VALLOUREC & MANNESMANN TUBES

The T91/P91 Book

The T91/P91 Book

K. Haarmann, J. C. Vaillant, B. Vandenberghe
VALLOUREC & MANNESMANN TUBES

W. Bendick
Mannesmann Research Center

A. Arbab
Vallourec Research Center

FOREWORD

The information printed in the present document relates to VALLOUREC & MANNESMANN TUBES own tests and experiments on grades T/P91 and to available published data.

This book is intended to summarize the knowledge on their fields of application, on metallurgy, on high-temperature properties and on recommended fabrication procedures.

Although prepared with the greatest care and attention, the information appearing in this book is only for general information.

VALLOUREC & MANNESMANN TUBES shall accept no responsibility for the use made of the information contained in this book.

Customers should therefore exercise particular attention with regard to their procedures, recommendations and equipments when using T91 tubes and P91 pipe.

TABLE OF CONTENTS

1 INTRODUCTION

VALLOUREC & MANNESMANN TUBES – in short V & M TUBES – results from the merger on October 1st 1997 of VALLOUREC INDUSTRIES and MANNESMANNROHR.

V & M TUBES is the leading seamless boiler tubes and pipes producer in the world, with eleven tube/pipe mills in Germany, France and Brazil, supplied with steel by wholly owned, affiliated or approved steel plants.

Some basic facts and figures about the company are:

- Sales about 2.1 billion US $ (1.9 billion €)
- Personnel: 12.000
- Production capacity: 2.3 million metric tons
- Size ranges:
  – OD (outside diameter) from 17 mm (0.669″) to 1500 mm (59″)
  – WT (wall thickness) from 2 mm (0.08″) to 270 mm (10 5⁄8″)
  – ID (inside diameter) controlled pipe and tight tolerances available thanks to state-of-the-art machining capabilities
- Sales offices in France, Germany, Brazil, U.S.A., China and Singapore and a worldwide network of representatives

2 T/P91 KEY FACTORS

2.1 Steel type

Grade 91 is a ferritic/martensitic (9% chromium, 1% molybdenum) steel micro-alloyed with vanadium and columbium (niobium) and with controlled nitrogen content.

2.2 Main applications

Boiler superheater and reheater tubes of power plants.
Header and steam piping (main steam and hot reheat) for high-temperature use.
Furnace tubular of petrochemical units.

2.3 Advantages

Excellent elevated temperature strength and creep behaviour. Increased corrosion-oxidation resistance compared to grade 22. Reduced weight of boiler and piping components. Improved resistance to thermal fatigue. Good heat transfer and low expansion coefficient compared to austenitic steels.

2.4 Standardization

In the U.S.A.:

- ASTM A 213 since 1983
- ASTM A 335 since 1984
- ASME A 213 since 1984
- ASME A 335 since 1985

For other products forms, see paragraph 4.1.

In Europe:
EN 10 216-2 under the designation X10CrMoVNb9-1

In France:
NF A 49-213 since 1989 under the designation of TU Z 10CDVNb 09-01

In Germany:
Approved in VdTÜV Data Sheet 511/2 (latest edition 06/2001) as X10CrMoVNb9-1

In U.K.:
Approved in BS 3059/3604 as grade 91

2.5 Experience

More than 100,000 tons of T/P91 and European equivalent grades delivered by V & M TUBES are already used all over the world in large utility boilers, piping systems and petrochemical units. Main references are given in paragraph 5 APPLICATIONS AND INDUSTRIAL EXPERIENCES.

2.6 V & M TUBES scope of supply

Seamless boiler tubulars:
– hot finished tubes with tight tolerances
– pipe and headers up to OD 1500 mm (59”)
– ID controlled pipe

3 TECHNICAL BACKGROUND

Steels for high-temperature service are a vital part in the construction of power stations. For over 50 years, the 2¼% Cr, 1% Mo alloy steel has been standardized in all national codes (e.g. ASTM: T/P22; NF A: TU 10CD 9.10; DIN: 10CrMo9-10; BS: 622 and EN 11CrMo9-10) and has been used worldwide in high capacity power stations with excellent operating performance.

The increase of operating parameters (pressure, temperature) and unit sizes required the development of higher-strength steels. In Europe, two steels with increased creep rupture strength have been developed in the early sixties for this application: EM12 in France and Belgium and X20CrMoV12-1 in Germany (see Table 3.1).

EM12 is a 9% Cr, 2% Mo steel with V and Cb (Nb) additions, used only in tubing.
X20CrMoV12-1 is a 12% Cr, 1% Mo steel with V addition. It has been used in European and many other countries all over the world for tubing and piping.

The next step forward was the development of the modified 9% Cr steel in the U.S.A. which was also followed up in Europe and Japan. Called T/P91, this grade was successfully accepted worldwide since the late 80's. Nowadays, both EM12 and X20CrMoV12-1 steels have been replaced by T/P91 in many cases.

Table 3.1: Application of high-temperature steels in Europe, in the U.S.A. and in Japan

Year	Europe	U.S.A.	Japan
Before 60's	10CrMo9-10 (2¼% Cr, 1% Mo)	T/P22	STBA24-STPA24
In 60's	14MoV6-3 (0.5% Cr, 0.5% Mo, 0.25% V)	T/P22	STBA24-STPA24
Middle 60's	X20CrMoV12-1 (12% Cr, 1% Mo, 0.25% V) EM12 (9% Cr, 2% Mo, V, Nb)	T/P22	STBA24-STPA24
Since middle 80's	X10CrMoVNb9-1 (9% Cr, 1% Mo, 0.25% V, Nb)	T/P91	STBA28-STPA28

Further developments took place in Europe and Japan since the late 80's as shown in Table 3.2.

Table 3.2: Further developments since the late 80's

Material designation
7 CrMoVTiB10-10 (T24)
E 911 (T/P911)
T23
T/P 92
T/P122

4 STANDARDS AND CODES

4.1 Codes

Since its approval by ASTM/ASME in 1983, T/P91 (tubes/pipe) as well as other product forms have been recognized by several other national standards. Table 4.1 hereafter summarizes the actual status.

Table 4.1: Modified 9Cr-1Mo in international standards

Specification and grade	Country	Description
A 213 T91	U.S.A.	Seamless ferritic and austenitic alloy-steel boiler, superheater, and heat-exchanger tubes
A 335 P91	U.S.A.	Seamless ferritic alloy-steel pipe for high-temperature service
A 387 GR91	U.S.A.	Pressure vessel plates Alloy-steel chromium-molybdenum
A 182 F91	U.S.A.	Forged or rolled alloy-steel pipe Flanges, forged fittings and valves and parts for high-temperature service
A 234 WP91	U.S.A.	Piping fitting of wrought carbon steel and alloy for moderate and elevated temperature
A 200 T91	U.S.A.	Seamless ferritic alloy-steel tubes for refinery service
A 336 F91	U.S.A.	Steel forgings, alloy for pressure and high-temperature parts
A 369 FP91	U.S.A.	Carbon and ferritic steel forged and bored pipe for high-temperature service
NF A 49213 Grade TU Z 10CDVNb 09-01	France	Hot finished and cold drawn seamless ferritic alloy-steel boiler – superheater and heat-exchanger tubes
NF A 49219 Grade TU Z 10CDVNb 09-01	France	Hot finished and cold drawn seamless tubes and pipe for refinery service
DIN 17 175 VdTÜV 511/2 X10CrMoVNb9-1	Germany	Seamless tubes of heat-resistant steels Technical conditions of delivery
BS 3604-2 Grade 91	U.K.	Steel pipe and tubes for pressure purpose, ferritic alloy steel with specified elevated temperature properties
BS 3059-2 Grade 91	U.K.	Steel boiler and superheater tubes Part 2 specification for carbon alloy and austenitic stainless steel tubes with specified elevated temperature properties
EN 10 216-2 X10CrMoVNb9-1	Europe	Seamless steel tubes for pressure purposes – Technical delivery conditions

4.2 Maximum allowable stresses

Design stresses for the equivalent modified 9Cr-1Mo steels (given in the Table 4.1) are calculated according to the applied code recommendations, e.g. American ASME, German DIN/TRD and French CODAP.

According to code ASME II and VIII (see Tables 4.2 and 4.3), maximum allowable stresses for SA 213 T91 tubes and SA 335 P91 pipe are specified.

Table 4.2: Maximum allowable stresses of grade 91 (WT ≤ 3″) according to ASME section II, Part D

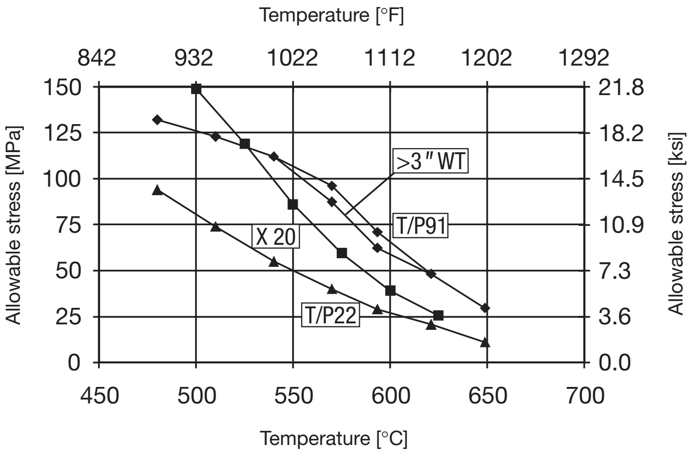
°C	371	399	427	454	482	510	538	566	593	621	649
°F	700	750	800	850	900	950	1000	1050	1100	1150	1200
MPa	158	153	147	140	132	123	112	96	71	48	30
ksi	22.9	22.2	21.3	20.3	19.1	17.8	16.3	14.0	10.3	7.0	4.3

Table 4.3: Maximum allowable stresses of grade 91 (WT > 3″) according to ASME section II, Part D

°C	371	399	427	454	482	510	538	566	593	621	649
°F	700	750	800	850	900	950	1000	1050	1100	1150	1200
MPa	158	153	147	140	132	123	112	89	66	48	30
ksi	22.9	22.2	21.3	20.3	19.1	17.8	16.3	12.9	9.6	7.0	4.3

Figure 4.4 compares the maximum allowable stress values of grade 91 to other well known ferritic and martensitic grades. Although, X 20 is not included in ASTM/ASME, maximum allowable stress values have been calculated for comparison according to the ASME design rules.

Figure 4.4: Maximum allowable stresses of grade 91 compared to grades 22 and X 20 according to ASME section II, Part D design rules



5 APPLICATIONS

5.1 New power boilers and piping systems

The national and international standards specify the creep rupture strength values or maximum allowable stresses for materials used in boilers and piping systems. The actual in-plant application is regulated by additional design codes (e.g. ASME, TRD).

In modern fossil-fired power plants, grade T/P91 allows higher operating parameters (pressure, temperature) and therefore higher efficiencies. Based on European experiences, T91 can be used inside the boiler (superheaters, reheaters) for steam temperatures up to 560°C/1050°F (maximum metal temperatures around 600°C/1110°F). Outside the boiler (pipe and headers), P91 could operate at steam temperatures up to about 610°C/1130°F.

In future power plants with conventional steam parameters, more flexibility and costs savings are obtained by using T/P91 instead of T/P22, by wall thickness reduction thanks to improved creep properties and oxidation resistance of T/P91.

5.2 Refurbishing – repair

In old power plants, tubing and piping were commonly made of steel grade T/P11, T/P22 or equivalent materials.

The better creep rupture strength of P91 allows design engineers to decrease considerably the wall thickness of headers and piping systems compared to P22 (up to 50% depending on design temperature). This reduced wall thickness decreases the thermal gradient in the wall during start-up and shut-down operations, thus preventing fatigue cracks which have been a problem in many P22 thick-wall components: a substantial number of P22 headers showing ligament cracking have been worldwide replaced by P91.

