Use of 9Cr-1Mo-V (Grade 91) Steel in the Oil Refining Industry

API TECHNICAL REPORT 938-B
FIRST EDITION, JUNE 2008

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Downstream Segment

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Introduction

Alloy steel 9Cr-1Mo-V was initially developed in the 1950s by the ORNL for the Clinch River Breeder Reactor. In 1974, a task force was initiated by the U.S. Department of Energy (DOE) to select materials for the Liquid Metal Fast Breeder Reactor Program (LMFBR). ORNL assisted by Combustion Engineering, initiated a program to develop a 9Cr-1Mo steel for 512 °C (970 °F) service temperature and with toughness of 54 J (40 ft-lbs) at room temperature [36, 37]. This was achieved through the controlled additions of vanadium (V), Nb and nitrogen (N) to become Grade 91. Later, the carbon content in Grade 91 was lowered to the range of 0.08 % to 0.12 % from 0.15 % maximum specified for the standard 9Cr-1Mo steel.

In the 1980s, it was recognized that the elevated temperature mechanical properties of Grade 91 made it a viable candidate for utility boiler applications. Code Case 1943 [20] approved on July 20, 1983, permitted the use of Grade 91 for Section I construction. The 9Cr-1Mo-V alloy steels are now included in Section II, Part D for ASME Section VIII, Division 1 [2], applications up to 649 °C (1200 °F) but their use is not permitted in ASME Section VIII, Division 2 [4], except as allowed by Code Case 1973-2 [22]. This alloy also has allowable stresses about 50 % higher than standard 9Cr-1Mo alloy steel for temperatures up to 510 °C (950 °F) and the difference is significantly more above 510 °C (950 °F). Therefore, in some services such as in steam generation, the 9Cr-1Mo-V often replaces 2 $^{1}/_{4}$Cr-1Mo (Grade 22) and even SSs.

The 9Cr-1Mo-V steel has good corrosion resistance to sulfidation and oxidation. However, because this high strength material could have relatively high weld hardness, the use of this alloy, especially in refinery environments where hydrogen sulfide is present, requires special material and fabrication specifications to obtain satisfactory weld hardness. Hence, it has not been widely used in these services. Also, the negligible economic benefits do not justify its use for low pressure applications.

Use of 9Cr-1Mo-V (Grade 91) Steel in the Oil Refining Industry

1 Scope

This report is only applicable to the 9Cr-1Mo-V alloy steel, Grade 91. There are newer, higher strength grades, namely 9Cr-2W (Grade P92) and 9Cr-1Mo-1W-Cb (Grade 911), however, because little fabrication and welding experience is available and application history for these grades is still evolving, they are not included in the scope of this report. Some data on these grades is included for comparison with Grade 91.

It covers the basic material and metallurgical properties of 9Cr-1Mo-V steel, including a summary of the physical and mechanical properties, corrosion and oxidation resistance, indicating possible corrosion and/or mechanical failure mechanisms and how to avoid them. The appropriate base metal heat treatment is also given.

This report provides guidelines on the proper specifications for base metal and welding consumables and successful fabrication, including welding and heat treatment requirements for use of 9Cr-1Mo-V alloy steel in the oil refinery services. This includes guidelines for preheat, postweld heat treatment, procedure qualification, and mechanical and nondestructive testing.

This document also defines hardness limits for the base material and welds in order to avoid cracking failures due to wet sulfide stress corrosion cracking or due to other possible failure mechanisms.

A discussion of both proper and improper refinery service applications for these steels is also provided.

2 Terms, Definitions, Acronyms, and Symbols

For the purpose of this document, the following terms, definitions, acronyms, and symbols apply.

2.1 Terms and Definitions

2.1.1
weld
Weld deposit composed of melted filler metal diluted with some melted base metal.

2.1.2
weldment
Weld deposit, base metal heat affected zones and adjacent base metal zones subject to residual stresses from welding.

2.2 Acronyms

CC	ASME code case
CCT	continuous cooling temperature diagram
CMTR	certified material test report
CS	carbon steel
CVN	Charpy V-notch impact toughness
DBTT	ductile-to-brittle transition temperature
DHT	dehydrogenation heat treatment

DOE	Department of Energy
ESR	electro-slag re-melting
ESW	electro-slag welding
FCAW	flux core arc welding
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HAZ	heat affected zone
HBN	Brinell hardness number using hardened steel ball indenter

NOTE Use of the hardened steel ball indenter has been eliminated from Brinell hardness test method in accordance with ASTM E 10-01 [25].

HBW	Brinell hardness number using tungsten ball indenter
HV	Vickers hardness number
MT	magnetic particle testing
Nb	niobium, which is also known as columbium (Cb)
NDE	nondestructive examination
N+T	normalized and tempered
OFW	oxy-fuel gas welding
ORNL	Oak Ridge National Laboratory
PQR	procedure qualification record
PT	liquid penetrant testing
PWHT	postweld heat treatment
RT	radiographic testing
SAW	submerged arc welding
SMAW	shielded metal arc welding
SS	austenitic stainless steel
SSC	sulfide stress cracking
TE	temper embrittlement
VIM	vacuum induction melting

VOD	vacuum-oxygen decarburization
VT	visual testing
UT	ultrasonic testing
WPS	welding procedure specification

2.3 Symbols

Ac_1	temperature at which austenite begins to form during heating
Ac_3	temperature at which transformation of ferrite to austenite is completed during heating
Cr_{eq}	chromium equivalent
M_s	start temperature of martensitic transformation
M_f	finish temperature of martensitic transformation
σ	creep-rupture strength

3 Base Metal Chemical, Physical, Mechanical and Metallurgical Properties

3.1 General

In order to clarify the advantages of using the 9Cr-1Mo-V (Grade 91) in the oil industry, the chemical composition, physical, mechanical and metallurgical properties including allowable stress and design stress intensity values are summarized in the following sections. Comparisons with conventional 9Cr-1Mo (Grade 9), Grades 911 and 92 and other relevant alloy steels are also summarized. Table 1 is a list of ASME material specifications for 9Cr-1Mo-V steels plates, forgings, fittings, and pipe for heater and vessel applications. The relevant CCs are also included.

3.2 Chemical Composition

Table 2 gives the chemical composition of Grade 91 for the specifications listed in ASME Section II, Part A [2]. This list applies to all product forms of 9Cr-1Mo-V materials. The main difference between the V-modified materials and the conventional 9Cr-1Mo steel is the controlled addition of vanadium (V), Nb and nitrogen (N). In addition, the carbon content of Grade 91 material is limited to a range from 0.08 wt % to 0.12 wt %, compared with 9Cr-1Mo, which limits carbon content to 0.15 wt % maximum.

Most of the base metal specifications for the 9Cr-1Mo-V steels specify a lower level of phosphorous (P), 0.020 wt % maximum and sulfur (S), 0.010 wt % maximum, although SA-336 and SA-369 specify 0.025 wt % maximum for both P and S. As an additional requirement, for better weldability and mechanical properties, the phosphorous content in the base metal is typically limited by user specifications to 0.010 wt % maximum.

