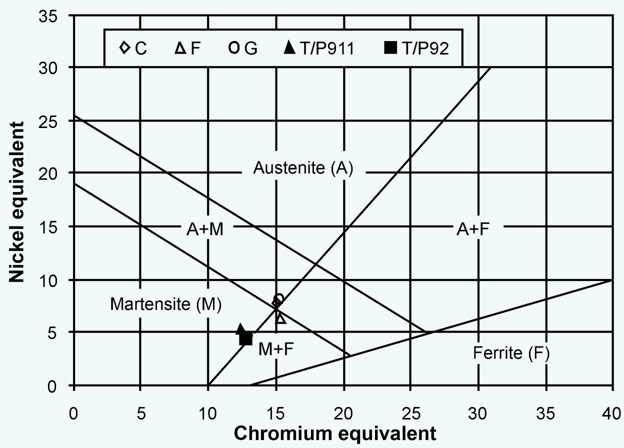
At a European level, the European Creep Collaborative Committee (ECCC) was set up in 1991 for similar purposes.

The first assessment at a European level of the steels X11CrMoWVNb9-1-1 (E911) and T/P92 was conducted in 1999. For T/P92, the only design values available were in fact only those listed in ASME standards which had been determined by Nippon Steel on the basis of Larson-Miller evaluations. For E911 steel, a VdTÜV Data Sheet (*VdTÜV-Werkstoffblatt 522/2* [4]) was already available at that time, and it also specified the values for long-time creep rupture strength. The first ECCC evaluation confirmed that the specified creep rupture strength values on which the ASME-Code Case 2179 [5] is based are too high for T/P92 steel. A 100,000 h creep rupture strength of 132 MPa at 600 °C was in contrast to an ECCC value of 123 MPa [6]. The data at that time was based on long-time values of maximum 43,513 h. For steel E911 tested under identical conditions, for instance, the values of the VdTÜV Data Sheet were confirmed.

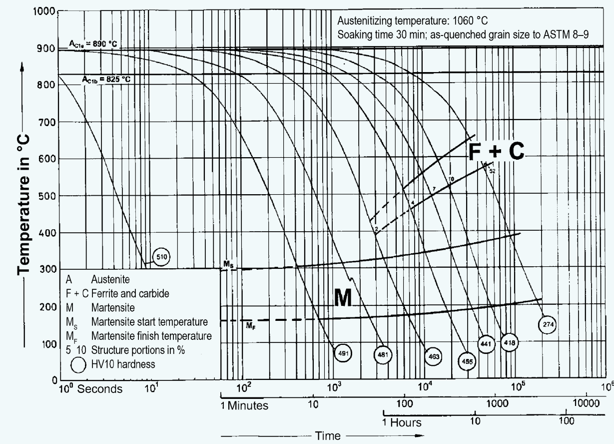
When extended creep data records became available, planning activities for new ultra super-critical power plants in Europe and especially in Germany prompted the initiation of a second assessment of the long-time creep behaviour of both steels by the ECCC Group in mid-2004. For this second

	Chemical composition in mass-%									
Material	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	Other
Martensitic steels (9 - 12 % Cr steels)										
X20CrMoV11-1 1.4922	0.17 - 0.23	0.15 - 0.50	< 1.0	10.0 - 12.5	0.30 - 0.80	0.80 - 1.20	0.25 - 0.35	-	-	-
X10CrMoVNb9-1 (T/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
X10CrWMoVNb9-2 (T/P92) 1.4901	0.07 - 0.13	< 0.50	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
VM12-SHC	0.10 - 0.14	0.40 - 0.60	0.15 - 0.45	11.0 - 12.0	0.10 - 0.40	0.20 - 0.40	0.20 - 0.30	1.30 - 1.70	0.03 - 0.08	Co 1.4 - 1.8 N 0.030 - 0.070 B 0.0030 - 0.0060 Al < 0.020

> Table 3 - Chemical composition of steel VM12-SHC compared to other 9 - 12 % Cr steels



❯ Fig. 9 - Schaeffler diagram modified according to H. Schneider (Creq = Cr + 2Si + 1.5Mo + 5V + 5.5Al + 1.75 Nb + 1.5Ti + 0.75W; Nieq1 = Ni + Co + 0.5Mn + 30C + 0.3Cu + 25 N)



❯ Fig. 10 - CCT diagram for steel VM12-SHC

assessment, comprehensive long-time data sets for the relevant temperature range of 550 to 650 °C were provided by Nippon Steel and Vallourec. The result of the assessment was presented in April 2005 [7] and revealed a significant drop in the characteristic values vis-à-vis the 1999 figures. **Figure 7** illustrates the current situation for the steel X11CrMoWVNb9-1-1 (E911) compared with the creep strength values specified in VdTÜV Data Sheet 522/2. Analogous to this, **Figure 8** plots the result of the ECCC's new T/P92 assessment from 2005 [8] compared with the ECCC's 1999 assessment and the underlying creep strength values as per ASME-Code Case 2179.

These new evaluations lead to the following conclusions:

- After extended exposure, both steels undergo microstructural changes, especially through the formation of new phases (Laves and Z phases), resulting in a significant drop in creep rupture strength which, however, only becomes clearly evident after creep test periods exceeding 50,000 h. From this it emerges that sufficiently reliable creep rupture strength data for these steels can only be extrapolated after testing for at least 50,000 h.
- The kinetics and, especially, the role of alloying effects in the microstructural processes are not completely understood as yet and require further investigations in greater depths.
- Both steels can continue to be assigned to a common scatter band (±20 %) in respect of their creep behaviour, with steel E911 in the lower (–20 %) and steel T/P92 in the upper (+20 %) region.
- Steel T/P92 should be the preferred structural material for the construction of new power plants with steam parameters up to 625 °C. For the time being, the design of thick-walled components (steam headers, fittings) has reached a technological limit at this point, since the wall thicknesses involved here and the associated thermal stresses would substantially restrict flexible start-ups and shutdowns of power plant units operated with any higher steam parameters.
- Besides the creep behaviour, the corrosion behaviour at high temperatures is another life-limiting factor for the steels used in power plants with high steam parameters. With their medium Cr content of 9 %, both the E911 and the T/P92 are inferior to the X20CrMoV11-1 steel in terms of their high-temperature corrosion behaviour and are thus no alternative or substitute for boiler applications in such power plants.

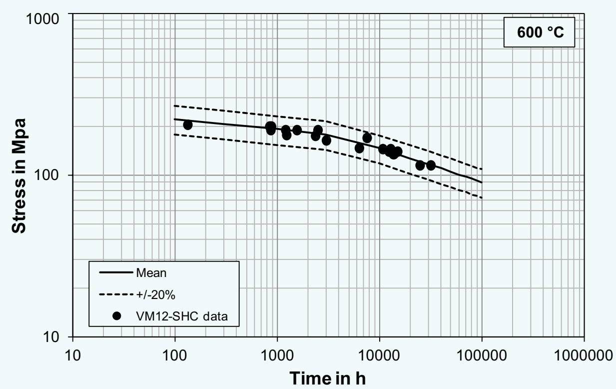
Heat treated condition	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A_5 (%)		Impact energy (J)
			long.	transv.	transverse
quenched and tempered	≥ 450	620 - 850	≥ 19	≥ 19	≥ 27