T91 can also be considered as an alternative to austenitic stainless steel in superheaters and reheaters when design parameters are properly applied.

5.3 Petrochemical applications

In distillation and cracking units as well as in refineries, grade T/P91 tubes, pipe and plates begin to replace grade 22 and grade 5 (pipe and plate) thanks to their better high-temperature mechanical properties and resistance against high-pressure hydrogen.

Moreover, T/P91 is preferred to T/P22 and T/P5 in sulfur-rich atmospheres furnaces.

5.4 Operating experience

More than 100,000 tons T/P91 and equivalent European grades have been delivered by V & M TUBES all over the world
(see Tables 5.1 and 5.2).

Table 5.1: Some references (examples) of installation of V & M T/P91/X 10 in power plants all over the world during 1990's (main steam conditions are mentioned)

Country	Project / Utility	Customer	Year of delivery	Steam temperature [°C/°F]	Steam pressure [bars/ksi]
Belgium	Baudour	Alstom	1993–97	550°C/1020°F	190 bars/2.9 ksi
France	Cordemais II	Babcock Entreprise	1994	550°C/1020°F	190 bars/2.9 ksi
Germany	Schwarze Pumpe	Alstom (EVT) [B] Lentges [P]	1994	570°C/1060°F	286 bars/4.4 ksi
Germany	Lippendorf	Deutsche Babcock [B, P]	1996	588°C/1090°F	285 bars/4.4 ksi
Germany	Boxberg	Steinmüller [B] Deutsche Babcock [P]	1996	583°C/1080°F	280 bars/4.1 ksi
Mexico	Lopez Mateos Tuxpan	Cerrey & Alstom (Stein)	1991–93	560°C/1040°F	180 bars/2.7 ksi
China	Wo Hang	Mitsui Babcock	1994–95	550°C/1020°F	180 bars/2.7 ksi
Kuwait	Sabiya	Mitsubishi	1990	560°C/1050°F	190 bars/2.9 ksi
Denmark	Nefo/Skaerbaeck	Deutsche Babcock [P]	1994	580°C/1080°F	310 bars/4.5 ksi

[B = Boiler]

[P = Piping]

Table 5.2: Other main references of installation of V & M T/P91 in power plants all over the world during 1990's

Country	Project (Utility)	Customer	Year of delivery
U.S.A.	J. M. Stuart (Dayton P&L)	ABB	1989–90
U.S.A.	Indianapolis P&L	ABB	1993
U.K.	Ferry Bridge	Nei	1993–95
S.A.	Eskom/Matla	B.E.C.	1993–97
U.K.	Keadby	Mitsui Babcock	1994
Korea	Poryong, etc.	Hanjung	1994–95
Indonesia	Pagbilao	Mitsubishi	1995
Malaysia	Port Kelang 1&2	BF Shaw (U.S.A.)	1995
U.S.A.	Clinch River	B & W	1995
U.K.	Didcot	Steel Engineering	1995
Finland	Veitsiluoto	Alstom	1995
China (Hong Kong)	Black Point	Mitsui Babcock	1995
China	Yang Zhou	Babcock & Wilcox	1995
China	Dangdong – Dalian	Mitsui Babcock	1996
U.S.A.	Big Rivers	Foster Wheeler	1997
Taiwan – China	Formosa Plastic	Technip	1998–99
U.S.A	Fort Meyers	IPS	1999
U.K.	Lakeroad	Alstom	1999
Mexico	Bajio, Saltillo	Cerrey	1999
Korea	Tea 5-6	Doosan	1999
Taiwan – China	Mansung	Alstom	1999–2000
U.S.A	Sanford	IPS	2000
India	Talcher 1–2	BHEL	2000
China	Heze	Mitsui Babcock	2000
China	Liaocheng	Mitsui Babcock	2000
Taiwan – China	Taichung	Mitsui Babcock	2000
Mexico	Altamira	Cerrey	2000
Korea	Young Hungdo	Hanjung	2000–01

6 METALLURGY OF T/P91

6.1 Chemical composition

Chemical composition of grade 91 specified by ASTM in different product standards is compared in Table 6.1 to other standard steel grades used for high-temperature applications. This Table clearly shows the more restrictive chemical limits applied to this grade.

Historically, the basic grade 9 was modified by the addition of vanadium (V) and columbium/niobium (Cb/Nb) as well as by the control of nitrogen (N). The creep strength was greatly improved. Afterwards, the carbon content was intentionally lowered with regard to the fabrication process.

Table 6.1: Chemical requirements in weight % of T/P91, EM12, T/P22, X 20 and TP304H

Grades		**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Mo**	**V**	**Cb (Nb)**	**N**	**Al**	**Ni**
T/P91	min.	0.08	0.30			0.20	8.00	0.85	0.18	0.06	0.030		
	max.	0.12	0.60	0.020	0.010	0.50	9.50	1.05	0.25	0.10	0.070	0.040	0.40
EM12	min.		0.80			0.20	8.50	1.70	0.20	0.30			
	max.	0.17	1.30	0.030	0.030	0.65	10.50	2.30	0.40	0.55			0.30
T/P22	min.		0.30				1.90	0.87					
	max.	0.15	0.60	0.025	0.025	0.50	2.60	1.13					
X 20	min.	0.17					10.00	0.80	0.25				0.30
	max.	0.23	1.00	0.030	0.030	0.50	12.50	1.20	0.35				0.80
TP304H	min.	0.04					18.00						8.00
	max.	0.10	2.00	0.040	0.030	0.75	20.00						11.00

6.2 Physical properties

Table 6.2 indicates the main physical properties needed for design purposes. In Figures 6.3 and 6.4, the comparison between T/P91's thermal conductivity and coefficient of linear expansion for T/P22 respectively TP304H austenite stainless steel shows a clear superiority of T/P91.

Table 6.2: Main physical properties of T/P91

Temperature	°C	20	50	100	150	200	250	300	350	400	450	500	550	600	650
	°F	68	122	212	302	392	482	572	662	752	842	932	1022	1112	1202
Modulus of elasticity	**GPa**	218	216	213	210	207	203	199	195	190	186	181	175	168	162
	10^3 ksi	31.6	31.3	30.9	30.5	30.0	29.5	28.9	28.3	27.6	27.0	26.3	25.4	24.4	23.5
Thermal conductivity	**W/mK**	26	26	27	27	28	28	28	29	29	29	30	30	30	30
Coefficient of linear expansion between R.T. and indicated temperature	**10^{-6}/°C**	0.0	10.6	10.9	11.1	11.3	11.5	11.7	11.8	12	12.1	12.3	12.4	12.6	12.7
	10^{-6}/°F	0.0	5.9	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.7	6.8	6.9	7.0	7.1
Specific heat capacity	**J/kg K**	440	460	480	490	510	530	550	570	600	630	660	710	770	860
Weight per volume	**x10^3 kg/m^3**	7.77													

The success of T/P91 compared to stainless steels is based on a better thermal conductivity and a lower mean coefficient of linear expansion as shown in Figures 6.3 and 6.4.

Figure 6.3: Thermal conductivity

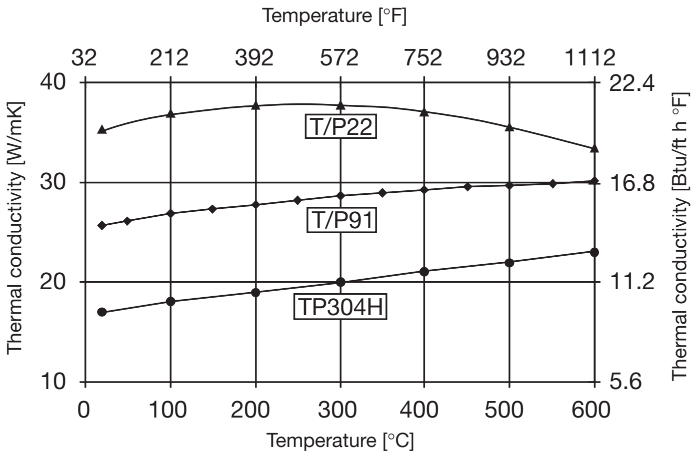


Figure 6.4: Mean coefficient of linear expansion

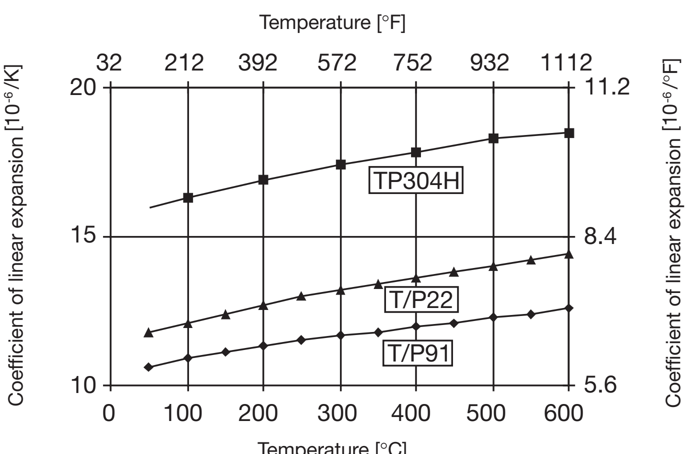
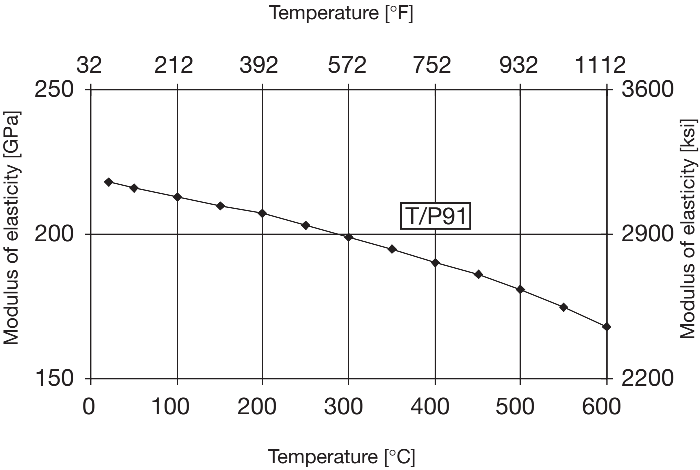


Figure 6.5 shows the modulus of elasticity of T/P91 versus temperature.

Figure 6.5: Modulus of elasticity versus temperature



6.3 Transformation behaviour

6.3.1 A_{C1} and A_{C3} temperatures

Transformation temperatures are determined by differential dilatometric method.
Depending on chemical composition, A_{C1} temperature was found to be between 800°C and 830°C (1472°F and 1526°F).
A_{C3} was found between 890°C and 940°C (1635°F and 1725°F).

6.3.2 Continuous cooling temperature (CCT) diagram

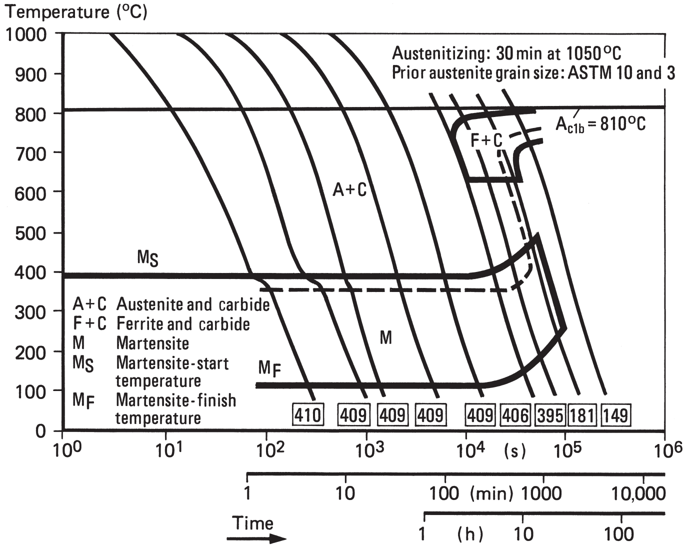
Figure 6.6 shows the CCT diagram of grade T/P91.