3.3 Physical Properties

Table 3 provides the physical properties used for design purposes. Figures 1 and 2 compare the thermal conductivity and mean coefficient of linear expansion versus temperature for 9Cr-1Mo-V, 2 $^{1}/_{4}$ Cr-1Mo alloy steels and 304H SS. The 9Cr-1Mo-V steel has higher thermal conductivity than 304H SS but lower than 2 $^{1}/_{4}$ Cr-1Mo steel. The 9Cr-1Mo-V steel has a lower mean coefficient of linear expansion than 304H SS and 2 $^{1}/_{4}$ Cr-1Mo. Figure 3 shows the modulus of elasticity of Grade 91 alloy vs. temperature [38].

Table 1—Specifications and Code Cases for 9Cr-1Mo-V Steels

Specification or Code Case Number and 9Cr-1Mo-V Steel Grade	Title
SA-182 (Grade 91)	*Specification for Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High Temperature Service*
SA-213 (Grades 91 & 92)	*Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat Exchanger Tubes*
SA-234 (Grade 91)	*Specification for Piping Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and Elevated Temperature Service*
SA-335 (Grades 91 & 92)	*Specification for Seamless Ferritic Alloy-Steel Pipe for HighTemperature Service*
SA-336 (Grade 91)	*Specification for Alloy Steel Forgings for Pressure and High Temperature Parts*
SA-369 (Grade91)	*Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service*
SA-387 (Grade 91)	*Specification for Pressure Vessel Plates, Alloy Steel, ChromiumMolybdenum*
CC 2179-3 (Grade 92)	*Seamless 9Cr-2W Material*, Section I and Section VIII, Division 1 (approved October 29, 1999)
CC 2327 (Grade 911)	*Normalized and Tempered 9Cr-1Mo-1W-Cb Materials*, Section I (approved on May 2, 2000)
CC 1973 (Grade 91)	*Modified 9Cr-1Mo Material*, Section VIII, Division 1 (approved on February 14, 1985; not active; requirements incorporated)
CC 1973-2 (Grade 91)	*9Cr-1Mo-V Material*, Section VIII, Division 2 (approved on August 12, 1996; annulled on January 1, 2005; requirements incorporated)
CC 1943 (Grade 91)	*Seamless Modified 9Cr-1Mo*, Section I (approved on July 20, 1983; not active; requirement incorporated)

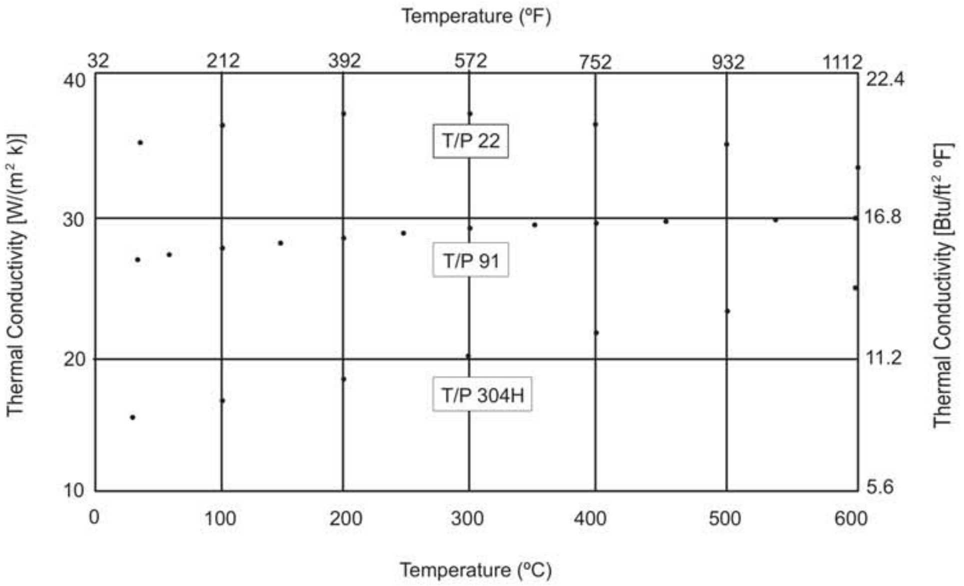

Figure 1—Thermal Conductivity

Table 2—Chemical Composition (Heat Analysis) of 9Cr-1Mo-V and 9Cr-1Mo Steels

Material	Specification or CC No.	Grade	UNS Designation	C	Mn	P Max	S Max	Si	Cr	Mo	V	Nb	N	Al Max	Ni Max	W	B
Forged Pipe, F1	SA-182	F9	K90941	0.15 max	0.30 – 0.60	0.030	0.030	0.50 – 1.00	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		F91	K90901	0.08 – 0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
		F911	K91061	0.09 – 0.13	0.30 – 0.60	0.020	0.010	0.10 – 0.50	8.50 – 10.50	0.90 – 1.10	0.18 – 0.25	0.06 – 0.10	0.04 – 0.09	0.04	0.40	0.90 – 1.10	0.0003 – 0.006
Seamless Tube	SA-213	T9	K90941	0.15 max	0.30 – 0.60	0.025	0.025	0.25 – 1.00	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		T91	K90901	0.08 – 0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
		T92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.03 – 0.07	0.04	0.40	1.50 – 2.00	0.001 – 0.006
Piping Fitting	SA-234	WP9	K90941	0.15 max	0.30 – 0.60	0.030	0.030	0.25 – 1.00	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		WP91	K90901	0.08 – 0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
Seamless Alloy Pipe	SA-335	P9	K90941	0.15 max	0.30 – 0.60	0.025	0.025	0.25 – 1.00	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		P91	K90901	0.08 – 0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
		P92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.03 – 0.07	0.04	0.40	1.50 – 2.00	0.001 – 0.006
Forgings	SA-336	F9	K90941	0.15 max	0.30 – 0.60	0.025	0.025	0.50 – 1.00	8.0 – 10.0	0.90 – 1.10	—	—	—	—	—	—	—
		F91	K90901	0.08 – 0.12	0.30 – 0.60	0.025	0.025	0.20 – 0.50	8.0 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
Forged & Bored Pipe	SA-369	FP9	K90941	0.15 max	0.30 – 0.60	0.030	0.030	0.50 – 1.00	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		FP91	K90901	0.08 – 0.12	0.30 – 0.60	0.025	0.025	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.04	0.40	—	—
		FP92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.03 – 0.07	0.04	0.40	1.50 –2.00	0.0001 – 0.006
Alloy Steel Plate	SA-387	9	K90941	0.15 max	0.30 – 0.60	0.030	0.030	1.00 max	8.00 – 10.00	0.90 – 1.10	—	—	—	—	—	—	—
		91	K91560	0.08 – 0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.03 – 0.07	0.02	0.40	—	—
	CC 2179-3	92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.03 – 0.07	0.04	0.40	1.50 – 2.00	0.001 – 0.006
	CC 2327	911	K91061	0.09 – 0.13	0.30 – 0.60	0.020	0.010	0.10 – 0.50	8.50 – 9.50	0.90 – 1.10	0.18 – 0.25	0.06 – 0.10	0.04 – 0.09	0.04	0.40	0.90 – 1.10	0.0003 – 0.006