❯ Table 4 - Mechanical properties of VM12-SHC steel at room temperature

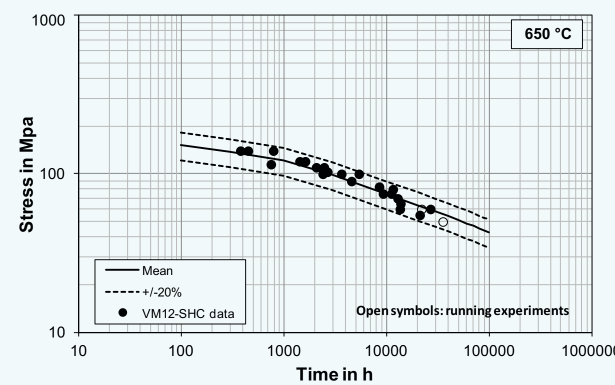
Temperature (°C)	100	200	250	300	350	400	450	500	550
YS min. (MPa)	412	390	383	376	367	356	342	319	287
TS min. (MPa)	565	526	510	497	490	479	448	406	338

❯ Table 5 - Mechanical properties at elevated temperatures (VM12-SHC)

❯ Fig. 11 - Microstructure of steel VM12-SHC after heat treatment (normalization 1060 °C/1h, cooling in air; tempering 780 °C/2h, cooling in air)



> Fig. 12 - Status of creep rupture testing of industrial VM12-SHC heats at 600 °C



> Fig. 13 - Status of creep rupture testing of industrial VM12-SHC heats at 650 °C

2.3 Development of a new 12 % Cr steel for steam temperatures up to 650 °C

Vallourec has initiated the development of a 12 % Cr steel for service temperatures up to 650 °C in order to close the gap between the X20CrMoV11-1 steel and 9 % Cr steels in creep and high-temperature oxidation behaviour. The objective of the development was as follows:

- Sufficiently high oxidation resistance for safe and reliable operation at service temperatures up to 650 °C;
- Short- and long-time creep rupture strength properties comparable or superior to E911 and T/P92;
- Good hot formability and weldability, with T/P91 being considered as the optimum to be aimed at;
- The new steel should have a martensitic microstructure;
- To ensure good oxidation resistance, its chromium content should be greater than 11 %;
- The vanadium, niobium and nitrogen contents should be similar to those of the 9 % Cr steels so as to ensure sufficient creep rupture strength through precipitation hardening via carbonitrides of the MX type. The additions of W, Co and B should be well balanced in order to achieve an optimum of their strengthening effect.

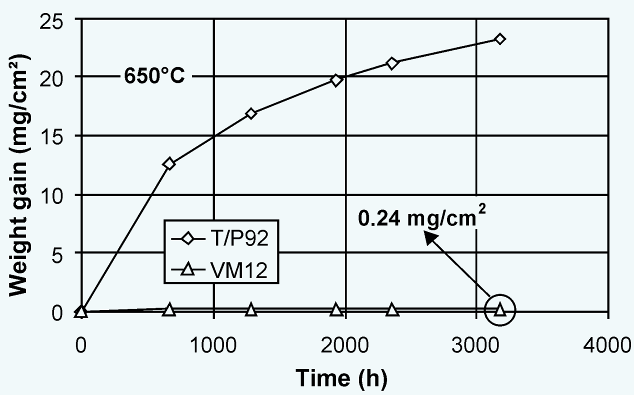
The first industrial-scale heats were preceded by extensive basic research, which has been the subject of several publications [9–11].

The development of thick-walled components has been stopped due to the fact the creep properties have not reached the objectives (i.e. superior to T/P92). Contrary to this, thin-walled components (max. wall thickness 10 mm) such as heated boiler tubes have been largely used in an industrial scale in all the new ultra- supercritical power plant units currently under construction or in service across Europe.
The newly developed steel has been designated as VM12-SHC for boiler tube applications. Its chemical composition is listed in **Table 3** and compared with the known 9 - 12 % Cr steels. The main differences to the steels E911 and T/P92 are a slightly higher C content, a medium Cr content greater than 11 %, and a medium Co content in the range of >1.0 %.

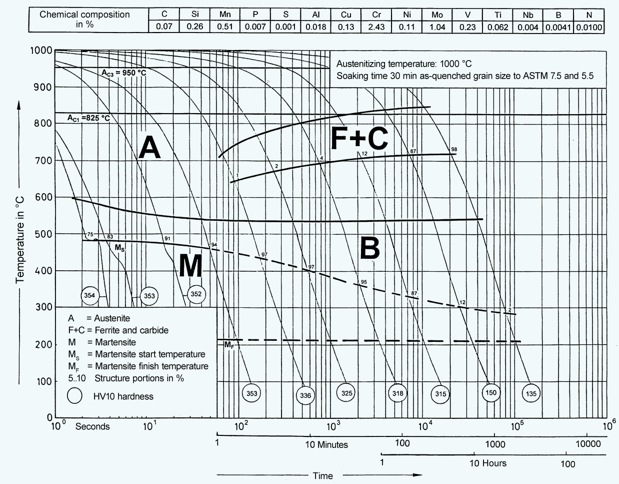
As can be seen from the Schaeffler diagram in **Figure 9**, the phase stability of the steels E911 (T/P911) and T/P92 would be affected if the chromium content would increase from 9 % to 11 %. In order to attain a fully martensitic microstructure it was necessary to rebalance the chromium and nickel equivalent. The addition of cobalt has been included in the alloying concept and the carbon content has been slightly modified compared to the well known

	T/P22 (10CrMo9-10)	T/P23 (7CrWVNb9-6)	T/P24 (7CrMoVTiB10-10)
C	0.08 - 0.14	0.04 - 0.10	0.05 - 0.10
Si	max. 0.50	max. 0.50	0.15 - 0.45
Mn	0.30 - 0.70	0.10 - 0.60	0.30 - 0.70
P	max. 0.025	max. 0.030	max. 0.020
S	max. 0.20	max. 0.010	max. 0.010
Ni	-	-	-
Cr	2.00 - 2.50	1.90 - 2.60	2.20 - 2.60
Mo	0.90 - 1.10	0.05 - 0.30	0.90 - 1.10
W	-	1.45 - 1.75	-
Ti	-	-	0.05 - 0.10
V	-	0.20 - 0.30	0.20 - 0.30
Nb	-	0.02 - 0.08	-
Al	max. 0.040	max. 0.030	max. 0.020
N	-	max. 0.030	max. 0.010
B	-	0.0005 - 0.0060	0.0015 - 0.0070

> Table 6 - Chemical composition of modern high-temperature steels and their predecessors according to EN10216-2



› **Fig. 14 - Oxidation behaviour of VM12-SHC steel vs. T/P92 in a steam atmosphere at 650 °C, (source: ALSTOM)**



› **Fig. 15 - CCT diagram for T/P24**

9 % Cr steels. As is shown in **Figure 9**, the steel VM12-SHC (heat F) lies close to the point where martensite, austenite and ferrite fields intersect.

The diagram indicates the possible presence of minor amounts of δ-ferrite. In practice, however, these have so far always been below 2 vol. %. The transformation behaviour of VM12-SHC steel does not differ from that of the well-established 9 % Cr steels, as can be seen from **Figure 10**.

The heat treated condition is normalized and tempered. The maximum tempering temperature is limited by the A_{c1b} temperature, which can lie between 810 °C and 830 °C, depending on the chemical analysis. Normalizing takes place in the temperature range of 1040 °C to 1080 °C. Optimum properties are achieved at tempering temperatures in the area of 750 °C to 800 °C.

Figure 11 shows the microstructure of a VM12 pipe of the size 406.4 mm x 35 mm (outside diameter x wall thickness) after heat treatment. The microstructure consists of tempered martensite. The δ-ferrite content detected is less than 2 vol. %.

Table 4 lists the specified mechanical / technological properties at room temperature. The strength properties at elevated temperatures are given in **Table 5**.

Creep tests have been carried out at temperatures between 525 and 700 °C. **Figures 12 and 13** plot the results obtained at 600 and 650 °C.