T/P91 is used in the normalized and tempered condition. By cooling from austenitizing temperature to room temperature, the structure of T/P91 transforms, over a wide area of cooling rates, totally into martensite. The maximum hardness of the martensite is less than 450 HV.

M_S temperature (starting of martensitic transformation) is rather high, around 400°C (750°F). M_f temperature (end of martensitic transformation) lies above 100°C (210°F), varying with prior austenite grain size.

Figure 6.6: CCT diagram of grade T/P91

Chemical composition (%)	C	Si	Mn	P	S	N	Al	Cr	Ni	Mo	V	Nb
	0.11	0.32	0.47	0.014	0.0030	0.038	0.018	8.50	0.13	0.85	0.22	0.076



Continuous cooling transformation diagram of T/P91 steel

6.4 Industrial heat treatment

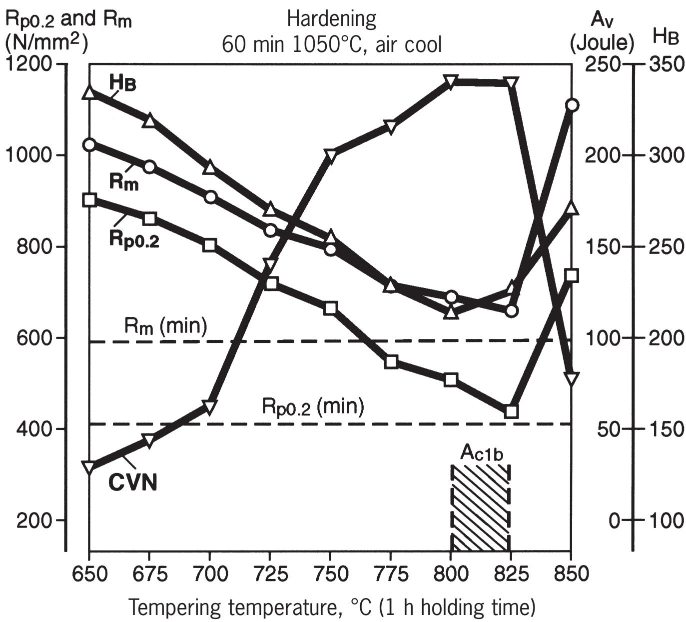
V & M has established, based on its long-time experience, a heat treatment procedure which provides an optimum compromise between:
– high creep rupture strength
– limited hardness
– good toughness

Normalizing at 1040°C–1080°C (1900°F–1980°F) provides dissolution of most carbides without significant grain growth.

Tempering at 750°C–780°C (1380°F–1435°F) allows carbides to precipitate homogeneously within the martensitic structure, thus contributing to improve the creep behaviour. Figure 6.7 shows the effect of tempering at different temperatures between 650°C (1200°F) and 850°C (1560°F) for 1 hour on the mechanical properties of grade 91: R_m (tensile strength), $R_{p0.2}$ (yield strength), HB (Brinell hardness) and CVN (Charpy V notch impact energy).

Figure 6.7 shows a decrease of yield strength ($R_{p0.2}$), tensile strength (R_m) and hardness and an increase of toughness with the increase of tempering temperature up to A_{C1}. Above A_{C1}, strength properties increase and the toughness decreases due to the formation of fresh martensite. Tempering above A_{C1} (800°C/1472°F) results in inferior creep properties.

Figure 6.7: Tempering effect on mechanical properties of T/P91



Tempering curve for T/P91 (test results at R.T.)

Table 6.8: Normalizing and tempering of grade T/P91

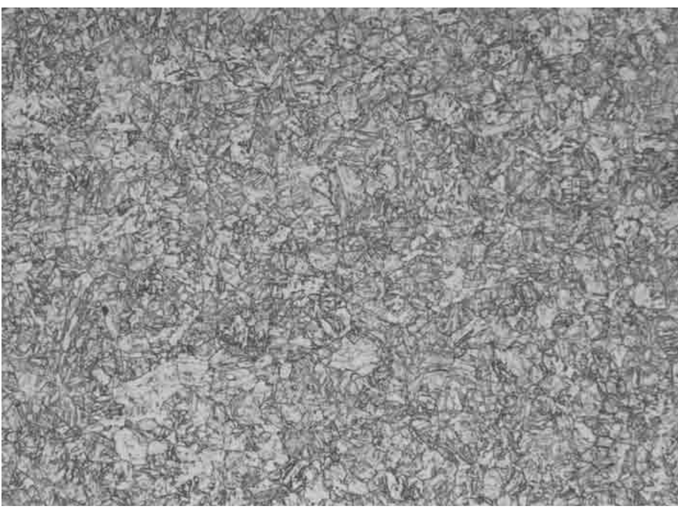
	According to ASTM A 213 ASTM A 335	V & M practice
Normalizing*)	1040°C (1900°F) minimum	1040°C to 1080°C (1900°F to 1980°F)
Tempering	730°C (1350°F) minimum	750°C to 780°C (1380°F to 1435°F)

*) For wall thicknesses larger than 3″ (76 mm) accelerated cooling is necessary to obtain a fully martensitic structure.

6.5 Microstructures

The specified heat treatment condition leads to a structure of tempered martensite with precipitation of $M_{23}C_6$ carbides and vanadium/columbium (niobium) rich carbo-nitride of type MX (M=V or Cb and X=C or N). The presence of these precipitates improves creep rupture strength by precipitation hardening. In addition, the $M_{23}C_6$ carbides mainly stabilize the martensitic lath structure.

Figure 6.9: Typical microstructure of T/P91 after normalizing and tempering



6.6 Mechanical properties

Table 6.10 compares the values of mechanical properties of T/P91 at room temperature with those of other steel grades (X 10 is the European designation of the steel grade equivalent to T/P91, see Table 4.1).

Table 6.10: Mechanical properties of T/P91 and similar grades at room temperature

Standard	Grades	Yield strength MPa (ksi)	Tensile strength MPa (ksi)	Minimum longitudinal elongation %	Maximum hardness HB	Impact Energy (J) 20°C
A 213 – A 335	T/P22	Min. 205 (30)	Min. 415 (60)	30 (1)	163 (3)	_
A 213 – A 335	**T/P91**	**Min. 415 (60)**	**Min. 585 (85)**	**20 (1)**	**250 (3)**	**–**
VdTÜV 511/2	**X 10**	**Min. 450 (65)**	**620 – 850 (90 – 123)**	**19 (2)**	**–**	**–**
EN 10 216-2	**X 10**	**Min. 450 (65)**	**630 – 830 (91 – 120)**	**19 (2)**	**–**	**T:27**
DIN 17 175	X 20	Min. 490 (71)	690 – 840 (100 – 122)	17 (2)	**–**	**L:40 T34**

(1) on 2″ specimen, (2) on 5D specimen, (3) only for ASTM A 213
T = transverse, L = longitudinal

6.6.1 Yield and tensile strength

Tensile properties of T/P91 were determined between 20°C (68°F) and 650°C (1200°F).

Figure 6.11 shows the 0.2 proof strength of T/P91 versus temperature.

Figure 6.12 shows the tensile strength of T/P91 versus temperature.

Figure 6.11: 0.2 proof strength of T/P91 versus temperature

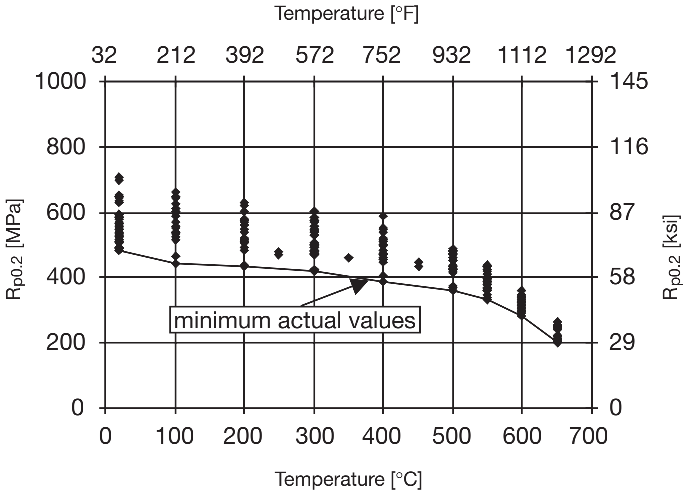
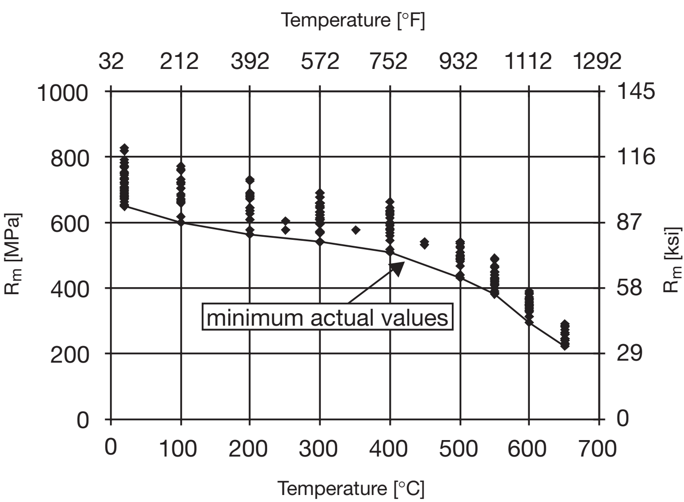


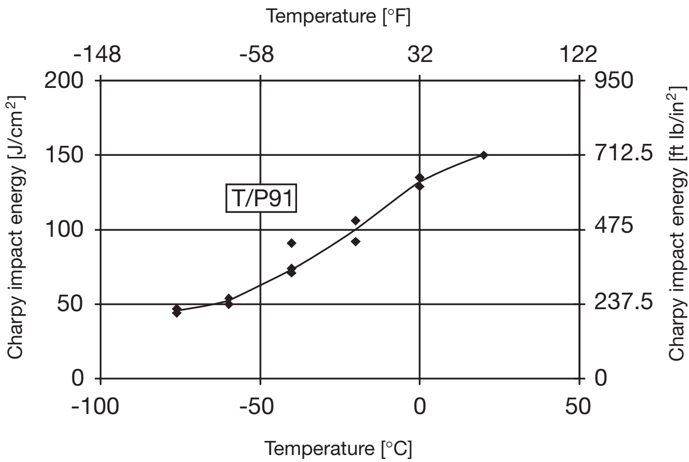
Figure 6.12: Tensile strength of T/P91 versus temperature



6.6.2 Impact tests

Additionally to tensile tests, Charpy V notch impact tests were performed. Figure 6.13 shows a typical example of Charpy impact tests on T/P91 versus temperature.