Table 3—Physical Properties of T/P91 Alloy vs. Temperature

Temperature ºC (ºF)	**Modulus of Elasticity** GPa (10^2 ksi)	**Thermal Conductivity** W/m K (Btu/ft^2 hr ºF/in.)	**Coefficient of L. Expansion Between Room Temperature and Indicated Temperature** 10^{-6} /ºK (10^{-6} /ºF)	**Specific Heat Capacity** J/Kg ºK (Btu/lb ºF)	**Weight/Volume** 10^3 Kg/m^3 (10^3 lb/ft^3)
20 (68)	218 (31.6)	26 (181)	0.0 (0.0)	440 (0.105)	7.77 (0.49)
50 (122)	216 (31.3)	26 (181)	10.6 (5.9)	460 (0.110)	—
100 (212)	213 (30.9)	27 (187)	10.9 (6.1)	480 (0.115)	—
150 (302)	210 (30.5)	27 (187)	11.1 (6.2)	490 (0.117)	—
200 (392)	207 (30.0)	28 (194)	11.3 (6.3)	510 (0.122)	—
250 (482)	203 (29.5)	28 (194)	11.5 (6.4)	530 (0.127)	—
300 (572)	199 (28.9)	28 (194)	11.7 (6.5)	550 (0.131)	—
350 (662)	195 (28.3)	29 (201)	11.8 (6.6)	570 (0.136)	—
400 (752)	190 (27.6)	29 (201)	12.0 (6.7)	600 (0.143)	—
450 (842)	186 (27.0)	29 (201)	12.1 (6.7)	630 (0.150)	—
500 (932)	181 (26.3)	30 (208)	12.3 (6.8)	660 (0.158)	—
550 (1022)	175 (25.4)	30 (208)	12.4 (6.9)	710 (0.170)	—
600 (1112)	168 (24.4)	30 (208)	12.6 (7.0)	770 (0.184)	—
650 (1202)	162 (23.5)	30 (208)	12.7 (7.1)	860 (0.205)	—

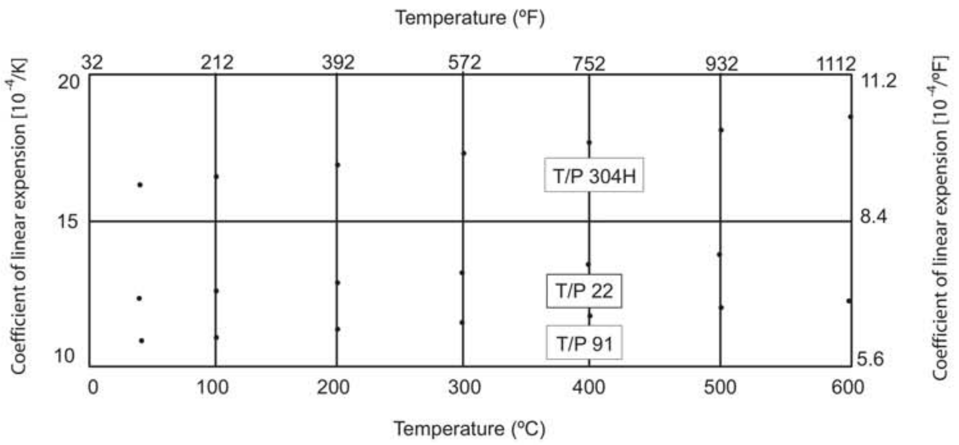

Figure 2—Mean Coefficient of Linear Expansion

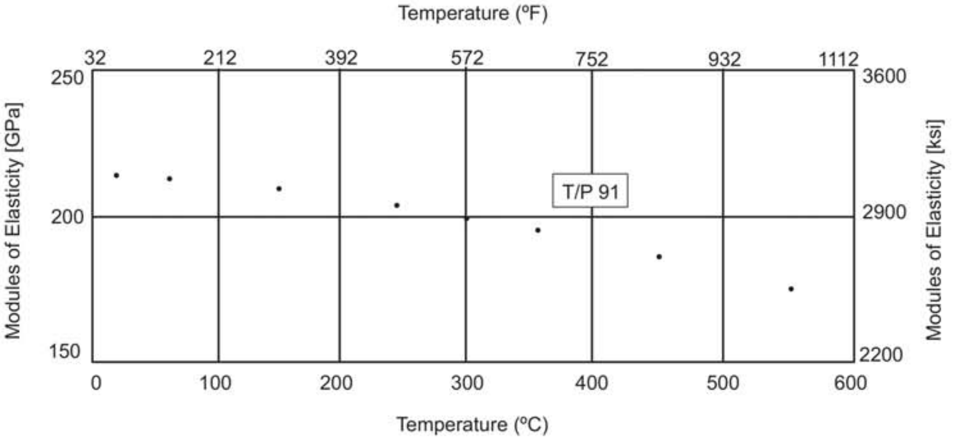

Figure 3—Modulus of Elasticity vs. Temperature

3.4 Metallurgical Properties

3.4.1 Transformation Data

Alloy 9Cr-1Mo-V is a deep hardening steel. Figure 4 shows the Jominy end quench HRC hardness test results for 101.6 mm (4 in.) long bars of Grade 91 and 2 $^1/_4$ Cr-1Mo steels of approximately the same carbon content [39, 40]. A metallurgical investigation showed that the critical cooling rate to obtain 100 % Martensite is about 0.2 °C/s (0.36 °F/s) [39]. Depending on the chemical composition, the Ac_1 temperature was found to be as low as 785 °C (1445 °F) with most values between 800 °C (1472 °F) and 830 °C (1526 °F). The Ac_3 temperature was found to be in the range of 891 °C (1635 °F) and 941 °C (1725 °F) [38]. Figure 5, shows Ac_1 values obtained for Grade 91 products listed in Table 2 as a function of their minimum and maximum Ni + Mn contents [37]. As indicated in 6.4.6, it is important that the Ac_1 is not exceeded during PWHT.

3.4.2 Martensite Formation

Figure 6 shows the Continuous Cooling Temperature (CCT) diagram for Grade 91 [41]. The alloy is typically used in the N + T condition as indicated in Table 4. By cooling from the austenitizing temperature to room temperature, the structure of this alloy transforms (over a wide area of cooling rates) nearly completely to martensite [38].