Improved oxidation resistance was one of the main requirements for the new steel. Therefore, extensive oxidation tests were carried out in steam atmospheres at 625 and 650 °C by Vallourec, but also within the framework of other national and international research projects. VM12-SHC steel showed excellent oxidation resistance in all the tests including long term tests. This can be seen in **Figure 14**, where weight gain per area unit is ploted against exposure time in steam atmosphere for VM12-SHC and T/P92 steels.

The industrial-scale heats were used for Vallourec's own extensive investigations. Furthermore and in cooperation with voestalpine Böhler Welding Germany GmbH, welding and weldability tests have been carried out. In addition to that, considerable research work on the formability properties (cold and hot) was done including numerous investigations under the MARCKO 2 research program.

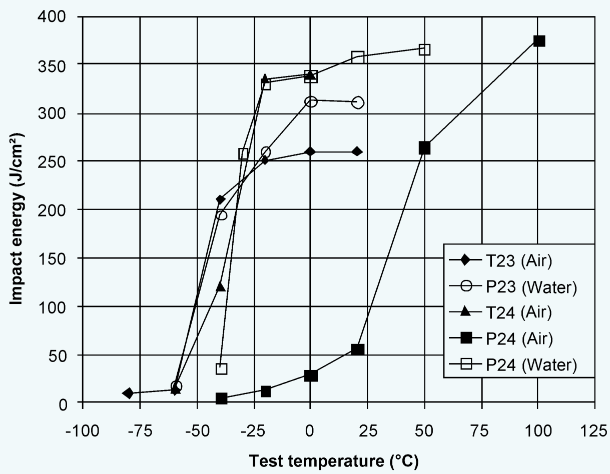
2.4 Recommendations for use and status of European standardization

The ECCC assessment of creep rupture properties has shifted the effective application range of the E911 and T/P92 steels. The preferred material for the temperature range of 600 to 625 °C is T/P92, because with E911 the diameter-to-wall thickness ratios – especially for thick-walled boiler headers and HP piping systems – not only approach the limits of producibility, but also impede flexible power plant operation during start-ups and shut-downs as well as under load fluctuations due to the increased thermal stresses generated in the thick-walled components. In the temperature range of 565 to 590 °C, E911 steel is an alternative to T/P91 steel.

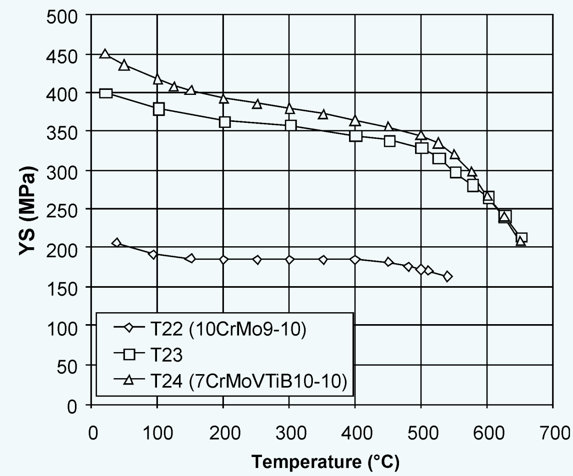
Vallourec has prompted the inclusion of the E911 and T/P92 into the EN 10 216-2 edition 2007 [12] and furthermore has incorporated the creep data results for this grades into the corresponding ECCC assessment. In addition VDTÜV data sheets (T/P92 = 552/2 [21] and E911 = 522/2 [4]) have been established for national standardization reasons. Since then the T/P92 has been used in all USC power plants already in service or still under construction in Europe and in Germany.

As most of the research targets for the VM12-SHC steel, i.e. good weldability, formability in combination with excellent oxidation and creep behaviour (on the level of P91) have been achieved, the research work is completed.

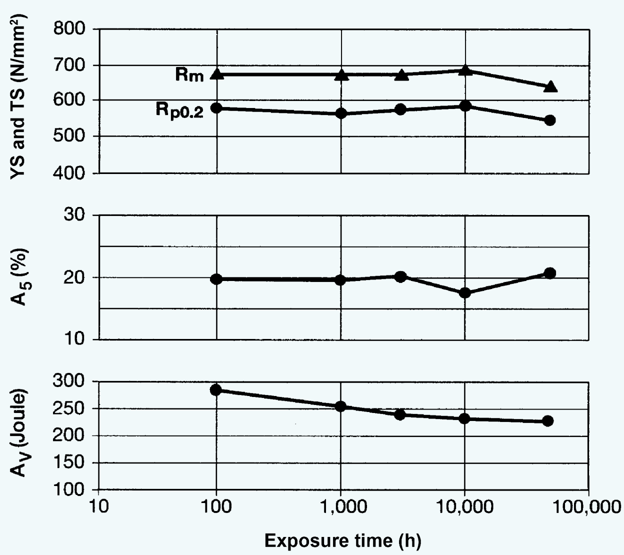
Indeed, the VM12-SHC alloy steel represents a very good option in the temperature range up to 610 °C for boilers, where – seemingly due to oxidation – a gap has emerged between X20CrMoV11-1 and austenitic steels, which cannot be closed by the 9 % Cr steels. For the use of VM12-SHC in European or



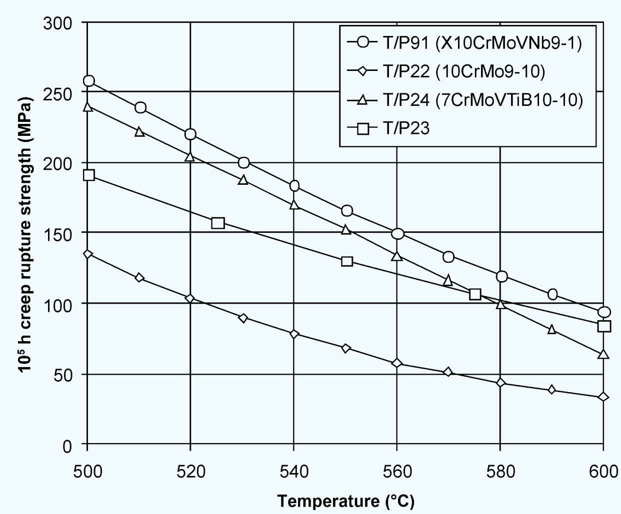
> Fig. 16 - Av-T curves for T23 (air), P23 (air), P23 (water), T24 (air), P24 (water)



> Fig. 17 - Minimum yield strength values as a function of temperature for T22, T23 and T24



> Fig. 18 - Mechanical characteristics of T/P24 after long-time exposure to 550 °C



> Fig. 19 - 10^5 h Creep rupture strength values as a function of temperature for T/P22, T/P23, T/P24 and T/P91

American boiler design and especially for the application as a tube for heated surfaces the following standards are presently available:

- V&M material data sheet 439 [17]
- TÜV data sheet 560/2 [18]
- ASME code case 2781 [19]

3 New low-alloy steels for boiler tubes/water wall panels and thick-walled piping system components

3.1 Metallurgical principles and material properties

The previously used water wall panel steels – 16Mo3 and 13CrMo4-5 – can no longer be used in the evaporator section of the new boilers with increased steam parameters because the loads involved here extend well into the creep range. Since a post-weld heat treatment is technically infeasible

Steel grade	YS (MPa)	TS (MPa)	A_5 (%)
T/P22	min. 280	480 - 630	min. 20
T/P23	min. 400	min. 510	min. 20
T/P24	min. 450	585 - 840	min. 17
T/P91	min. 450	620 - 850	min. 17