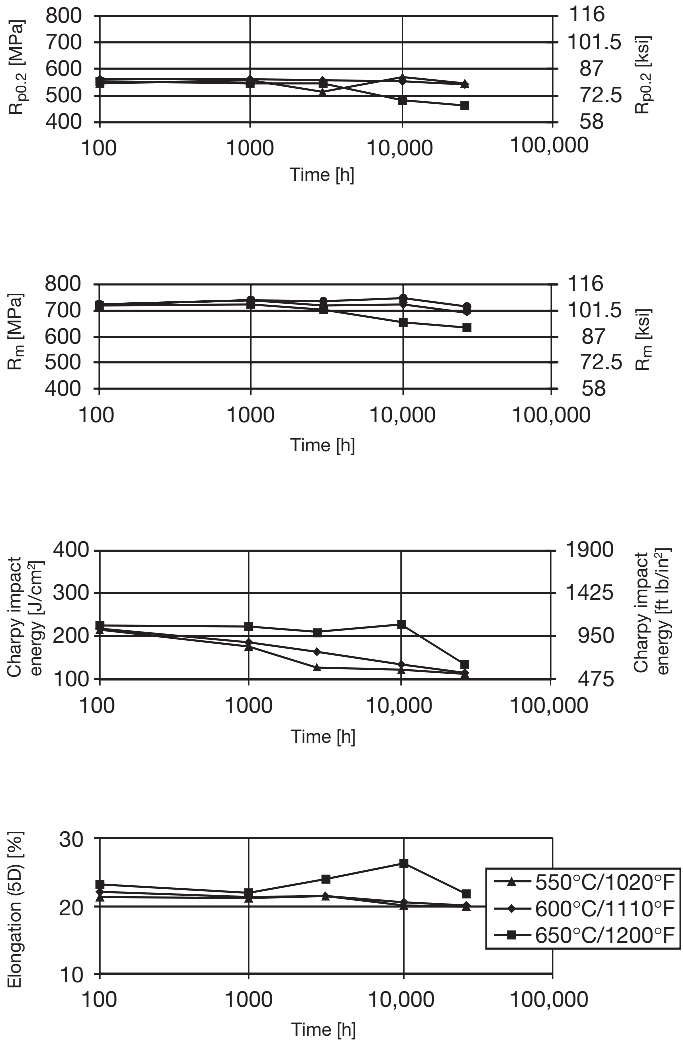
Figure 6.13: Charpy impact tests of T/P91 versus temperature



6.7 Properties after aging

The mechanical properties were determined after artificial aging. Specimens were aged at 550°C, 600°C and 650°C (1020°F, 1110°F and 1200°F) from 100 hours up to about 30,000 hours. The results in terms of yield strength, tensile strength, elongation and toughness are given in Figure 6.14.

Figure 6.14: Strength, elongation and toughness of grade T/P91 after aging

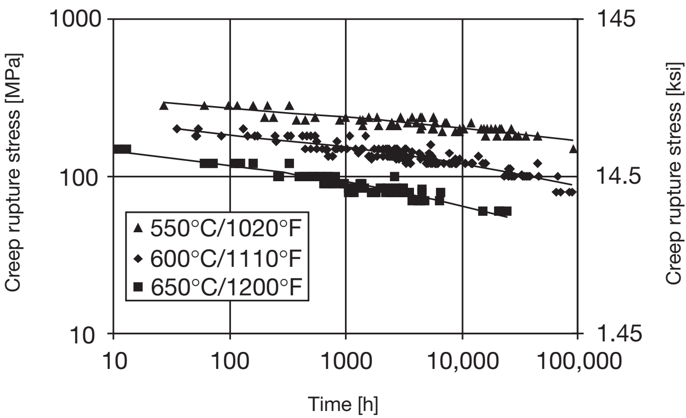


6.8 Creep properties

6.8.1 Creep tests

Creep tests were performed on tubes and pipe from different heats of T/P91, and at different temperatures and stresses. Figure 6.15 shows V & M creep rupture strength data of grade T/P91, at 3 different temperatures 550°C (1020°F), 600°C (1110°F) and 650°C (1200°F).

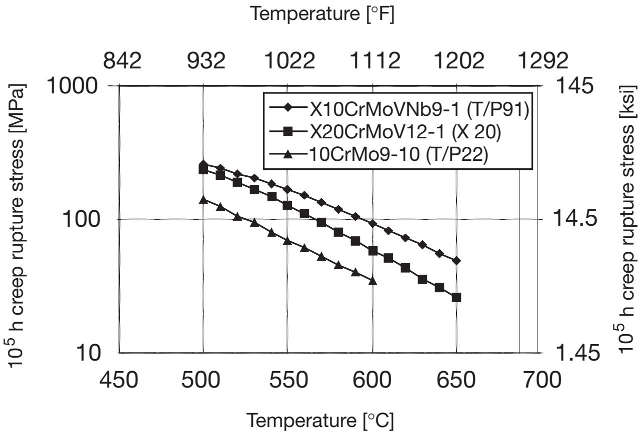
Figure 6.15: V & M creep test results of grade T/P91 at 3 different temperatures



6.8.2 Comparison of grade T/P91 with grades T/P22 and X 20

According to the EN 10 216-2 standard, Figure 6.16 shows the comparison of 100,000 hours creep rupture stress between grades T/P91, X 20 and T/P22 versus temperature.

Figure 6.16: Comparison of creep rupture strength after 100,000 hours according to EN 10 216-2



Grade T/P91 has been investigated over the years in many laboratories all over the world and presently around 1800 individual test results are known. Table 6.17 shows the creep rupture values for ASTM, VdTÜV and EN materials.

Table 6.17: Creep rupture strength according to ASTM A 213 and A 335, VdTÜV and EN evaluations

Temperature	**[°C] [°F]**	**500 930**	**525 980**	**550 1020**	**575 1070**	**600 1110**	**625 1160**
$\sigma_{R\ 100{,}000\ h}$ **[MPa/ksi]**	***ASME**	164/24	153/22	141/20	124/18	98/14	68/10
	VdTÜV	253/37	206/30	162/24	122/18	90/13	63/9
	EN	258/37	210/31	166/24	127/18	94/14	69/10

*ASME: Creep rupture value is ASME maximum allowable stress multiplied by 1.5.

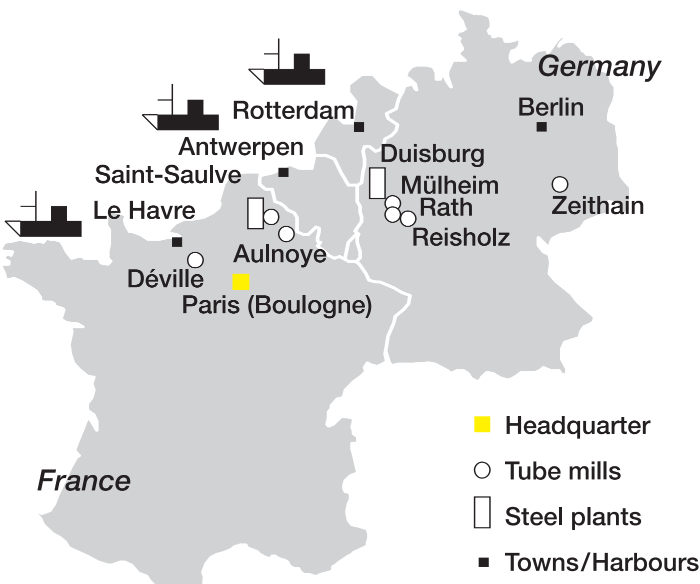
7 TUBE PRODUCTION

7.1 Manufacturing process

Tubes and pipe are manufactured using various processes mastered by V & M TUBES (see Figure 7.1):

- Hot rolling on:
  - continuous mandrel mills in Saint-Saulve (France) and Mülheim (Germany)
  - push bench in Zeithain (Germany)
  - plug mill in Aulnoye, Déville (France) and Düsseldorf-Rath (Germany)
  - pilger mill in Düsseldorf-Rath
- Hot piercing and drawing in Düsseldorf-Reisholz (Germany)

Figure 7.1: VALLOUREC & MANNESMANN TUBES manufacturing plants and mills in Europe



7.2 Size ranges

Today, V & M TUBES produces a complete range of hot finished tube and pipe in accordance with T91 (ASTM A 213) and P91 (ASTM A 335) and equivalent standards, as it is shown in Table 7.2.

Table 7.2: VALLOUREC & MANNESMANN TUBES size range

Mills with	OD mm [inch]	WT mm [inch]	Max. length m [feet]
OD ≤ 7″ (177.8 mm)	26.9 to 177.8 [1.05″ to 7″]	2.0 to 30 [0.08″ to 1.80″]	25 (1) [82″]
OD > 7″ (177.8 mm)	177.8 to 1500 [7″ to 59″]	8.0 to 270 [0.31″ to 10 5/8″]	14 (1) [46″]

(1) Depending upon actual tubes and pipe size

8 FABRICATION

8.1 General considerations

As already pointed out in paragraph 6.4 (Heat treatment T/P91 – base material), during all the different fabrication steps the metallurgical background of this martensitic steel has to be considered. That is especially of importance for all hot forming operations (bending, swaging, upsetting, etc.) but also for the temperature cycle during and after welding.

During the different fabrication steps the heat treatment must be carried out as per the relevant standard/code. Adequate temperature controls are recommended and in our opinion are absolutely necessary. Incorrect heat treatment will result in premature failures of individual components or of complete systems.

In case of cold bending the setup of the machine has to be optimized and the high yield/tensile strength and high toughness of T/P91 has to be considered. Normal practice is that cold bending is carried out up to OD of around 152.4 mm (6″).

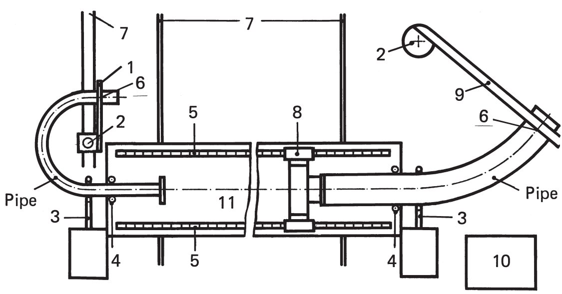
8.2 Hot bending

As determined by Gleeble tests, the optimum hot forming temperature range for T/P91 lies between 750 and 1100°C (1560 – 2010°F). Forming operations such as forging and upsetting should be performed in the upper part of the temperature range between 1100 and 950°C (2010 – 1740°F), while hot bending and stretching should be carried out in the lower part of the temperature range. In case of the latter the temperature can decrease to 750°C (1380°F) during processing. Depending upon the actual capability of the induction bending machine, it is recommended to carry out a qualification test to determine the optimum bending parameters (temperature, speed, etc.). After hot forming the material has to receive a complete new normalised and tempered (N+T) treatment as specified for the tube and pipe.

Hot bending of tube is normally performed only in the case of very small radius (R ≤ 1.5). In many cases it is a two-step bending process (1. step: cold forming; 2. step: hot forming).

Nowadays hot bending of pipe is normally carried out using computer-aided induction bending machines. An induction-bent pipe features high accuracy of shape. Induction bending is a technologically advanced and largely automated process in which the pipe is gradually bent in consecutive narrow zones heated by an inductor ring. The bending force acts axially on the pipe whose front end is clamped to a pivoting arm. Set to the desired bending radius, this bending arm describes a circular arc around the pivot point. Under the effect of radial thrust applied to it, the pipe automatically follows this curve. The induction bending process requires no forming tools. It is very flexible with respect to geometric dimensions. Figure 8.2.1 shows a sketch of a high-power induction bending machine, in this case equipped with two bending arms.

Figure 8.2.1: Induction bending machine equipped with two bending arms



1 Bending arm (light)
2 Pivot
3 Inductor
4 Guide rollers
5 Drive chains
6 Clamping device
7 Rails
8 Feed mechanism
9 Bending arm (heavy)
10 Power source
11 Machine bed

The pipe diameter which can be bent by this process depends upon the type of the machine. The general size range reaches from 88.9 mm (3½″) to 1626 mm (64″) OD or the equivalent ID and wall thickness up to 100 mm (3.95″). This diameter and wall thickness range satisfies the requirements for the construction of power stations.

Actual bending experience exists in a Mannesmann company for the size range between 260 mm ID x 77 mm nominal wall thickness (10.24″ x 3.02″) and 950 mm ID x 40 mm nominal wall thickness (37.40″ x 1.58″). Bends with bending angles up to 180° and bending radii down to 1.2 D can be produced by this process and have already been used in the modified 9% Cr, 1% Mo steel. Induction bending of P91 has to be carried out at an optimized temperature range to be sure that no microcracks or microfissures occur.