At the lower end of chemical composition range of the ASME Grade 91 (0.08C, 8.0Cr, 0.85Mo, 0.20Si, 0.18V), the start and finish temperatures of martensitic transformation (M_s) and (M_f), are rather high, at about 400 °C (752 °F) and 209 °C (408 °F) respectively. At the higher end of the chemical composition range for ASME Grade 91 major alloys (0.12C, 9.5Cr, 1.05Mo, 0.50Si, 0.25V), the M_s and M_f temperatures are about 339 °C (642 °F) and 149 °C (300 °F) respectively. It can be assumed conservatively that the Mf lies above 100 °C (212 °F) [42], which also varies with prior austenite grain size [38].

3.4.3 Heat Treatment

Normalizing and tempering heat treatment is specified for the 9Cr-1Mo-V steels, while the standard 9Cr-1Mo steel may be annealed or N + T. For best strength and ductility of 9Cr-1MoV steel, the normalizing temperature is 1040 °C to 1095 °C (1900 °F to 2000 °F), followed by air cooling and tempering at 732 °C (1350 °F) minimum.

The tempering temperature for the 9Cr-1Mo-V (Grade 91) steel is 732 °C (1350 °F) minimum, at least 56 °C (100 °F) higher than the tempering temperature specified for the standard 9Cr steel. However, Grade 91 is typically specified with tempering temperature higher than 732 °C (1350 °F), and in the range of 760 °C to 780 °C (1400 °F to 1436 °F),

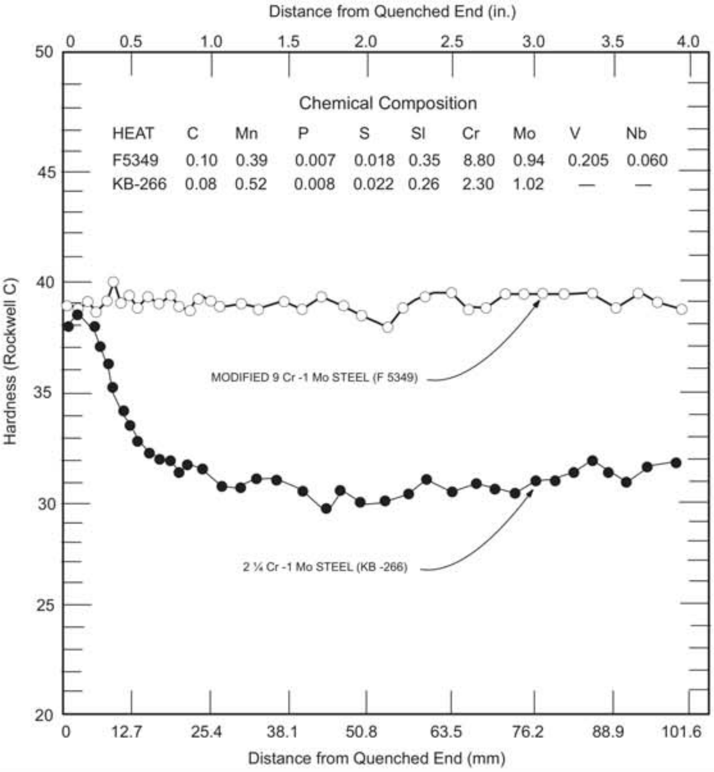

Figure 4—Deep Hardening Behavior of Grade 91 Steel

to permit PWHT at a higher temperature to achieve acceptable weld metal hardness as indicated in 6.4.6.1 [43]. Higher tempering temperature improves toughness but slightly reduces Grade 91 mechanical properties (tensile and yield strengths and elongation percent). It is important to be sure that the tempering temperature does not exceed 788 °C (1450 °F) to avoid getting into the two-phase region, i.e. exceeding Ac_1. Moreover, over-tempering during mill heat treatment, results in coarsening of the carbides and possibly even the carbonitrides, such that the “pinning” action on the lath boundaries and dislocations is lost, and the creep-rupture strength is compromised [42].

The normalizing and tempering heat treatment leads to a structure of tempered martensite with $M_{23}C_6$ carbides and vanadium/columbium rich carbo-nitride precipitates. The creep rupture strength is improved by the presence of these precipitations. Typical microstructure of 9Cr-1Mo-V steel after normalizing and tempering is shown in Figure 7 [38, 44].