> Table 7 - Mechanical properties of modern low-alloy high-temperature steels vs. 10CrMo9-10 and X10CrMoVNb9-1

Straight pipe		
Material	Wall thickness e as per EN 13480-3 (mm)	Wall thickness t as per ASME B31.1 (mm)
P22	105.2	96.2
P23	58.6	55.7
P24	52.3	50.0
P91	41.3	39.8

> Table 8 - Wall thickness calculation for straight pipe as per EN 13 480-3 [14] and ASME B31.1 [13], design pressure p = 191 bar, design temperature T = 545 °C, pipe diameter D_i = 450 mm

T-joint		
Material	Wall thickness e as per EN 13480-3 (mm)	Wall thickness t as per ASME B31.1 (mm)
P22	155.0 / 103.0	135.0 / 96.0
P23	91.0 / 61.0	91.0 / 61.0
P24	83.0 / 55.0	84.0 / 55.0
P91	67.0 / 45.0	68.0 / 45.0

> Table 9 - Wall thickness calculation for a T-joint as per EN 13 480-3 [14] and ASME B31.1 [13], design pressure p = 191 bar, design temperature T = 545 °C, parent pipe D_i = 450 mm / socket D_i = 300 mm

for water wall panels, a shift to the use of the established higher-alloy steels T/P22 (10CrMo9-10) or T/P91 is ruled out. In response to the urgent need for new water wall panel steels, T/P23 steel (7CrWVNb9-6) was developed in Japan and T/P24 (7CrMoVTiB10-10) by Vallourec in Germany.

The development of both T/P23 and T/P24 was based on the well-established 10CrMo9-10 (T/P22), steel, as can be seen from **Table 6**.

The creep rupture strength of the new steels was significantly raised by alloying with the carbide forming elements V, Nb and Ti. Tungsten was also added to the T/P23, with the molybdenum content appropriately reduced. A special feature shared by the two new steels is their reduced carbon content, the effect of which is clearly noticeable in the CCT diagram (**Figure 15**) for T/P24 steel. Even rapid cooling at the martensite stage leads to maximum hardness values of only 350 to 360 HV10. This behaviour means that post-weld heat treatment of thin-walled boiler tubes with wall thicknesses <10 mm can be dispensed with. Both steels are used in the heat treated (quenched and tempered) condition, with normalizing being carried out at 1060 °C ± 10 °C for T/P23 steel and at 1000 °C ± 10 °C for T/P24. Accelerated cooling (water quenching) from the austenitizing temperature is essential to ensure optimum material properties with wall thicknesses >10 mm. Subsequent tempering of T/P23 steel takes place at 760 °C ± 15 °C. In the case of T/P24 steel, tempering at 750 °C ± 15 °C has proved to yield optimum results.

The general material properties of T/P23 and T/P24 correspond largely to those of the T/P22 steel underlying their development. This applies both to their physical properties and scaling resistance, as well as to their high impact energy. However, depending on the speed of cooling from the normalizing temperature, a shift of the Av-T curve can be observed and is plotted in **Figure 16** for various heat treated conditions and wall thicknesses (T: Tube, P: Pipe). To ensure high impact energy levels at room temperature, therefore, water quenching is absolutely essential for thick-walled components in both steels.

Compared with T/P22, both T/P23 and T/P24 show much higher strength values (see **Table 7**).

Figure 17 compares the minimum yield strength values for thin-walled tubes. As can be seen from the long-time exposure test results of T/P24 in **Figure 18**, no significant changes can be observed in the long term in either strength or ductility. T/P23 steel shows an analogous behaviour.

Creep rupture strength is generally considered as the most decisive characteristic of a high-temperature steel. Here too, there are significant differences to T/P22 steel, as can be seen in **Figure 19**: The long-time values in the lower temperature range are only slightly below those of P91 steel. The T/P23 values lie somewhat lower, but still substantially above the level of T/P22. In the area of 575 °C, they intersect with the creep strength curve of T/P24 steel and come close to the T/P91 curve at 600 °C. Nevertheless, because the scaling resistance is limited due to the low Cr content, continuous operation at temperatures above 575 °C cannot be recommended for either of the two steels.

The steels T/P23 and T/P24 show good processing characteristics, comparable with those of T/P22. For the cold bending of thin-walled boiler tubes, the same rules apply as for T22. In the case of induction bending or other hot forming operations on thick-walled tubes, renewed water quenching is essential in every case.

3.2 Recommendations for use and status of standardization

Given the increased thermal stresses prevailing in the boiler section of new power plants with superheated steam temperatures above 585 °C, the use of T23 or T24 steels is a technical necessity. The main application area here is water wall panels. As for thick-walled components for service temperatures of 500 to 550 °C, the steels P23 and P24 are a good alternative to the established low-alloy steels, not just for boiler headers, but also for complete piping systems in both new plants and upgrading projects. As can be seen from **Figure 19**, the two new steels offer a clear advantage in the temperature range of 500 to 550 °C over P22, the classical pipe steel for this application area. Their creep strength properties reach values that are exceeded only by the new martensitic pipe steels, such as P91, E911 and P92.

The advantage of the new pipe steels in the field of high-pressure piping systems is demonstrated by the results of wall thickness calculations for representative components of a 350 MW power station unit, which were originally designed in P22 steel in accordance with ASME B31.1 [13].

Tables 8 and 9 provide further evidence based on the example of wall thickness calculations for straight pipe for a superheated steam piping system and a fitting integrated into this system.

Analogously, the same effects of wall thickness reduction apply in the design calculations for the hot reheat pipe. In the temperature range of 500 to 545 °C – an obvious application area for both steels – wall thickness reductions of between 35 % and 50 % can be considered realistic for piping system components, compared with the low-alloy steels conventionally used here.

Another advantage over the higher-grade 9 % Cr steel P91 is its handling in welding fabrication, which is comparable to that of T/P22 steel.

T/P23 steel is currently standardized in ASTM A 213 (Code Case 2199) [15] and ASTM A 335. A Code Case for T24 steel has been successfully approved by the ASME and it has been incorporated into the ASME Code 2540 [20] and the ASME standard A 213. Under the designation 7CrMoVTiB10-10 (material no. 1.7378) a suitability specification is available as VdTÜV Data Sheet 533 [16]. Vallourec had both steels included in the revised EN 10216-2 analogously to the steels X11CrMoWVNb9-1-1 (E911) and X10CrWMoVNb9-2 (T/P92), and they are anchored in the latest edition [12] with the material designations 7CrWVMoNb9-6 (T/P23) and 7CrMoVTiB10-10 (T/P24) since October 2007.

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Part 2: Filler metals and their use in welding

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This article focuses on the welding characteristics of the martensitic (E911, P92, VM12-SHC) and bainitic (T/P23 und T/P24) parent materials described in more detail in Part 1. The matching filler metals are examined in each case, and notes for preparation, welding and treatment provided.