The modern induction bending technology allows the definition of optimized temperatures, depending upon the actual radius. A typical bending program is shown in Figure 8.2.2. Provided the outside diameter and bending radius are known, the required minimum wall thickness can be read in the bottom line. Conversely, the required minimum radius can be derived for a specific outside diameter and minimum wall thickness.

The influence of the bending geometry on wall thickness and ovality is given in Figure 8.2.3. When bending a steel pipe, its wall thickness is reduced at the extrados and increased at the intrados. The percentage of deviation from the straight pipe depends primarily on the ratio of bending radius over outside diameter of pipe (R/D). The ovality is mainly influenced by R/D, too.

It is recommended to make qualification bends under the same bending parameters as for actual production and investigate such bends non-destructively and destructively very carefully.
Qualification bends have been produced from the following grade 91 pipe:

a) OD 380 x 50.0 mm WT (14.96″x 1.97″), R/D = 2.5
b) OD 434 x 17.0 mm WT (17.09″x 0.67″), R/D = 1.4
c) OD 121 x 20.0 mm WT (4.76″x 0.79″), R/D = 2.0
d) OD 159 x 20.0 mm WT (6.26″x 0.79″), R/D = 1.5
e) OD 201 x 19.5 mm WT (7.91″x 0.77″), R/D = 4.0

Figure 8.2.2: Typical bending program for ferritic steel pipe

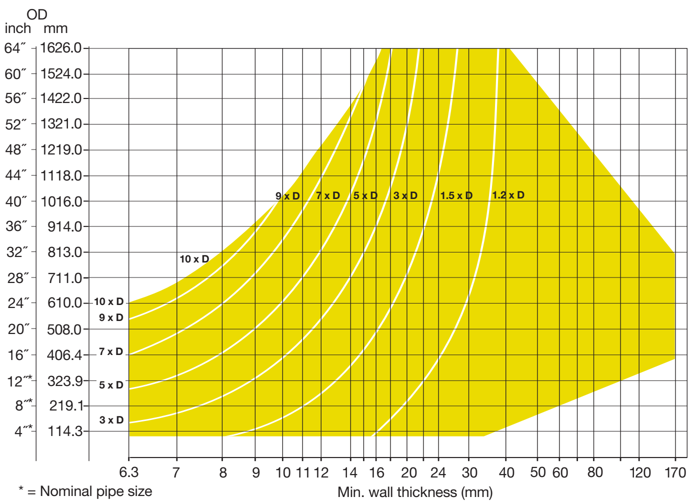
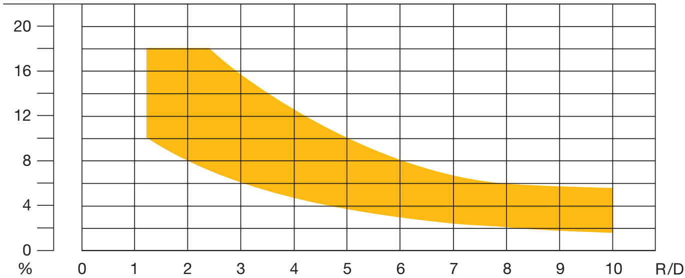


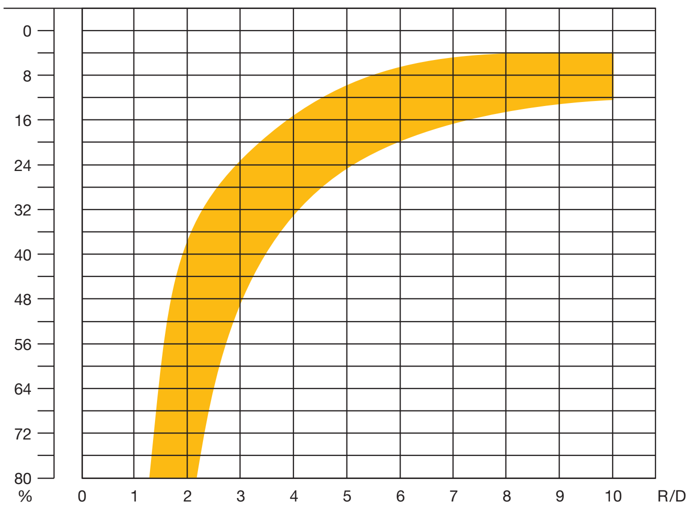
Figure 8.2.3: Change in wall thickness and ovality during inductive bending

Wall thickness



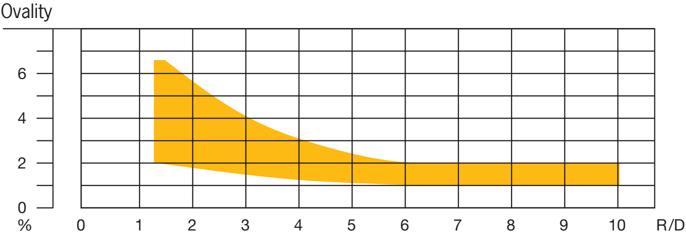
Wall thickness reduction at extrados

Wall thickness



Wall thickness increase at intrados

Ovality

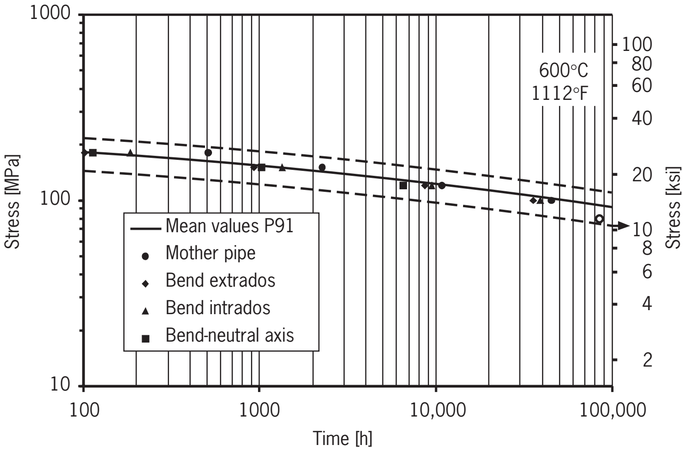


The qualification bends were subjected to a post bending heat treatment (PBHT) consisting of normalizing at 1050°C (1920°F) for 1 min/mm WT followed by air cooling and tempering at 750°C (1380°F) for 2 min/mm WT, again followed by air cooling. Afterwards qualification tests were made by cutting samples out of different locations of the bends. Examples of test results are given in Table 8.2.4. In one case also creep tests were performed at 550 and 600°C (1020/1110°F) on specimens taken out of the extrados and intrados (Fig. 8.2.5). All test results lie well within the material's scatterband with no substantial difference between extrados and intrados. Only after proper PBHT (N+T) over the full length, the induction pipe bend has the same creep rupture properties as specified for pipe. Heat treatments deviating from this practice (e.g. only tempering) will result in premature failures in the "transition zones" of the bend.

Table 8.2.4: Test results on P91 qualification bends

Details on bending	**Qualification bend a)**	**Qualification bend b)**
Pipe dimensions	380 mm OD x 50 mm WT (14.96" x 1.97")	434 mm OD x 17 mm WT (17.09" x 0.67")
Bending radius	950 mm (37.40")	600 mm (23.62")
R/D	2.5	1.4
Test results on bend		
Hardness	198 – 220 HB	197 – 220 HB
Yield strength (20°C/68°F)	529 – 555 MPa (76.7 – 80.5 ksi)	497 – 511 MPa (72.1 – 74.1 ksi)
Tensile strength (20°C/68°F)	697 – 718 MPa (101.1 – 104.1 ksi)	681 – 694 MPa (98.8 – 100.7 ksi)
0.2 proof strength (550°C/1022°F)	395 – 433 MPa (57.3 – 62.8 ksi)	342 – 362 MPa (49.6 – 52.5 ksi)
Tensile strength (550°C/1022°F)	475 – 497 MPa (68.9 – 72.1 ksi)	410 – 414 MPa (59.5 – 60.0 ksi)
Impact energy (20°C/68°F)	110 – 214 J (81 – 158 ft lbf)	199 – 223 J (147 – 164 ft lbf)
Ultrasonic inspection (5% notch)	no indications	no indications
Surface crack inspection	no indications	no indications
Microscopic examination at the extrados with magnification of 1000 x	no microcracks	no microcracks

Figure 8.2.5: Creep tests on qualification bend with R/D = 2.5



8.3 Cold bending

For all alloyed steels including T/P91 cold deformation without heat treatment is generally accepted by most codes for deformation grades < 5%.

Table 8.3.1: Admissible cold deformation without heat treatment

Code		Admissible deformations alloyed steels
ASME VIII	(USA)	< 5%
AD-Merkblatt	(Germany)	< 5%
BS 5500	(GB)	< 3.5%
CODAP	(France)	< 5%
ANCC	(Italy)	< 3%

Cold bending can be done on T/P91 without any problem. Generally, requirements for heat treatment after cold bending (PBHT) are given in the national and international codes.
As an example the following recommendations are made in a European code:

- For OD ≤ 76.1 mm (3″) and R/D ≥ 1.5 no heat treatment is required.
- For OD ≤ 76.1 mm (3″) and R/D < 1.5 a stress relieving should be performed in the temperature range between 650 and 750°C (1200/1380°F) for 2 min/mm WT, followed by air cooling.
- For OD > 76.1 mm (3″) and R/D ≥ 3 no heat treatment is required.
- For OD > 76.1 mm (3″) and R/D < 3 a complete new NT treatment is required.

Own tests were performed on tubes with the following characteristics:

Outer diameter	48.3 mm (1.901″)
Minimum wall thickness	7.1 mm (0.280″)
Yield strength (+20°C)551 MPa (80 ksi)	
Tensile strength (+20°C) 712 MPa (103 ksi)	
Elongation 28%	

The bending radius was 1.5 D.

Visual examination as well as dye penetrant testing showed no defect as can be seen on pictures taken out of sections of three bends (Figure 8.3.2).

An investigation on creep strength of cold-bent T91 tubes with OD 44.5 x 7.1 mm ($1\frac{3}{4}$″ x 0.28″) and R/D = 1.3 was carried out as part of a European research project by Arav et al. Iso stress creep tests on ring specimens taken out of the bend showed a decrease in creep rupture strength at 600°C (1110°F) which amounted to 13% with respect to the unbent tube tested in the same way (Figure 8.3.3). A stress relieving at 740°C (1360°F) could only improve the creep rupture strength below 580°C (1080°F).

Own creep tests were performed on a pipe bend in the as-bent condition with OD 139.7 x 10 mm ($5\frac{1}{2}$″ x 0.39″) and R/D = 3. The test results at 600°C show that the creep rupture strength of the bend lies within the scatterband of the base material (Figure 8.3.4).

Figure 8.3.2: Internal view on cold-bent tubes

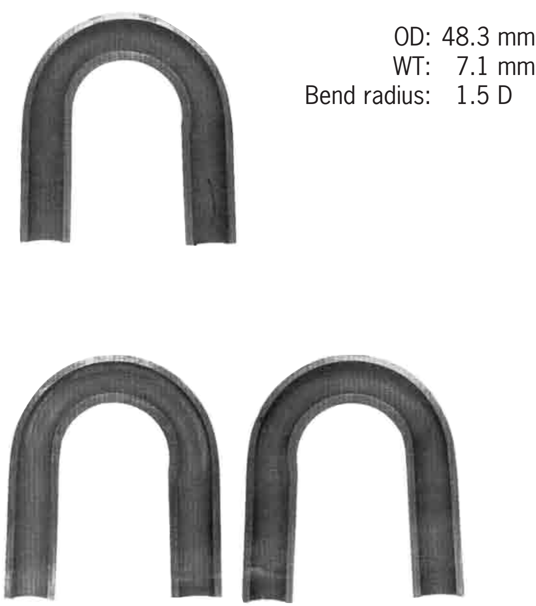


Figure 8.3.3: Iso stress creep tests on cold-bent tube
(after Arav et al.)