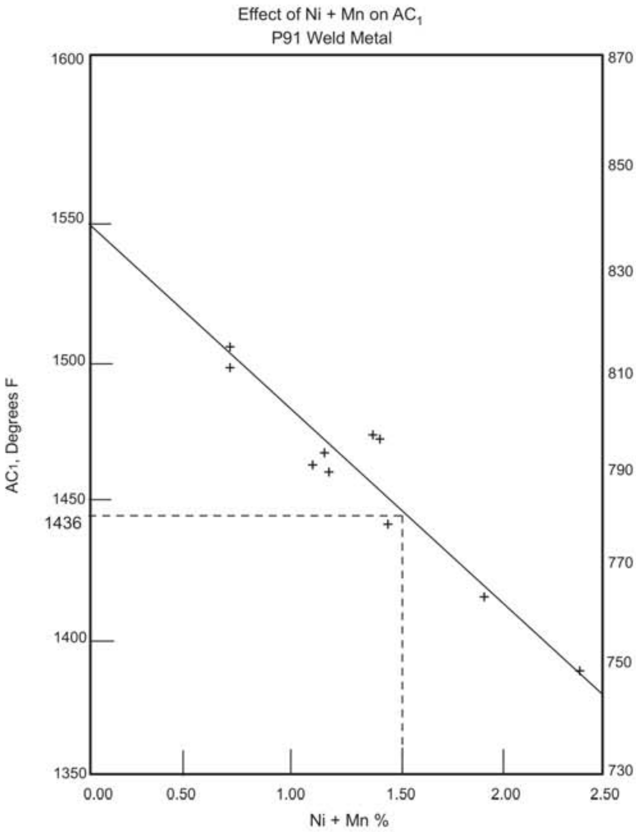

Figure 5—Effect of Ni + Mn on AC_1

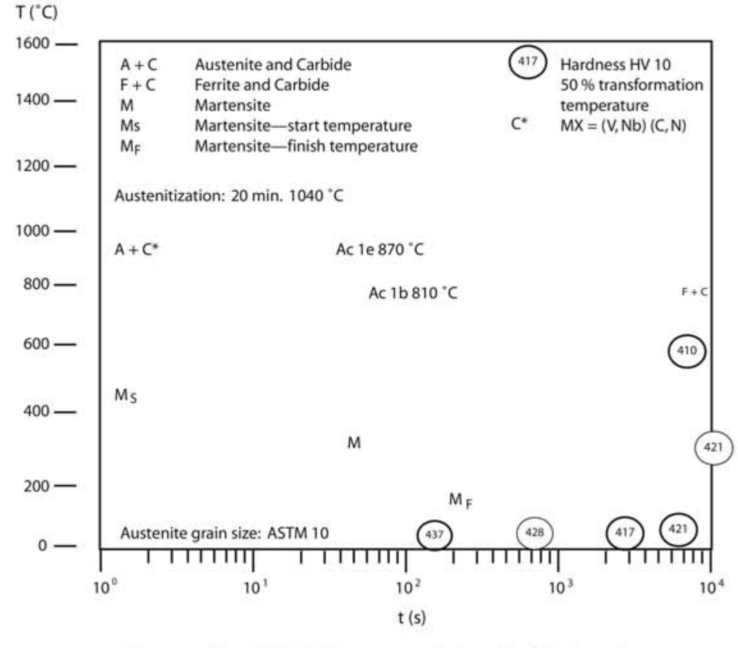

Figure 6—CCT Diagram of Grade 91 Steel

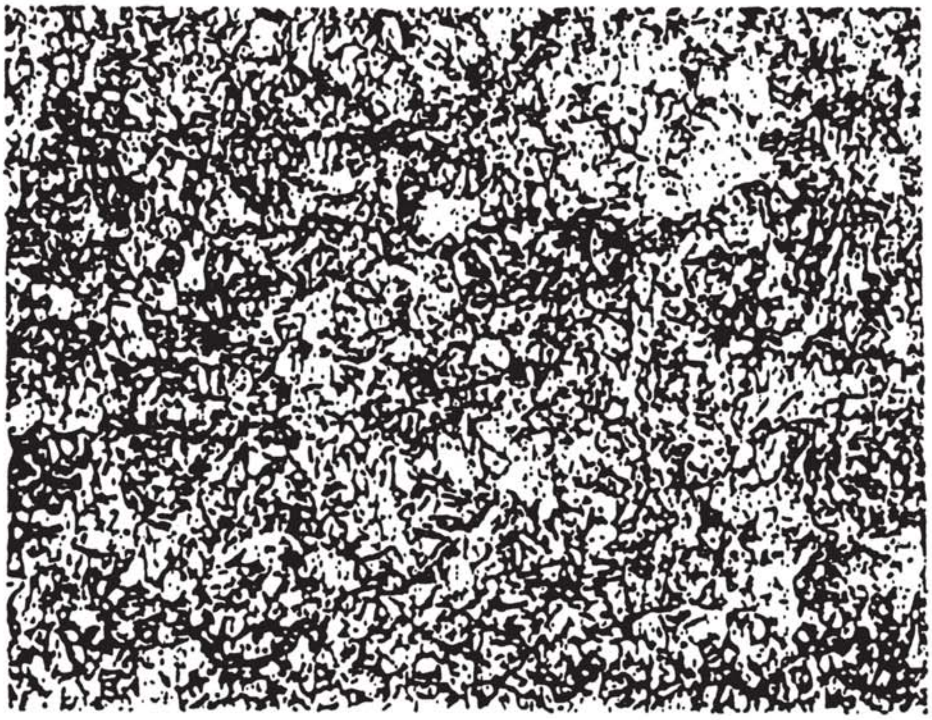

Figure 7—Typical Microstructure of T/P91 After Normalizing and Tempering

Table 4—Heat Treatment and Mechanical Properties of 9Cr-1Mo-V Steel and 9Cr-1Mo Steel

Specification or CC Number	**Grade**	**Heat Treatment Type**	**Minimum Austenitizing Temperature** °C (°F)	**Minimum Tempering Temperature** °C (°F)	**Minimum Tensile Strength** MPa (ksi)	**Minimum Yield Strength** MPa (ksi)	**Minimum Elongation in 50 mm (2 in.) or 4D** %	**Minimum Reduction of Area** %	**Brinell Hardness Number**
SA-182	F9	Annealed or N + T	955 (1750)	If N + T 675 (1250)	585 (85)	380 (55)	20	40	179 – 217
	F91	N + T	1040 – 1095 (1900 – 2000)	730 (1350)	585 (85)	415 (60)	20	40	248 max
SA-213	T9	Full-annealed, isothermal annealed or N + T	—	If N + T 675 (1250)	—	—	—	—	179 max
	T91	N + T	1040 (1900)	730 (1350)	585 (85)	415 (60)	20	—	250 max
	T92	N + T	1040 (1900)	730 (1350)	620 (90)	440 (64)	20	—	250 max
SA-234	WP9	Full-annealed, isothermal annealed or N + T	—	If N + T 675 (1250)	415 – 585 (60 – 85)	205 (30)	22	—	217 max
	WP91	N + T	1040 – 1095 (1900 – 2000)	730 (1350)	590 – 760 (85 – 110)	415 (60)	20	—	248 max
SA-335	P9	Full-annealed, isothermal annealed or N + T	—	If N + T 675 (1250)	415 (60)	205 (30)	30	—	—
	P91	N + T	1040 (1900)	730 (1350)	585 (85)	415 (60)	20	—	—
	P92	N + T	1040 (1900)	730 (1350)	620 (90)	440 (64)	20	—	—
SA-336	F9	Annealed or N + T	—	If N + T 675 (1250)	585 – 760 (85 – 110)	380 (55)	20	40	—
	F91	N + T	1040 – 1095 (1900 – 2000)	730 (1350)	585 – 760 (85 – 110)	415 (60)	20	40	—
SA-369	FP9	Full-annealed, or N + T	—	If N + T 680 (1250)	415 (60)	210 (30)	30	—	—
	FP91	N + T	1040 – 1095 (1900 – 2000)	730 (1350)	585 (85)	415 (60)	27	—	—
SA-387	9 Class 2	Annealed, N + T and accelerated cooled	—	Except annealed	515 – 690 (75 – 100)	310 (45)	18	40 – 45	—
	91Class 2	N + T	1040 – 1095 (1900 – 2000)	730 (1350)	585 – 760 (85 – 110)	415 (60)	18	Not specified	—
CC 2179-3	92	Normalized/quenched and tempered	1040 (1900)	730 (1350)	620 (90)	440 (64)	20	—	250 max

Table 4—Heat Treatment and Mechanical Properties of 9Cr-1Mo-V Steel and 9Cr-1Mo Steel (Continued)

Specification or CC Number	Grade	Heat Treatment Type	Minimum Austenitizing Temperature ºC (ºF)	Minimum Tempering Temperature ºC (ºF)	Minimum Tensile Strength MPa (ksi)	Minimum Yield Strength MPa (ksi)	Minimum Elongation in 50 mm (2 in.) or 4D %	Minimum Reduction of Area %	Brinell Hardness Number
CC 2327	911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 (90) [a]	440 (64) [a]	20 [a]	—	238HB/250HV [a]
					620 (90) [b]	440 (64) [b]	20 [b]		238HB/250HV [b]
					620 (90) [c]	440 (64) [c]	20 [c]		238HB/250HV [c]
					620 – 795 (90 – 115) [d]	— 440 (64) [d]	— 20 [d]		— —
					620 (90) [e]	440 (64) [e]	20 [e]		238HB/250HV [e]
					620 – 795 (90 – 115) [f]	— 440 (64) [f]	— 20 [f]		— —
					620 – 795 (90 – 115) [g]	— 440 (64) [g]	— 20 [g]		— —

[a] Seamless tubes.
[b] Seamless pipe.
[c] Forged and bored pipe.
[d] Fittings.
[e] Forgings (otherwise meeting SA-182).
[f] Forgings (otherwise meeting SA-336).
[g] Plate.