1. Matching filler metals for E911 and P92

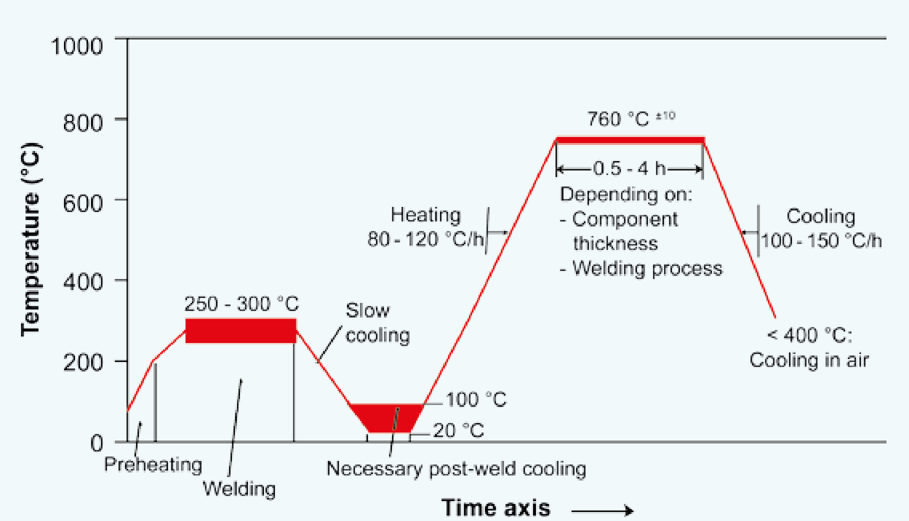
Almost parallel to the development of the base materials E911 and P92 came the development of welding fillers of the same composition for gas tungsten arc welding (GTAW), manual metal arc welding (SMAW) and submerged-arc welding (SAW). The properties of these welding materials have been the subject of numerous publications [1 – 4]. At this point therefore it may suffice to mention that, besides precisely controlled additions of the creep-relevant alloying elements C, V, Nb, N, B and W, what requires particularly close attention is the heat control during welding.

The martensitic steels E911 and P92 are welded in the martensitic temperature range, i.e. at between 200 and 350 °C. Because of the martensitic microstructure, temperature control during welding and during the post-weld heat treatment must be carried out with the utmost care.

After welding, the weld metal hardness of both steels lies at around 400 HV10. This is reduced to about 250 HV10 by the post-weld heat treatment.

Due to this relatively low hardness, the risk of cold cracking in the welded condition is reduced, so components with low residual stresses may be cooled down to room temperature after welding. However, they must be stored dry and free from external loads.

Power plant operators and supervisory agencies attach great importance to maximum toughness properties of the welding fillers used. Metallurgically, however, there is not much scope with the martensitic grades for raising the impact energy of electrode and submerged-arc weld metals to a level significantly above 41 J. The toughness of these weld metals can be influenced to a certain extent via the selection of the welding and heat treatment parameters. Here it is important to allow the welded joint to cool down to below the martensite finish temperature (M_f) before the heat treatment so as to ensure complete tempering of the martensite. The M_f temperature for the welding fillers of the same composition as E911 and P92 lies at approximately 150 °C, so the welded joint must be cooled to at least 100 °C. As an additional safeguard against hydrogen-induced cold cracking, the material can be “soaked” immediately after welding (250 to 300 °C, soaking time 2-3 h) to allow the hydrogen to diffuse.



› Fig. 1 - Temperature control in welding of E911 / P92

Figure 1 is a schematic illustration of heat control during welding and post-weld heat treatment. Keeping the welding passes thin will improve the joint toughness: the thinner the individual passes, the greater the tempering effect. This must be taken into account especially in submerged-arc welding.

Several different pipe joints were welded within the framework of welding material development and qualification measures. The results are presented in [1–4]. **Table 1** lists some results for welding fillers of the same composition as P92 and for welded joints in P92 pipes.

The same-composition welding fillers for E911 and P92 were subjected to creep tests at 600, 625 and 650 °C. The creep properties were determined on pure weld metal (SMAW and SAW) and also on pipe joints in E911 and P92 pipe [1, 2].

The longest tests on E911 welded joints were conducted for >50,000 h. At 600 °C, the rupture points in the

Chemical composition of pure deposited metal in %											
	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	N	B
SMAW Ø 4.0 mm	0.11	0.27	0.65	8.95	0.70	0.53	0.19	1.72	0.044	0.04	30 ppm
SAW wire Ø 3.2 mm	0.09	0.36	0.60	8.45	0.73	0.41	0.17	1.57	0.04	0.05	32 ppm

Mechanical properties a) Pure deposited metal at RT					
Welding process	Heat treatment (°C / h)	YS (MPa)	TS (MPa)	A_5 (%)	CVN (ISO-V) (J)
SMAW Ø 4.0 mm	760 / 2	675	800	17.6	50 / 55 / 58
SAW wire Ø 3.2 mm	760 / 4	621	742	20.8	57 / 61 / 41

b) Weld; P92 pipe Ø 300 mm; wall thickness 40 mm					
Welding process	Heat treatment (°C / h)	TS (MPa)	Rupture location	CVN (ISO-V) (J)	Hardness HV10
SMAW Ø 4.0 mm	760 / 2	665	Base metal	60 / 58 / 62	236 - 262
SAW wire Ø 3.2 mm	760 / 4	678	Base metal	84 / 88 / 96	234 - 249

Table 1 - Results for pure deposited metal and welds in P92 pipes

pure weld metal and in the pipe joints lay within the lower scatter band of the base material. At higher temperatures (625 and 650 °C) the rupture points shifted downwards and beyond the scatter band of the base material as the test periods lengthened. Rupture in the welded joints only occurred in the heat-affected zone, in particular with longer test periods. No ruptures were observed in the weld metal itself.

In the tests on P92 joints, all the rupture points at 600 °C were within the scatter band of the base material. At higher temperatures, however, some of the rupture points were located outside the scatter band, and at high stresses and test periods <20,000 h a few isolated ruptures were found in the weld metal. Specimens subjected to extended testing >20,000 h suffered creep ruptures in the heat-affected zone. At 650 °C, all the ruptures were located in the heat-affected zone [2]

1.1 Re-assessment of E911 and T/P92 joints [5]

Since the base material was being re-assessed, the long-time behaviour of the welded joints in E911 and T/P92 also had to be re-assessed. The objective was to determine weld strength factors. Determining creep rupture strength values for welded joints is more problematic than for the base material because, firstly, there is usually much less data available and, secondly, the creep behaviour is much more complex due to the shift of the rupture locations from the base metal to the heat-affected zone. Therefore, the only possibility was to refer to the evaluation of the base material.

The evaluation covered results of manual-arc and submerged-arc welded joints tested in the temperature range of 575 to 650 °C. The total number of values obtained from E911 joints was 82; the longest rupture duration was 36,456 h.

Under high stresses, the test results lay in the lower half of the base material's scatter band. At low stress levels, however, a mean value curve with the factor 0.56 was obtained as the lower boundary for the base material. The objective was to determine a minimum value curve for the welded joint.

The same procedure was applied in the re-assessment of the T/P92 joints. In all, 64 rupture points in SMAW and SAW joints were tested at between 600 and 650 °C and assessed. The longest rupture duration was 48,375 h.

As in the case of E911, the T/P92 test results were parameterized using the Manson-Haferd method. Based on the minimum values for 10^5 h, weld strength factors can be determined by relating these values to the minimum values of the base material (lower scatter band boundary) [5].

2 Matching filler metals for the new martensitic 12 % Cr steel – VM12-SHC

For thin-walled components, (boiler tubes; max. wall thickness 10 mm), the development of matching filler metals for GTAW and SMAW can be considered as completed.

At the same time, however, the welding fillers only have a toughness of around 40 J, which is lower than that of the previously mentioned fillers for 9 – 10 % Cr steels. It has also been shown that a Ni/Nb modification of the weld metal, which was successful for matching filler metals for E911 and P92, yields no improvement for this alloy. Nevertheless, the toughness level is still sufficient, given the specified minimum values of >27 J. But the greatest possible care in welding is absolutely essential (low heat input, correct selection of electrode diameter, observation of maximum permissible pass thickness, etc.). The heat treatment should be carried out at 770 °C, because high enough toughness cannot be guaranteed at 760 °C.