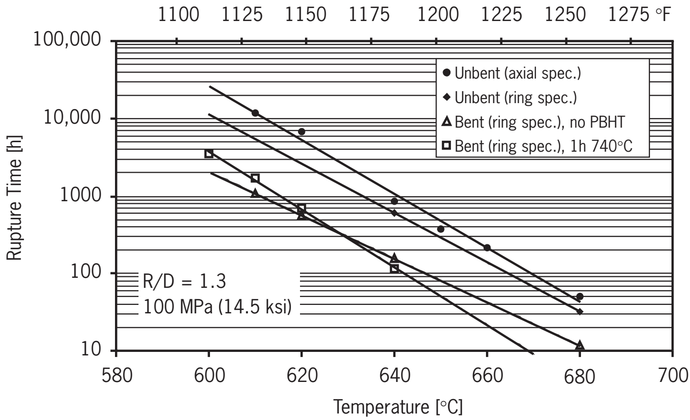
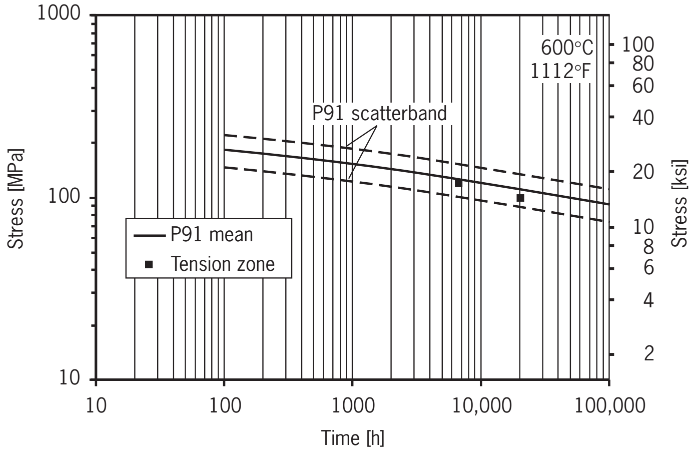


Figure 8.3.4: Creep tests on a cold-bent pipe
without PBHT (R/D = 3)



8.4 Welding

8.4.1 Introduction

The first research program on weldability of modified 9Cr-1Mo steels (T/P91) was started in 1978 by ORNL and was followed later by many research groups in the USA, Europe and Japan. In the meantime T/P91 has been welded successfully by all common welding processes, i.e. TIG, SMAW and SAW, covering a wide range of wall thicknesses. However, it was necessary to develop suitable welding consumables.

8.4.2 Welding consumables

For the welding of grade 91 several consumables producing companies have been involved in the research work to develop optimum wires, stick electrodes and flux wire combinations (see Table 8.4.1). Not all of them followed originally the same optimization route. This was especially related to the chemical composition and the resulting mechanical properties after the required stress relieving. Besides the strength requirements at room temperature (YS/TS), the weld metal has to meet certain toughness requirements and naturally the required strength at operating temperature (creep strength).

Table 8.4.1: Suppliers of consumables

Welding process	Producer*	Trade name
SMAW	SAF/Oerlikon	CDV 95 S CDV 95 SC Chromocord 9 M
	Metrode	Chromet 9-B9
	Böhler/Thyssen Schweißtechnik	Chromo 9V Fox C9MV
SAW	SAF/Oerlikon	Fluxocord 9 Cr
	Böhler/Thyssen Schweißtechnik	Thermanit MTS 3 Marathon 543 C9MVIG/UP/BB910
MIG Welding TIG/GMAW	SAF/Oerlikon	Fluxofil 9 Cr
	Metrode	9 CrMoV-N
	Böhler/Thyssen Schweißtechnik	Thermanit MTS 3 C9MVIG

*There are other producers, but we are most familiar with the products of the below mentioned producers. In the case of other suppliers we recommend to ask for references.

Right from the beginning of the development work it became clear that it was not possible to meet minimum requirements e.g. of impact strength by using the same range of base material composition. Thus it was necessary to study the effect of single elements and their interaction especially with respect to impact strength but also with respect to other properties. Most of all the nitrogen, nickel, manganese and columbium contents had to be optimized.

By forming carbonitrides, nitrogen has an important influence on creep rupture strength. It also increases yield and tensile strength, but lowers ductility and toughness. Manganese and nickel have less influence on strength properties. However, it has been found out that Ni and Mn contents in access of the upper limits of the base material specifications can improve toughness considerably. Limitations are given by their influence on A_{c1} temperature.

Figure 8.4.2 shows the results of impact tests after various post-weld heat treatments (PWHT). Acceptable tempering times can only be reached at temperatures of 750 to 760°C (1382–1400°F). Therefore the sum of Ni and Mn contents should be limited to 1.5% keeping the N content at around 0.04%.

Niobium (Columbium) has also a negative influence on toughness. However, because of its great influence on creep strength the Nb (Cb) content can only be reduced to 0.04%, which is the lower limit specified for the base material.

Not all developments of welding consumables have considered in their specifications the relationships given above. From our point of view the welding consumables should have typical compositions as given in Table 8.4.3.

Figure 8.4.2: Toughness of T/P91 weld metal after various tempering treatments

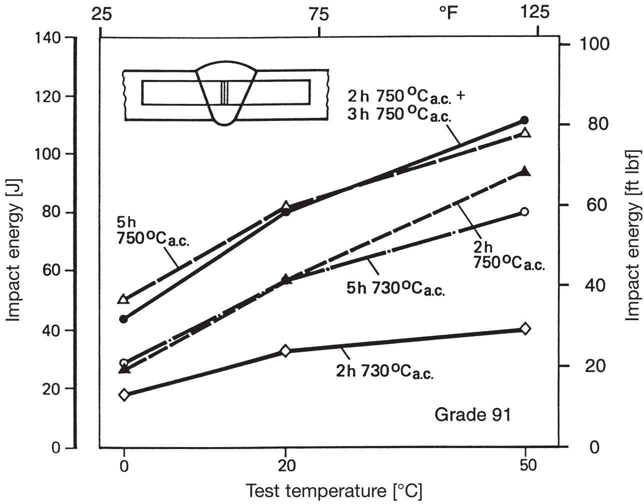


Table 8.4.3: Typical chemical composition of weld metal (wt.-%)

Process	C	Si	Mn	Cr	Mo	Ni	Cb	V	N
GTAW welding rods	0.10	0.20	0.50	9.0	1.0	0.8	0.05	0.20	0.04
Coated stick electrodes	0.09	0.20	0.65	9.0	1.10	0.8	0.05	0.20	0.04
Submerged arc welding:									
Wire	0.11	0.30	0.50	9.0	1.0	0.8	0.06	0.20	0.04
Weld metal	0.11	0.30	0.50	8.5	0.95	0.75	0.05	0.20	0.04

The typical mechanical properties of such optimized weld metals are given in Table 8.4.4.

Table 8.4.4: Typical mechanical properties of weld metal

Process	Heat treatment	Yield strength	Tensile strength	Elongation	Impact energy
GTAW welding rods	760°C/1400°F stress relief	min. 420 MPa (60.9 ksi)	min. 580 MPa (84.1 ksi)	min. 17%	50 J at RT (37 ft lbf)
Coated stick electrodes	2 h 760°C (1400°F)	min. 550 MPa (79.8 ksi)	min. 680 MPa (98.6 ksi)	min. 17%	60 J at RT (44 ft lbf)
	4 h 760°C (1400°F)	min. 500 MPa (72.5 ksi)	min. 620 MPa (89.9 ksi)	min. 18%	65 J at RT (48 ft lbf)
Submerged arc welding	2 h 760°C (1400°F)				
	or 4 h 750°C (1382°F)	min. 540 MPa (78.3 ksi)	min. 700 MPa (101.5 ksi)	min. 20%	47 J at RT (35 ft lbf)

8.4.3 Welding procedure

The welding procedure of T/P91 is typical for martensitic 9–12% chromium steels. That is why welding technology from e.g. X20 can be transfered directly to T/P91. In fact, weldability is somewhat easier because of the lower carbon content which reduces hardening and in consequence reduces the sensitivity to cold cracking and stress corrosion cracking. Figure 8.4.5 shows the typical heating cycle during and after welding. Pre-heating and welding occurs at temperatures around 250°C (482°F). After welding it is essential to cool down to a temperature below 100°C (212°F) in order to allow a complete transformation into martensite. Afterwards PWHT has to be performed, normally at a temperature between 750 and 760°C (1382–1400°F). Typical heating and cooling rates are given in Figure 8.4.5. In the case of storage after welding and before PWHT, the maximum time should be one week and during this time the components must be kept dry.

The parameters can be slightly changed depending on the type of component to be welded. Weldments with low internal stresses, like butt welds of tubes, can be welded below 200°C (392°F) depending on the wall thickness. Up to a wall thickness of 80 mm (3.15″) they can be cooled down to room temperature. On the contrary, heavy thick wall forgings or castings must not be welded below 200°C (392°F) and cooling after welding has to be limited to a minimum temperature of 80°C (176°F) in order to avoid cracking.

Figure 8.4.5: Typical heating cycle for welding T/P91

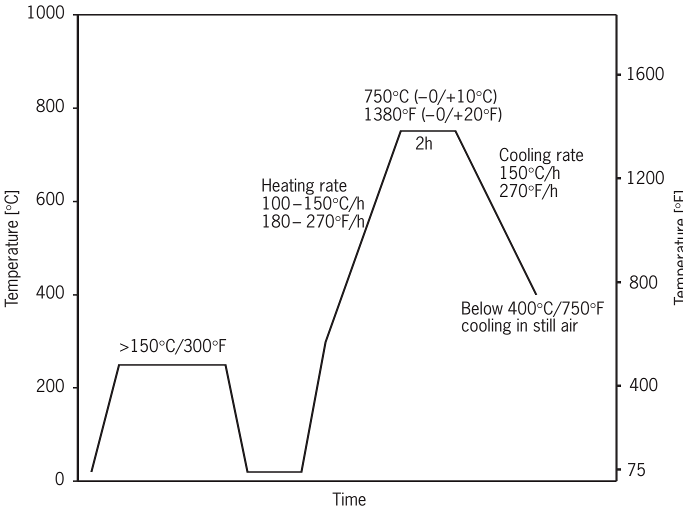
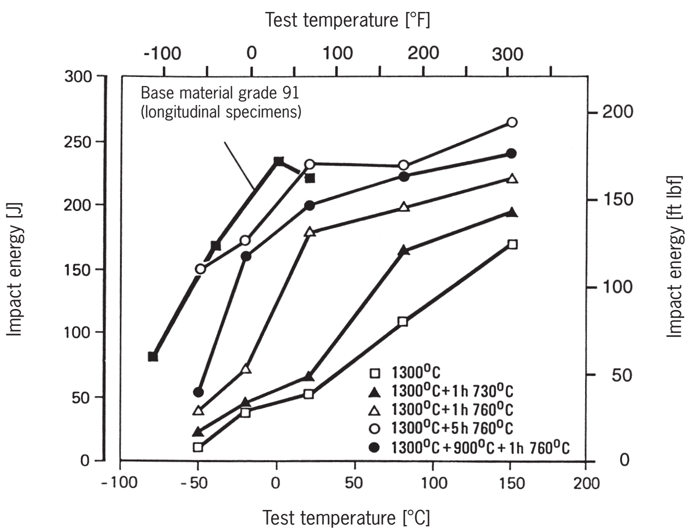


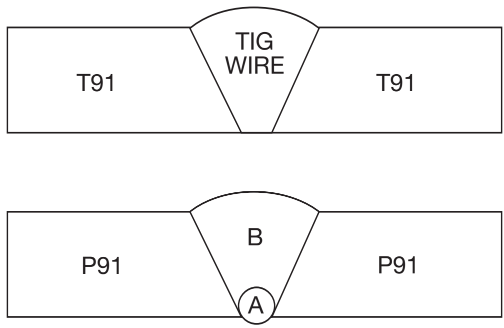
Figure 8.4.6: Toughness of weld heat-affected zone (cooling time $t_{8/5}$ = 22 sec)



In order to realize high toughness levels in the weld metal, it is recommended to use a multiple bead welding technique. Typical toughness results are given in Figure 8.4.2. There are no toughness problems to be expected in the heat affected zone (HAZ) after PWHT. Figure 8.4.6 shows impact test results after a weld simulation of the coarse-grained HAZ by a Gleeble machine.