3.4.4 Resistance to Grain Coarsening

The 9Cr-1Mo-V steel is resistant to extensive grain coarsening even when held at temperatures near 1066 °C (1950 °F) for eight hours. Grain coarsening is minimal at temperatures up to 1121 °C (2050 °F) when held for one hour. Figure 8 shows grain coarsening behavior [39].

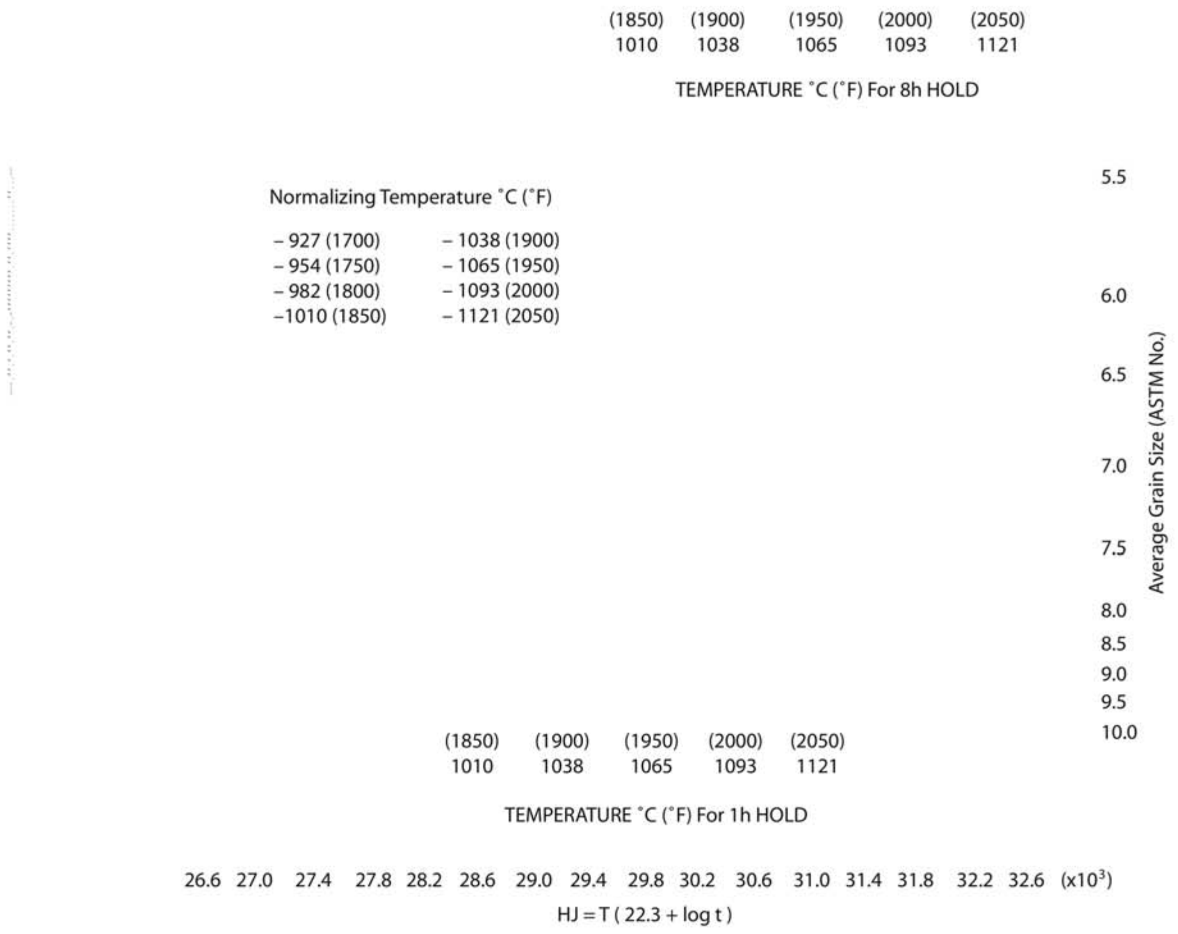

Figure 8—Grain Coarsening Behavior

3.4.5 Resistance to Softening

Resistance to softening of this steel at different tempering temperatures was studied. The hardness results vs. tempering temperature of 9Cr-1Mo-V base metal are shown on Figure 9 [39].

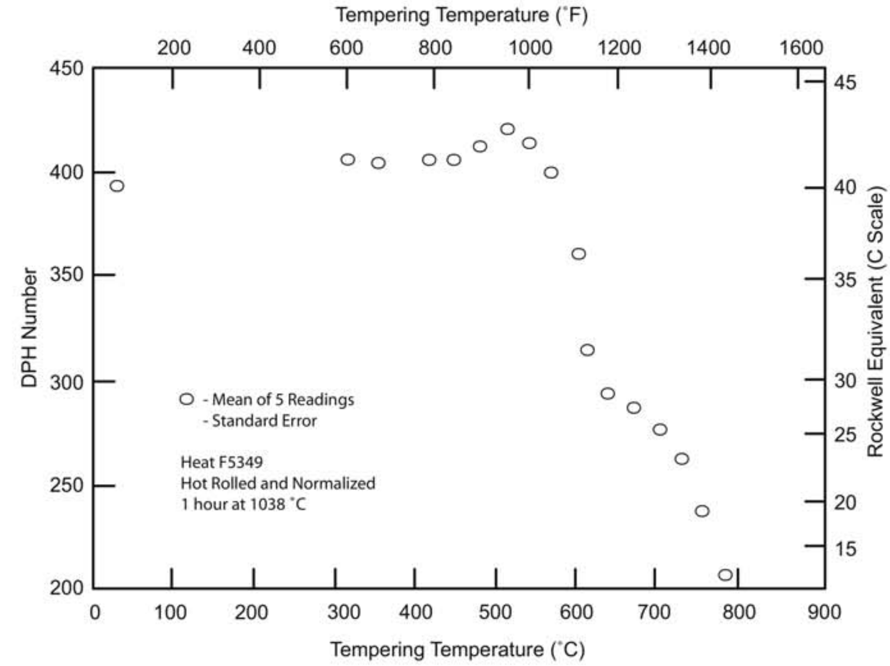

Figure 9—Typical Plot of Hardness vs. Tempering Temperature for Heat Rolled and Normalized Grade 91 Steel

3.5 Mechanical Properties

3.5.1 General

The mechanical properties of 9Cr-1Mo-V products from the ASME specifications and CCs are given in Table 4. A summary of the mechanical properties including tensile strength and ductility, Charpy V-notch toughness, creep and stress rupture strength is given below.