Chemical composition of pure deposited metal in %												
	C	Si	Mn	Cr	Ni	Mo	V	W	Nb	N	Co	B
GTAW	0.17	0.2	0.43	11.6	0.40	0.3	0.22	1.44	0.06	0.04	1.64	0.003
SMAW Ø 4.0 mm	0.13	0.33	0.66	11.2	0.79	0.33	0.24	1.48	0.06	0.05	1.59	0.003

Mechanical properties a) Pure deposited metal at RT						
Welding process	Heat treatment (°C / h)	YS (MPa)	TS (MPa)	A_5 (%)	CVN (ISO-V) (J)	Hardness HV10
GTAW	770 / 2	684	822	18.5	33 / 38 / 43 / 47 / 50	297
SMAW Ø 4.0 mm	770 / 2	689	832	17.2	40 / 41 / 42 / 48 / 49	281

b) Welded joint; pipe Ø 140 mm; wall thickness 10 mm					
Welding process	Heat treatment (°C / h)	TS (MPa)	Rupture location	CVN (ISO-V) (J)	Hardness HV10
GTAW	770 / 0.5	745	Base metal	37 / 38 / 40	max. 351
SMAW Ø 4.0 mm	770 / 2	728	Base metal	47 / 51 / 51	max. 297

› Table 2 - Results for pure deposited metal and a weld in a VM12 pipe

Figure 2 illustrates the temperature control requirements during welding. Unlike with E911 and P92, the interpass temperature must not exceed 280 °C to ensure that welding takes place in the martensitic range. The martensite start temperature (M_s) for the base material is about 300 °C.

Table 2 lists results for the GTAW and SMAW processes.

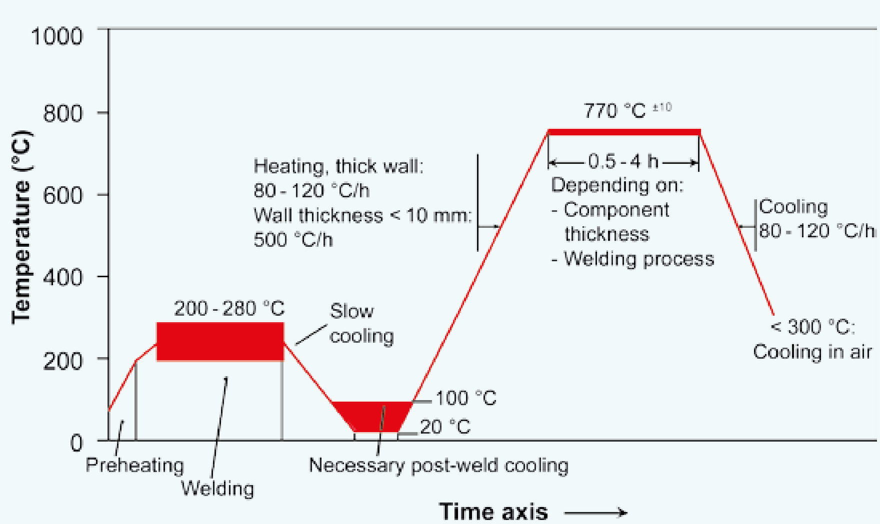
The Cr content of this alloy is higher than in E911 and P92. The associated ferrite formation must be counteracted by alloying with an austenitizer, in this case Co, which, unlike Ni, has no effect on the A_{c1b} temperature.

Creep tests are being conducted at present on the welded joints. **Figure 3** shows the microsection of a VM12-SHC / VM12-SHC pipe joint.

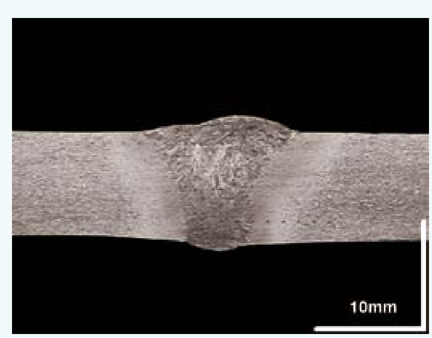
In new power plant projects in Germany, the steel VM12-SHC and the above welding fillers are used for pipes with wall thicknesses <10 mm.

3 Matching filler metals for the bainitic steels T/P23 und T/P24

These steels require no post-weld heat treatment for wall thicknesses <10 mm due to their low C content. Both are therefore particularly well suited for the manufacture of membrane walls. However, components with thicker walls require a post-weld heat treatment, especially after manual arc and submerged-arc welding. This heat treat-



› Fig. 2 - Temperature control in welding of VM12 12 % Cr steel



› Fig. 3 - VM12-SHC pipe joint; wall thickness 10 mm; GTA-welded using same-composition filler metal

Chemical composition of various deposited metals in %									
	C	Si	Mn	Cr	Ni	Mo	V	W	Nb
GTAW Ø 2.4 mm	0.08	0.27	0.54	2.14	0.04	0.08	0.21	1.58	0.031
SMAW Ø 4.0 mm	0.06	0.22	0.46	2.28	0.12	0.02	0.28	1.72	0.043
SAW wire Ø 4.0 mm	0.05	0.27	0.94	2.04	0.09	0.11	0.19	1.61	0.043

Mechanical properties of pure deposited metal at RT						
Welding process	Heat treatment (°C / h)	YS (MPa)	TS (MPa)	A_5 (%)	CVN (ISO-V) (J)	Hardness HV10
GTAW Ø 2.4 mm	. /. 740 / 2	639 520	818 620	21.4 20.2	228 / 230 / 268 261 / 286 / 299	270 250
SMAW Ø 4.0 mm	740 / 2	509	625	19.0	128 / 136 / 140	227
SAW wire Ø 4.0 mm	740 / 2	615	702	18.1	187 / 204 / 208	237

› Table 3 - Chemical composition and mechanical properties of pure deposited metal of matching filler metals for T/P23 with various welding processes

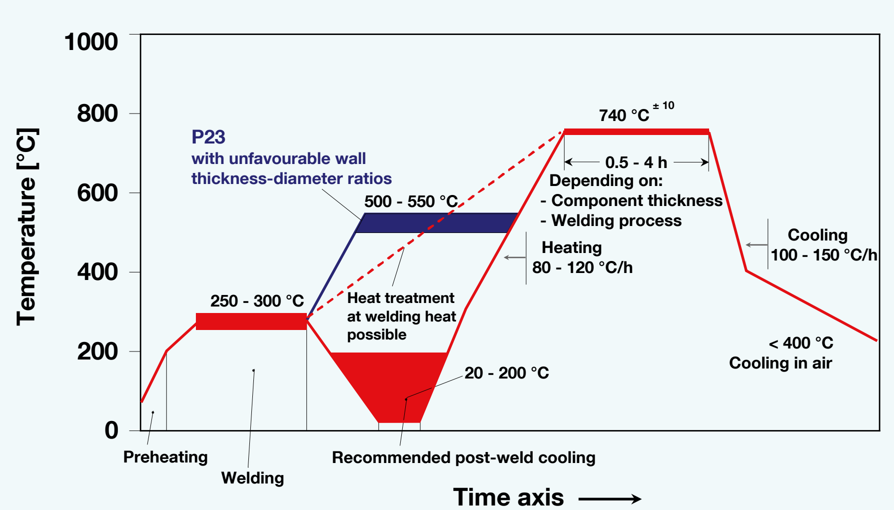
ment should be carried out at between 740 and 750 °C. The PWH-time depends on the wall thickness and the welding process. **Figure 4** shows the recommended temperature control for the two steels during welding and post-weld heat treatment.

The heat treatment must be carefully adjusted to the design conditions, particularly in the case of T/P23 steel, which has a tendency to stress relief cracking. If there are extreme wall thickness variations, intermediate stress relieving should be performed at between 500 and 550 °C immediately after welding. Components with an uniform wall thickness can be heat treated while still at the welding heat.