Examples for procedures of typical T/P91 welds are given schematically in Figures 8.4.7 to 8.4.9.

Figure 8.4.7: Welding of T/P91 to T/P91



A – Root pass – GTAW (TIG) with filler metal

B – Filling passes – SMAW or SAW

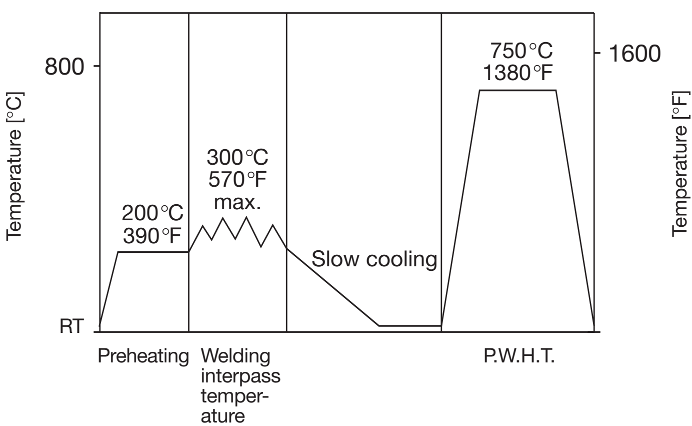
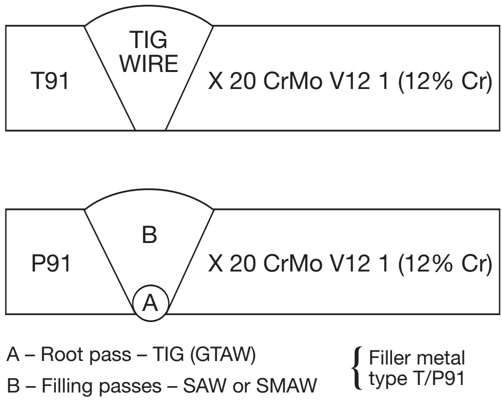


Figure 8.4.8: Welding of T/P91 to 12% Cr material



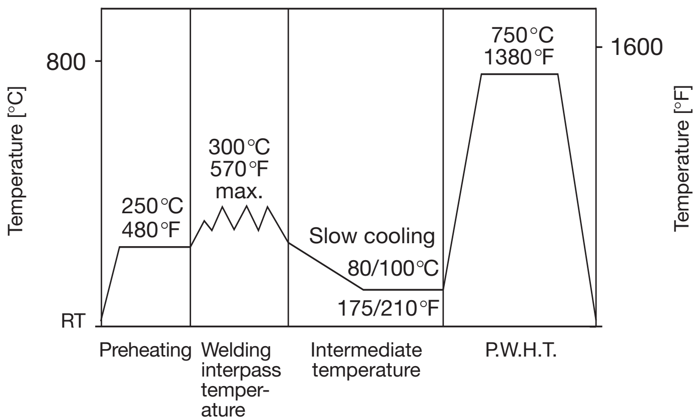
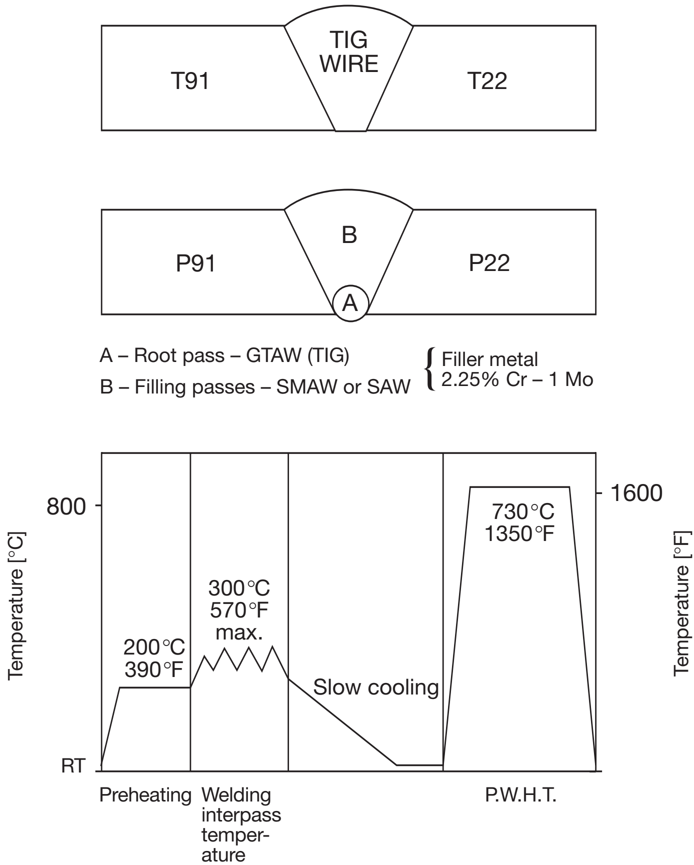


Figure 8.4.9: Welding of T/P91 to T/P22



8.4.4 Properties of weldments

Mechanical properties of T91 weldments (Orbital TIG process) are shown in the following Table 8.4.10 and in Figure 8.4.11.

Table 8.4.10: Mechanical properties of T91 weldments (Orbital TIG process)

Tube T91: 32–48 mm (1.26–1.90″) OD; 5–5.6 mm (0.20–0.22″) WT	
Input energy	8–12 kJ/cm
Filler metal	Modified 9Cr-1Mo (Fluxofil 9 Cr)
Post weld heat treatment	750°C – 30 min (1380°F – 30 min)
Tensile strength at RT	688–735 MPa (100–106 ksi) Rupture in base material
Tensile strength at 550°C (1020°F)	426–467 MPa (62–68 ksi) Rupture in base material
CVN impact energy at 0°C (32°F)	97 J (71 ft lbf) in base material 59 J (44 ft lbf) in heat affected zone 38 J (28 ft lbf) in weld metal

Figure 8.4.11: Root bending and face bending of T91 welds
(Orbital TIG process, PWHT: 30 min 750°C)

Side view (magnification: 0.8x)

View on strained surface with indication of weld position
(magnification: 2.7x)

The majority of our own studies have been performed on SMA and SA welds covering a size range of pipes from OD 159 x 20 mm WT (6 1/4″ x 0.79″) to OD 485 x 80 mm WT (19.09″ x 3.15″).

The hardness profile of a weld seam in the as-welded condition and after PWHT is given by Figure 8.4.12. After PWHT a typical hardness dip occurs in the fine-grained region of the HAZ close to the base material (intercritical zone). This softened zone in a weldment usually is very thin. Nevertheless it governs the creep rupture strength of the whole weldment in the case of stresses operating in transverse direction. Under such conditions, the supporting effect of neighbouring regions with higher strength decreases more and more as the operating time increases and the fracture mode becomes increasingly intergranular. Thus cross-weld creep tests show a shift in fracture location from base material to the fine-grained HAZ, which is well known as Type IV Cracking (Figure 8.4.13). The shift in fracture location is stress- and temperature-dependent with stress being of greater influence. The critical stress is in the range of 150 to 120 MPa (22–17 ksi) associated with a decrease in creep rupture strength.

Figure 8.4.12: Hardness of weld seam in as-welded condition and after PWHT

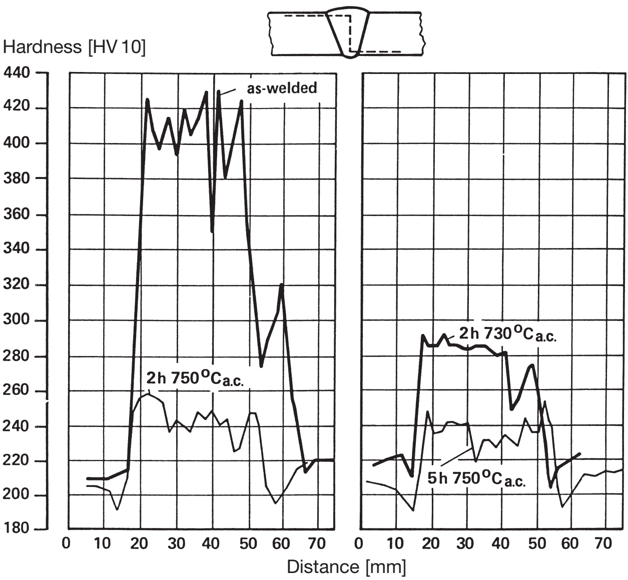
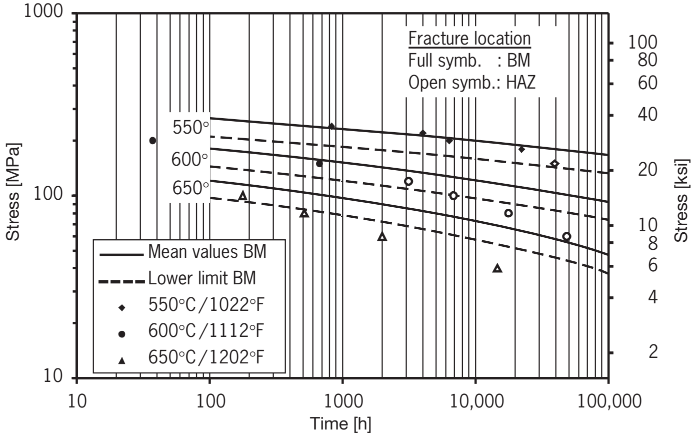


Figure 8.4.13: Creep rupture strength of a P91 weld



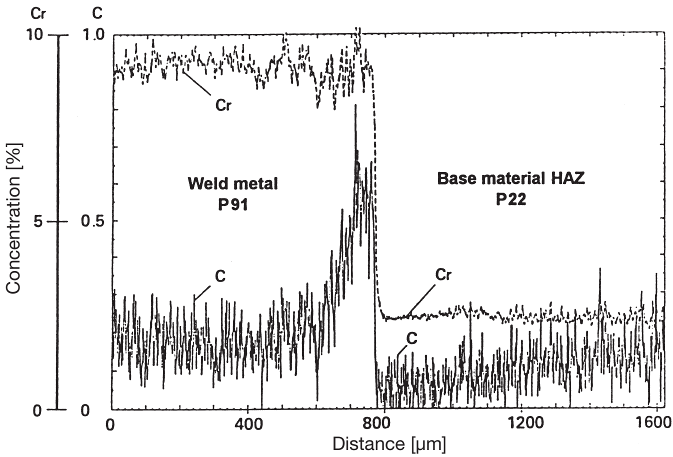
Such a decrease in creep rupture strength is of great importance only in welds with the principle stress acting in cross-weld direction, e.g. in the case of longitudinally seam-welded pipes. In such cases an additional safety factor has to be considered for the design. This can be avoided by using an NT treatment after welding (see ASTM A 691). For butt welds the stress transverse to the weld is considerably lower than the one acting in circumferential direction on the base material. In this case a weld is not considered to be a weak point. However, possible additional stresses from the piping system have to be considered case by case.

8.4.5 Dissimilar welds

Dissimilar welds between T/P91 and low-alloy ferritic steels, e.g. T/P22, as well as austenitic steels can be produced without problem. The behaviour is comparable to any other dissimilar weld of heat resistant ferritic steels with 9 to 12% chromium content, like T/P9, EM12 or X 20.