3.5.2 Tensile Strength

3.5.2.1 General

The minimum tensile strength for the conventional 9Cr-1Mo is 415 MPa, 515 MPa, or 585 MPa (60 ksi, 75 ksi, or 85 ksi) depending on the specification. Various specifications for 9Cr-1Mo-V specify either 585 MPa or 620 MPa (85 ksi or 90 ksi) minimum tensile strength. The effect of temperature on the tensile and 0.2 % offset yield strengths is shown on Figure 10 [39]. The ASME specifications require a minimum room temperature elongation value of 18 % to 20 % in 50 mm (2 in.) specimens, which is readily achieved on all commercial product forms.

3.5.2.2 ASME Temperature Limits and Use Restrictions

Table 5 lists the maximum temperatures for using 9Cr-1Mo-V steels per ASME Section II, Part D [2] for Section VIII, Division 1 [4] and CC 2179-3 [23] and CC 2327 [24]. The limit is 649 °C (1200 °F) except for CC 2179-3, where the limit is 621 °C (1150 °F). However, fitting specification SA-234 [8] and forging specification SA-369 [13] are not permitted in ASME VIII, Division 1.

For ASME VIII, Division 2, the 9Cr-1Mo-V steels are not permitted above 482 °C (900 °F), as shown in Table 6. Previously, CC 1973-2 [22] was used to permit its use, but this CC has now been incorporated into the code.

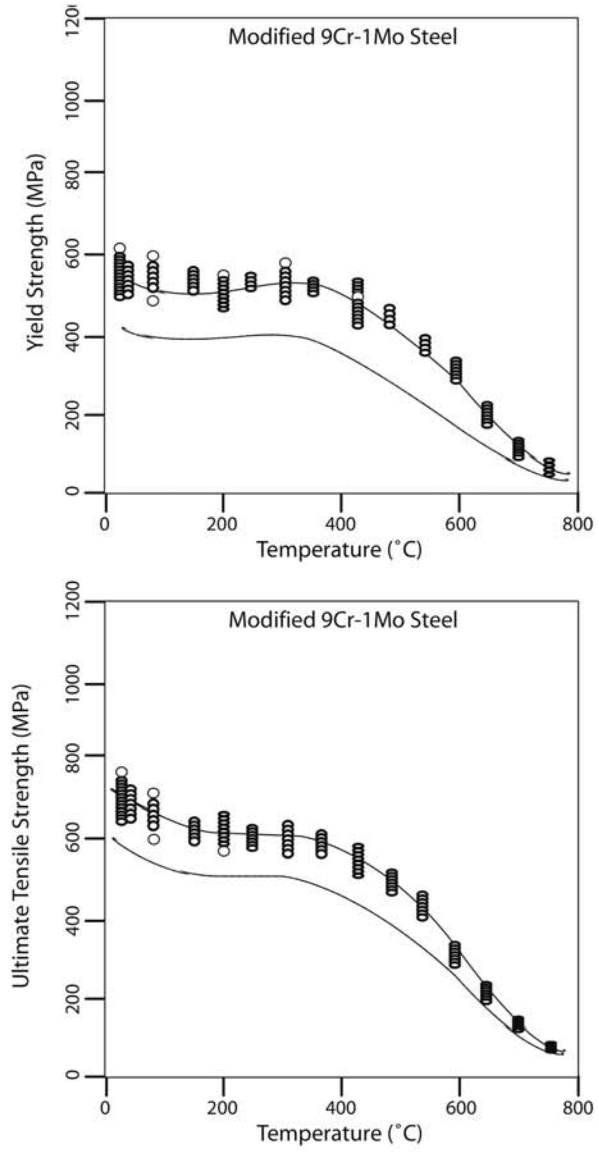

Figure 10—Yield (0.2 %) and Ultimate Tensile Strengths vs. Temperature for Grade 91 Alloy Steel

3.5.2.3 ASME Maximum Allowable Stresses

The maximum allowable stresses values "*S*" of ASME Section VIII, Division 1 [4], and design stress intensity values of Division 2 for 9Cr-1Mo-V grades are given in Table 7 and Table 8 respectively. For comparison, the stress values for 2 $^1/_4$ Cr-1Mo-V steel, conventional 2 $^1/_4$ Cr-1Mo and 9Cr-1Mo and 316H SS are also provided.

Steel 9Cr-1Mo-V has high allowable stresses about 50 % more than the standard 9Cr-1Mo up to 510 °C (950 °F). The allowable stress ratio increases significantly to about 120 % to 212 % more between 538 °C (1000 °F) and 649 °C (1200 °F).

In comparison to Type 316H stainless steel, the allowable stress of 9Cr-1Mo-V is higher by about 22 % at 316 °C (600 °F) and 43 % at 482 °C (900 °F). This ratio drops to 6.5 % at 538 °C (1000 °F) and 16 % at 510 °C (950 °F). At 566 °C (1050 °F) and 649 °C (1200 °F), 316H SS has higher allowable stresses than 9Cr-1Mo-V of 7.8 % to 42 % respectively.

Table 5—Temperature Limits for 9Cr-1Mo-V Steel per ASME Section VIII, Division 1 (Section II, Part D)

Specification or CC No.	Grade	Product Form	Minimum Tensile Strength MPa (ksi)	Minimum Yield Strength MPa (ksi)	Maximum Temperature Limit ºC (ºF)
SA-182	F91	Forgings	585 (85)	415 (60)	650 (1200)
SA-213	T91	Seamless Tube	585 (85)	415 (60)	650 (1200)
SA-234	WP91	Fittings	585 (85)	415 (60)	NP [a]
SA-335	P91	Seamless Pipe	585 (85)	415 (60)	650 (1200)
SA-336	F91	Forgings	585 (85)	415 (60)	650 (1200)
SA-369	FP91	Forged Pipe	585 (85)	415 (60)	NP [a]
SA-387	91	Plate	585 (85)	415 (60)	650 (1200)
CC 2179-3	9Cr-2W (92)	Forgings Forged Pipe	620 (90)	440 (64)	621 (1150)
CC 2179-3	9Cr-2W (92)	Tube Pipe	620 (90)	440 (64)	650 (1200)
CC 2327	9Cr-1Mo-1W-Cb (911)	Seamless Tubes Seamless Pipe Forged and Bored Pipe Forgings [b] Forgings [c] Plate	620 (90) 620 (90 620 (90) 620 – 795 (90 – 115) 620 (90) 620 – 795 (90 – 115) 620 – 795 (90 – 115)	440 (64) 440 (64) 440 (64) 440 (64) 440 (64) 440 (64) 440 (64)	—

[a] Not Permitted by ASME Section VIII, Division 1.
[b] Otherwise meeting SA-182.
[c] Otherwise meeting SA-336.