Table 3 lists the chemical composition and mechanical properties of same-composition filler metals for T/P23. The results of a P23 pipe girth weld are summarized in **Table 4**.

The results of pure GTA- and SMA-weld metal for the base material T/P24 are listed in **Table 5**. The high impact energy values in the as-welded condition at GTAW are only reproducible with very thin welding beads. T/P24 contains Ti as a carbide former and thus as an element that promotes creep resistance. However, Ti burns off uncontrollably in the weld metal of slag-generating welding processes. In general, therefore, Ti must be dispensed with in stick electrodes and also in submerged-arc welding. Instead, filler metals here are alloyed with Nb. Results from creep tests at 550 °C and test periods >25.000 h are already available for these welding fillers, and here the scatter band of the base material has already been reached. Meantime, the changeover from Ti to Nb has also been effected for GTA-weld metal so as to provide for a uniform alloying composition in the weld metals.

Thin welding passes must be ensured with both T23 and T24, especially in GTAW pipe girth welds (wall thicknesses <10 mm), because otherwise it is impossible to achieve sufficiently high impact energy levels without a post-weld heat treatment. In addition, the welding current reduction in GTAW root passes should be optimized in preliminary tests so as to avoid end crater cracks in the lower surface of the root. Welders must be specifically trained to avoid such “endcrater cracks” in the root. The cap



› Fig. 4 - Temperature control in welding of T/P23 and T/P24 (wall thickness >10 mm)

Pipe size: Ø 219 mm x 30 mm
Weld filler: Root GTAW
2 filler passes with SMAW
10 SAW filler passes; wire Ø 3.2 mm
Preheating temperature: 250 °C; Interpass temperature: max. 300 °C
SAW: Welding current = 450 A (=/+); Voltage = 28 V; Welding speed = 52 cm/min.; energy input = 14.5 kJ/cm

Heat treatment (°C / h)	Test temperature (°C)	TS (MPa)	Rupture location	Bending angle	CVN (ISO-V) (J)		Hardness HV10
					WM	HAZ	
740 / 1	+20	580	BM	180°	124 / 150 / 153	92 / 156 / 223	< 250
740 / 1	+600	333	BM	---	---	---	---

Table 4 - Results for a P23 pipe girth weld using same-composition weld fillers

pass, in particular, must be kept very thin, and it should "temper" the beads below it. For a boiler tube with a wall thickness of 6 mm this means three passes are required (**Figure 5**). Two-pass welds cannot meet the toughness requirements because the cap pass will lack this tempering effect.

The SMAW data listed in **Table 5** need a post-weld heat treatment. Another electrode with reduced C content has been developed for welds without a post-weld heat treatment. Such stick electrodes are marked –WW in their designation and are particularly suitable for onsite welding fabrication.

In the submerged-arc welding of membrane walls (pipe-fin-pipe joints), Ti burnout is practically irrelevant where a Ti-alloyed wire is used because, on the one hand, dilution with the pipe and web materials ensures there is a sufficient amount of Ti present in the fillet weld and, on the other, the bead cross-section of the fillet weld overcompensates any limitation of creep rupture strength in the weld metal. The use of Nb-containing wires has generally eliminated this problem.

Adequate pre-heating and reheating must always be ensured in the SA-welding of membrane walls. To avoid hydrogen-induced transverse cracks in the SA-welds, the flux must be appropriately dried. The preheating temperature should be >100 °C. Reheating to about 300 °C immediately after welding is recommended so as to allow for hydrogen effusion (soaking).

4 Summary

This article presents martensitic and bainitic materials which will in future allow steam temperatures of up to 625 °C in fossil-fired power plants. The re-assessment of the creep rupture strengths of E911 and P92 provide design engineers with reliable reference values. The new 12 % Cr steel VM12-SHC closes the gap between the 9 % Cr steels E911 / P92 and austenitic pipe steels for heated boiler pipe applications in the temperature range up to 620 °C.

The development of the described welding filler metals must progress almost simultaneously with the development of the respective base materials. Design engineers need the strength

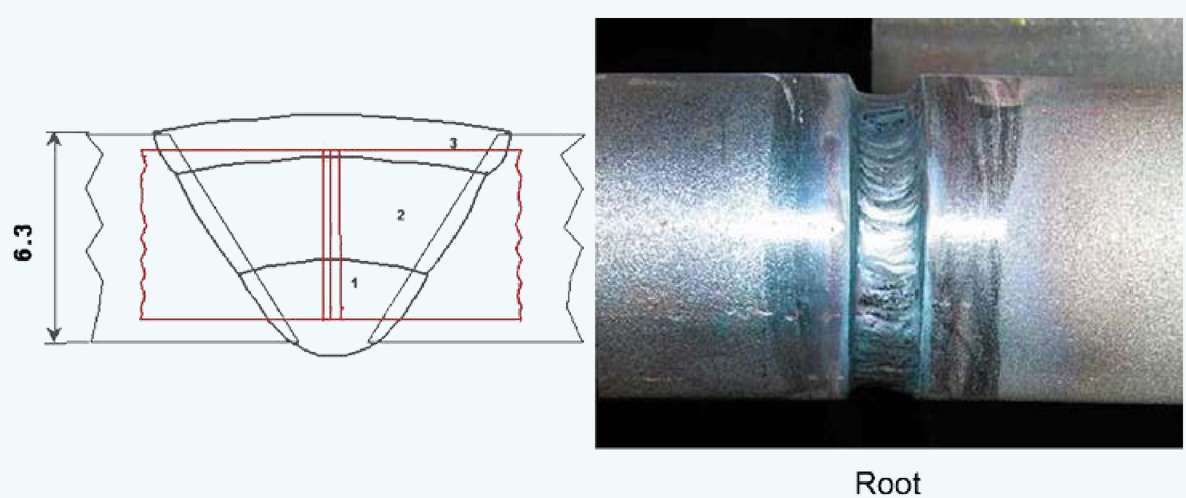


Fig. 5 - GTA-welding of a T24 boiler tube (38 x 6.3 mm); the site of a notched impact test specimen is shown

Chemical composition of the wire and various deposited metals in %										
	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	0.003
GTAW Ø 2.4 mm	0.061	0.23	0.49	2.29	1.00	0.24	0.034	0.007	0.014	0.002
SMAW Ø 4.0 mm	0.091	0.25	0.55	2.51	1.03	0.22	-	0.046	0.013	0.001

Mechanical properties of pure deposited metal at RT						
Welding process	Heat treatment (°C / h)	YS (MPa)	TS (MPa)	A_5 (%)	CVN (ISO-V) (J)	Hardness HV10
GTAW Ø 2.4 mm	. /. 740 / 2	664 595	803 699	19.1 20.3	298 / 298 / 298 264 / 280 / 292	322 230
SMAW Ø 4.0 mm	740 / 2	577	689	18.1	154 / 152 / 148	221

› Table 5 - Chemical analysis of T24 matching filler metals and mechanical properties of pure deposited metal from GTA- and SMA-welding

values of the welded joint determined in creep tests for the reliable design of the components which are subject to high pressure and temperature loads. Developing filler metals for high-temperature steels which satisfy the strength and corrosion requirements of the base materials while at the same time ensuring good weldability and sufficient toughness is and will remain a real challenge.

The strict observation of stringent welding parameters is essential, especially for welded joints in T23 and T24 pipe without post-weld heat treatment (PWHT). Preliminary tests under operating conditions are indispensable here if hardness values <350 HV10 in the weld metal are to be ensured and cracks in the welded joints avoided.