For dissimilar welds with low-alloy ferritic steels, consumables matching T/P91 or the low-alloyed ferritic steel can both be used. In Europe longtime experience exists with X 20 – P 22 welds. Joints with X 20 and T/P22 weld metal have both been in service and have excellent service records. There is a phenomenon that has to be encountered with such type of welds. Due to the differences in chromium contents between the materials involved, carbon diffuses during PWHT from the low-chromium material into the neighbouring high-chromium partner steel or weld metal (Figure 8.4.14). As a result, a carbon-depleted zone evolves in the low-chromium and a carbon-enriched zone (so-called "carbon band") in the high-chromium material. The extensions of these zones depend on tempering time and temperature. It is not possible to avoid this phenomenon, unless a nickel-base consumable is used.

Figure 8.4.14: Carbon diffusion in a dissimilar P91 – P22 weld

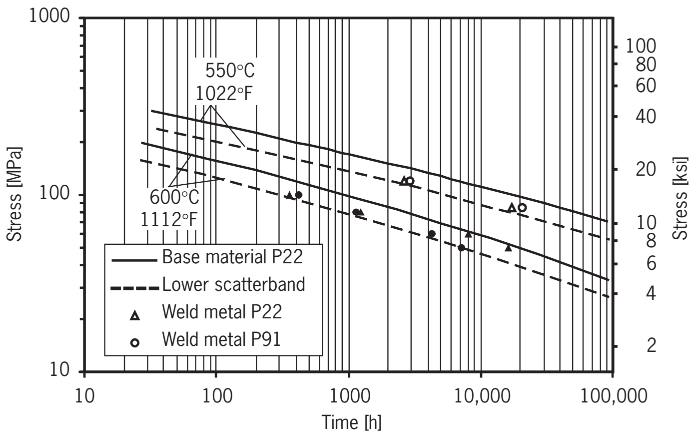


These microstructural changes have an effect on room temperature toughness. However, the creep rupture strength of such a dissimilar weld usually is not affected. The fine-grained intercritical HAZ of the low-alloy ferritic steel still remains the weak zone after longtime service exposure. Thus the creep behaviour of such a dissimilar weld is comparable to a normal T/P22 weld (Figure 8.4.15). PWHT has to be in accordance with the specifications of the low-alloy ferritic steel.

The best way to realize a transition between T/P91 and an austenitic steel is by making a transition joint at the shop. First nickel-base weld metal is deposited on one side of the T/P91 piece followed by an NT treatment similar to T/P91 base material. This transition piece can then be welded on site to T/P91 and to the austenitic steel. The T/P91 side is a regular similar weld with matching consumable and local PWHT, whereas the austenitic side is welded to the nickel-base weld deposit by using a nickel-base consumable without PWHT.

In the case of thin-wall tubes, a transition between T91 and an austenitic steel is usually done by direct welding with a nickel-base consumable followed by a PWHT at about 760°C (1400°F). For this procedure, the austenitic steel should either be a stabilized or a low-carbon type (e.g. TP 316LN) in order to avoid a possible sensitization to stress corrosion cracking by the PWHT. In the case of thick-wall transitions, a buttering of the P91 pipe with nickel-base weld deposit should first be made, followed by an ordinary PWHT. Then the welding to the austenitic pipe can be performed by using a nickel-base consumable. In order to reduce welding stresses, a multiple bead technique with low heat input should be used.

Figure 8.4.15: Creep rupture strength of a dissimilar weld P91–P22



9 CONCLUSIONS

The modified 9% Cr, 1% Mo steel which was developed by ORNL and ABB (now Alstom) more than 25 years ago for the application in fast breeder reactors has found in the meantime a new big field of application in conventional power stations (superheater and reheater as well as main and hot reheat piping systems).

The advantages of this material have been recognized in many countries by engineering companies, boiler makers, piping companies and utilities with the result that grade 91 is being installed in many power stations worldwide.

The excellent creep rupture strength values allow the optimum use of this material in the temperature range from 540 to 600°C (1000 – 1110°F). Compared with the conventional material (T/P22) considerable wall thickness and weight reductions are possible and have been realized in many cases. The optimum chemical composition with its low carbon content results in good fabricability and weldability.

Care must be taken that the specifics of this ferritic-martensitic steel are always carefully watched during heat treatment and the different fabrication steps. Normalizing and tempering temperatures as specified in the delivery conditions have to be controlled. The lower transformation temperature as well as the martensite finishing temperature have to be kept in mind when heat treatments like tempering or the cooling after normalizing or after welding are carried out. Qualified consumables are recommended for welding. The chemical composition of the weld metal has to be optimized without reducing the lower transformation point of the weld metal into the temperature range of the normal tempering heat treatment.

The grade 91 material can also be used with substantial technical and economical advantages in the case of refurbishment of old power stations. Here we see the field of replacement of old P22 or X20 headers by P91 headers with a wall thickness reduction and less risk of ligament cracking as well as the replacement of old piping systems by the new material.

This material has also been installed in the petrochemical industry in many parts of the world because of its excellent resistance against high hydrogen pressure.

The increase of efficiency by higher steam parameters still is a major goal of power plant technology. In order to reach this goal, new steels with higher creep strength are needed. Europe and Japan have mainly been engaged in the development of such new steels, like E911, T/P92 and T/P122. They all belong to the group of martensitic steels with 9 to 12% chromium and with a basic composition equivalent to T/P91. As a special feature the newly developed steels contain tungsten with average contents between 1 and 2%. Also some boron around 0.0030% has been added. While E911 and T/P92 are 9% Cr steels, the chromium content of T/P122 has been raised to 12%. Due to this increase in Cr content the oxidation resistance could be improved, which favours this steel to be used for boiler tubes. On the other hand, E911 and T/P92 are of more advantage for use as material in thick-wall components of the piping system. Although these new steels have already reached an advanced state of development, they have found their way into industrial practice only in a few countries.

10 LITERATURE

Canonico, D. A.:
Thick-walled Pressure Vessels for Energy Systems. Technical Program and Data Package for Use of Modified 9Cr-1Mo Steel, ASME Sect. I and VIII, April 7, 1982

Sikka, V. K.; Ward, C. T. and Thomas, K. C.:
Modified 9Cr-1Mo Steel – An Improved Alloy for Steam Generator Application Ferritic Steels for High Temperature Applications. (Proc. Conf.), Warren, Pa./USA, October 6–18, 1981. American Society for Metals (1983), pp. 65–84

Brinkman, C. R.; Alexander, D. J. and Maziasz, P. J.:
Modified 9Cr-1Mo Steel for Advanced Steam Generation Applications. Proc. Jt. ASME/IEEE Power Generation Conference, Boston, Mass./USA, October 21–25, 1990

Guntz, G.; Julien, M.; Kottmann, G.; Pellicani, F.; Pouilly, A. and Vaillant, J. C.:
The T91 Book, Vallourec Industries, 1990

Dugré, D.; Julien, M.; Pellicani, F. and Vaillant, J. C.:
The P91 Book, Vallourec Industries, 1992

Brühl, F.; Haarmann, K.; Kalwa, G.; Weber, H.; Cerjak, H.; Müsch, H.; Niederhoff, K.; Wellnitz, G. and Zschau, M.:
Behaviour of the 9% Chromium Steel P91 and its Weldments in Short and Long Term Tests. Proc. Jt. ASME/IEEE Power Generation Conference, Boston, Mass./USA, October 21–25, 1990

Niederhoff, K.; Wellnitz, G. and Zschau, M.:
Experience with the Fabricability of the Creep Resistant 9% Chromium Steel X10CrMoV9-1 (P91). Proc. Int. Power Generation Conference, San Diego, Calif./USA, October 6–10, 1991

Bendick, W.; Haarmann, K.; Ullmann, K. and Zschau, M.:
Use of P91 in Europe and Overseas. Proc. ASME Jt. Int. Power Generation Conference, Phoenix, Ariz./USA, October 2–6, 1994

The Manufacture and Properties of Steel 91 for the Power Plant and Process Industries. Proc. ECSC Information Day, held by the Commission of the European Communities, VDEh, Düsseldorf, November 5, 1992

Scarlin, R. B. and Franklin, C. J.:
Critical Components for Advanced Steam Cycles. Final Report COST 501–2, WP3, Sub-Programs D,E,F (Pressure Vessels and Boiler Tubing), Vol. 2 and 3, Ed. by P. J. L. Mériguet, COST Action 501, 200 rue de la Loi, 1049 Bruxelles, Belgium, 1994

Franklin, C. J. and Henry, C.:
Material Developments and Requirements for Advanced Boilers. Proc. Conf. Materials for Advanced Power Engineering 1994, Liège, Belgium, 3–6 October, 1994, D. Coutsouradis et al. (eds.), Kluwer Academic Publishers, 1994, pp. 89–107

Blum, R.; Hald, J.; Bendick, W.; Rosselet, A. and Vaillant, J. C.:
Newly Developed High-Temperature Ferritic-Martensitic Steels from USA, Japan and Europe. VGB Kraftwerkstechnik (English Issue) 74 (1994), pp. 553–563

Arav, F.; Lentferink, H. J. M.; Etienne, C. F. and van Wortel, J. C.:
Effect of Fabrication Processes on the Creep Behaviour of 9–12% Chromium Steels. Proc. 5th Int. Conf. on Creep, Orlando, Fla./USA, 17–21 May 1992

Bendick, W.; Haarmann, K.; Wellnitz, G. and Zschau, M.:
Properties of 9 to 12% Chromium Steels and Their Behaviour Under Creep Conditions. VGB Kraftwerkstechnik (English Issue) 73 (1993), pp. 73–79

Haneda, H.; Masuyama, F.; Kaneko, S. and Toyoda, T.:
Fabrication and Characteristic Properties of Modified 9Cr-1Mo Steel for Header and Piping. Proc. Conf. Advances in Material Technology for Fossil Power Plants, Chicago, Illinois/USA, September 1–3, 1987, pp. 231–241

Iseda, A.; Kubota, M.; Hayase, Y.; Yamamoto, S. and Yoshikawa, K.:
Application and Properties of Modified 9Cr-1Mo Steel Tubes and Pipe for Fossil-fired Power Plants. The Sumitomo Search, No. 36, May 1988, pp.17–30

Bendick, W.; Deshayes, F.; Haarmann, K. and Vaillant, J. C.:
New 9–12% Cr Steels for Boiler Tubes and Pipes – Operating Experiences and Future Developments. Proc. EPRI Conference Advanced Heat Resistant Steels for Power Generation, San Sebastian, Spain, 27–29 April 1998

Zschau, M. and Niederhoff, K.:
Construction of Piping Systems in the New Steel P91 Including Hot Induction Bends. VGB Kraftwerkstechnik (English Issue) 74 (1994), pp. 142–149

V&M

T91

P91

T91

P91

VALLOUREC & MANNESMANN TUBES

V & M FRANCE
Powergen Division
27, avenue du Général Leclerc
92100 Boulogne-Billancourt, France
Phone +33 (1) 49 09 36 40
Fax +33 (1) 49 09 36 76
E-mail sylvia.bouskela@vmtubes.fr

V & M DEUTSCHLAND GmbH
Powergen Division
Theodorstraße 90
40472 Düsseldorf, Germany
Phone +49 (211) 960 39 48
Fax +49 (211) 960 23 74
E-mail gisela.graumann@vmtubes.de

VALLOUREC & MANNESMANN
TUBES CORPORATION
1990 Post Oak Blvd., Suite 1400
Houston, Texas 77056-3813, USA
Phone +1 (713) 479 32 00
Fax +1 (713) 479 32 02
E-mail james.bean@vmtubes.com

V & M do BRASIL
Powergen Department
Av. Paulista, 949 – 14° andar
01311-917 São Paulo – SP, Brazil
Phone +55 (11) 3371 6131
Fax +55 (11) 289 7632
E-mail celso@vmtubes.com.br

Vallourec Group

V&M 5B0001B-8GB

UM - 90217