All the welding fillers presented here have been approved by VdTÜV and are thus suitable for use in pressure-bearing components. The developments were conducted in close cooperation with Vallourec Deutschland GmbH.

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Recommended Welding Consumables for Modern Power Plant Steels

Base Material Examples ASTM / EN	Welding Process	Welding Process	Classification AWS	Classification EN ISO
T/P23 / 7CrWVMoNb9-6	SMAW	Thermanit P 23	A5.5: E9015-G	3580-A: E ZCrWV 2 1,5 B 4 2 H5
		BÖHLER FOX P 23	A5.5: E9015-G	3580-A: E ZCrWV 2 1,5 B 4 2 H5
	GTAW	Union I P23	A5.28: ER90S-G	21952-A: W ZCrWV 2 1,5
		BÖHLER P 23-IG	A5.28: ER90S-G	21952-A: W ZCrWV 2 1,5
	SAW wire	Union S P23	A5.23: EG	24598-A: S Z CrWV 2 1,5
		BÖHLER P 23-UP	A5.23: EG	24598-A: S Z CrWV 2 1,5
	SAW flux	UV P23		14174: SA FB 1 55 AC
		UV 305 (only single layer)		14174: SA AR 1 76 AC H5
		BÖHLER BB 430		14174: SA FB 1 55 AC
		BÖHLER BB 305 (only single layer)		14174: SA AR 1 76 AC H5
T/P24 / 7CrMoVTiB10-10	SMAW	Thermanit P 24	A5.5: E9015-G	3580-A: E ZCrMo2WVNb B 4 2 H5
		BÖHLER FOX P 24	A5.5: E9015-G	3580-A: E ZCrMo2VNb B 4 2 H5
	GTAW	Union I P24	A5.28: ER90S-G	21952-A: W ZCrMo2VTi/Nb
		BÖHLER P 24-IG	A5.28: ER90S-G	21952-A: W ZCrMo2VTi/Nb
	SAW wire	Union S P24	A5.23: EG	24598-A: S ZCrMo2VNb
		BÖHLER P 24-UP	A5.23: EG	24598-A: S ZCrMo2VNb
	SAW flux	UV P 24		14174: SA FB 1 55 AC
		UV 305		14174: SA AR 1 76 AC H5
		BÖHLER BB 430		14174: SA FB 1 55 AC
		BÖHLER BB 305 (only single layer)		14174: SA AR 1 76 AC H5
T/P91 / X10CrMoVNb9-1	SMAW	Thermanit Chromo 9 V	A5.5: E9015-B9	3580-A: E CrMo9 1 B 4 2 H5
		Thermanit Chromo T 91 (root)	A5.5: E9018-B9	3580-A: E CrMo9 1 B 4 2 H5
		BÖHLER FOX C 9 MV	A5.5: E9015-B9	3580-A: E CrMo9 1 B 4 2 H5
	GTAW	Thermanit MTS 3	A5.28: ER90S-B9	21952-A: W CrMo 9 1
		BÖHLER C 9 MV-IG	A5.28: ER90S-B9	21952-A: W CrMo 9 1
	GMAW	Thermanit MTS 3	A5.28: ER90S-B9	21952-A: G CrMo 9 1
		BÖHLER C 9 MV-IG	A5.28: ER90S-B9	21952-A: G CrMo 9 1
	FCAW	Thermanit MTS 3-PW	A5.29: E91T1-B9M	17634-B: T 69 T1-1M-9C1MV
		BÖHLER C 9 MV Ti-FD	A5.28: E91T1-B9M	17634-B: T 69 T1-1M-9C1MV
	SAW wire	Thermanit MTS 3	A5.23: EB9	24598-A: S CrMo9 1
		BÖHLER C 9 MV-UP	A5.23: EB9	24598-A: S CrMo9 1
	SAW flux	Marathon 543		14174: SA FB 2 55 DC H5
		BÖHLER BB 910		14174: SA FB 2 55 DC H5

Base Material Examples ASTM / EN	Welding Process	Welding Process	Classification AWS	Classification EN ISO
T/P92 / X10CrWMoVNb9-2	SMAW	Thermanit MTS 616	A5.5: (E9015-B9 mod.)	3580-A: E ZCrMoWVNb 9 0,5 2 B 4 2 H5
		BÖHLER FOX P 92	A5.5: (E9015-B9 mod.)	3580-A: E ZCrMoWVNb 9 0,5 2 B 4 2 H5
	GTAW	Thermanit MTS 616	A5.28: (ER90S-B9 mod.)	21952-A: W ZCrMoWVNb 9 0,5 1,5
		BÖHLER P 92-IG	A5.28: (ER90S-B9 mod.)	21952-A: W ZCrMoWVNb 9 0,5 1,5
	GMAW	Thermanit MTS 616	A5.28: (ER90S-B9 mod.)	21952-A: G ZCrMoWVNb 9 0,5 1,5
		BÖHLER P 92-IG	A5.28: (ER90S-B9 mod.)	21952-A: G ZCrMoWVNb 9 0,5 1,5
	FCAW	Thermanit MTS 616-PW	A5.29: E91T1-GM	17634-A: T ZCrWMo9VNb P M 1
		BÖHLER P 92 Ti-FD	A5.29: E91T1-GM	17634-A: T ZCrWMo9VNb P M 1
	SAW wire	Thermanit MTS 616	A5.23: EB9 (mod.)	24598-A: S ZCrMoWVNb 9 0,5 1,5
		BÖHLER P 92-UP	A5.23: EB9 (mod.)	24598-A: S ZCrMoWVNb 9 0,5 1,5
	SAW flux	Marathon 543		14174: SA FB 2 55 DC H5
		BÖHLER BB 910		14174: SA FB 2 55 DC H5
T/P911 / X11CrMoWVNb9-1-1	SMAW	Thermanit MTS 911	A5.5: E9015-B9 (mod.)	3580-A: E ZCrMoWVNb 9 1 1 B 4 2 H5
		BÖHLER FOX C 9 MVW	A5.5: E9015-B9 (mod.)	3580-A: E ZCrMoWVNb 9 1 1 B 4 2 H5
	GTAW	Thermanit MTS 911	A5.28: ER90S-B9 (mod.)	21952-A: W ZCrMoWVNb 9 1 1
		BÖHLER C 9 MVW-IG	A5.28: ER90S-B9 (mod.)	21952-A: W ZCrMoWVNb 9 1 1
	GMAW	Thermanit MTS 911	A5.28: ER90S-B9 (mod.)	21952-A: G ZCrMoWVNb 9 1 1
		BÖHLER C 9 MVW-IG	A5.28: ER90S-B9 (mod.)	21952-A: G ZCrMoWVNb 9 1 1
	SAW wire	Thermanit MTS 911	A5.23: EB9 (mod.)	24598-A: S ZCrMoWVNb 9 1 1
		BÖHLER C 9 MVW-UP	A5.23: EB9 (mod.)	24598-A: S ZCrMoWVNb 9 1 1
	SAW flux	Marathon 543		14174: SA FB 2 55 DC H5
		BÖHLER BB 910		14174: SA FB 2 55 DC H5
VM12-SHC / X12CrCoWVNb11-2-2	SMAW	Thermanit MTS 5 CoT	A5.5: E9015-B9 (mod.)	3580-A: E ZCrCoW11 2
		BÖHLER FOX C12 CoW	A5.5: E9015-B9 (mod.)	3580-A: E ZCrCoW11 2
	GTAW	Thermanit MTS 5 CoT	A5.28: ER110S-G	21952-A: W ZCrCoW 11 2 2
		BÖHLER C12 CoW-IG	A5.28: ER110S-G	21952-A: W ZCrCoW 11 2 2

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