Table 6—Temperature Limits of 9Cr-1Mo-V Steel per Section VIII, Division 2 (Section II, Part D)

Specification or Code Case Number	Grade	Product Form	Minimum Tensile Strength MPa (ksi)	Minimum Yield Strength MPa (ksi)	Maximum Temperature Limit ºC (ºF)
SA-182	F91	Forgings	585 (85)	415 (60)	482 (900)
SA-213	T91	Seamless Tube	585 (85)	415 (60)	482 (900)
SA-335	P91	Seamless Pipe	585 (85)	415 (60)	482 (900)
SA-387	91	Plate	585 (85)	415 (60)	482 (900)

The use of 2 $^{1}/_{4}$ Cr-1Mo-V steel is limited to 482 °C (900 °F), while 9Cr-1Mo-V has maximum allowable stress values up to 649 °C (1200 °F) as shown on Table 7. It should be noted that Grade 91 materials have two sets of allowable stresses depending on whether the thickness is above or below 75 mm (3 in.). The allowable stress values for temperatures at 566 °C (1050 °F) and above are obtained from time dependent creep properties. CC 2179-3 [23] for Grade 92 groups the maximum allowable stress values into two levels depending on the product form. CC 2327 [24] (for Grade 911) is not permitted for Section VIII, only for Section I.

3.5.3 Impact Properties

The results of Charpy V-notch (CVN) impact tests performed on T/P91 material vs. temperature are shown in Figure 11 [38]. The toughness of Grade 91 steel is affected by the following factors.

3.5.3.1 Effect of Steel Melting Practice

The CVN impact toughness has been shown to be related to the employed melting practice [39]. It is also sensitive to inclusion size and shape. Melting practices, which achieve low sulfur and phosphorous levels and produce favorable

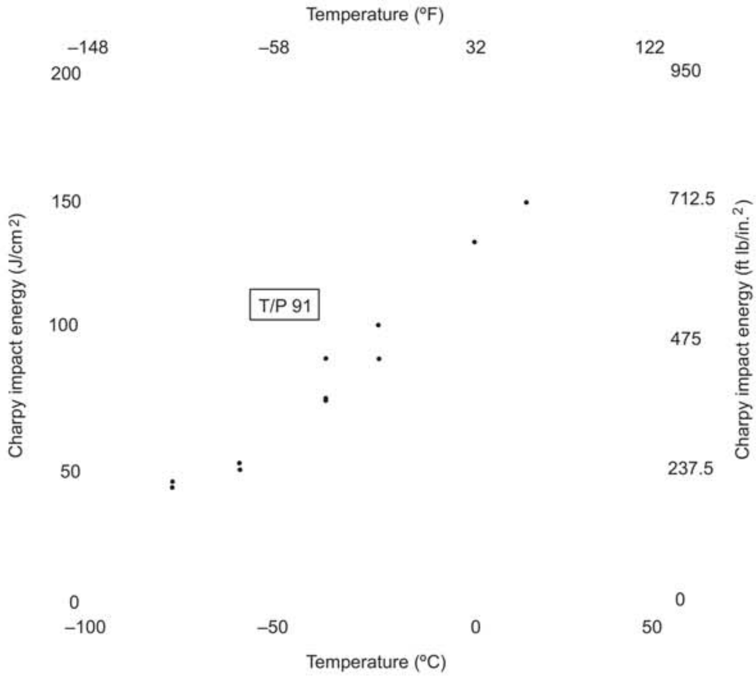

Figure 11— Charpy Impact Energy vs. Temperature of Grade 91 Alloy Steel

shape control tend to produce excellent toughness. However, experience has shown that acceptable, as-delivered toughness has been obtained in steels meeting their respective ASME materials specification and requirements.

3.5.3.2 Effect of Aging

The effect of long-term exposure at high temperatures on the strength and toughness behavior of Grade 91 steel is called "aging" [45]. Aging is a different phenomenon than TE mentioned in 4.5. Aging is related to micro-structural changes with a low dislocation density. It should be mentioned that the recognized limit for Grade 91 is 649 °C (1200 °F) because of concern with aging and loss of strength with long exposure at service temperatures above 649 °C (1200 °F).

Aging does not practically affect the strength of Grade 91 steel in the range of 550 °C to 600 °C (1022 °F to 1112 °F) with some reduction in strength and hardness at 650 °C to 700 °C (1202 °F to 1292 °F). However, this material suffers a significant loss in toughness (up to 50 % of absorbed energy) after exposure of 10,000 hours at 550 °C to 600 °C (1022 °F to 1112 °F). Normalizing temperature variations in the range of 1050 °C to 1100 °C (1922 °F to 2012 °F) did not affect the mechanical properties (yield strength, elongation percent and hardness) after aging. This embrittlement is not influenced by phosphorous content up to 200 ppm [45].

Table 7—Maximum Allowable Stress Values “*S*” in ASME Section VIII, Division 1, for 9Cr-1Mo-V Steel in Comparison with 2 1/4 Cr-1Mo-V, 2 1/4 Cr-1Mo 9Cr-1Mo Alloy Steels and 316H Stainless Steel

Nominal Composition and/or Code Case	Product Form	Specification	Grade	Thickness cm (in.)	Maximum Metal Temperatures C° (°F)																
					–29 to 38 (–20 to 100)	93 (200)	149 (300)	204 (400)	260 (500)	316 (600)	343 (650)	371 (700)	399 (750)	427 (800)	454 (850)	482 (900)	510 (950)	538 (1000)	566 (1050)	593 (1100)	621 (1150)	649 (1200)
					Maximum Allowable Stress MPa (ksi)																	
2 1/4 Cr-1Mo	Forgings Forgings Plates	SA-182 SA-336 SA-387	F22 F22 22 Class 2	—	148 (21.4)	148 (21.4)	144 (20.9)	142 (20.6)	141 (20.5)	141 (20.4)	139 (20.2)	138 (20.0)	136 (19.7)	133 (19.3)	129 (18.7)	109 [a b] (15.8) [a b]	78.6 [a b] (11.4) [a b]	12.4 [a b] (7.8) [a b]	35.2 [a b] (5.1) [a b]	22.1 [a b] (3.2) [a b]	13.4 [a b] (2.0) [a b]	8.3 [a b] (1.2) [a b]
2 1/4 Cr-1Mo -V	Forgings Forgings Forgings Plates Plates	SA-182 SA-336 SA-541 SA-542 SA-832	F22V F22V 22V D 22V	—	168 (24.3)	168 (24.3)	168 (24.3)	168 (24.3)	168 (24.3)	163 (23.7)	160 (23.2)	157 (22.8)	153 (22.2)	149 (21.6)	148 (21.0)	140 (20.3)	—	—	—	—	—	—
9Cr-1Mo	Seamless Tubes Seamless Pipe Forged and Bored Pipe Fittings	SA-213 SA-335 SA-369 SA-234	T9 P9 FP9 WP9	—	118 (17.1)	118 (17.1)	114 (16.6)	114 (16.5)	113 (16.4)	112 (16.2)	110 (15.9)	108 (15.6)	104 (15.1)	100 (14.5)	95 (13.8)	90 (13.0)	73 [a c] (10.6) [a c]	51 [a c] (7.4) [a c]	34 [a c] (5.0) [a c]	23 [a c] (3.3) [a c]	15 [a c] (2.2) [a c]	10 [a c] (1.5) [a c]
	Forgings	SA-182/336	SA-182/336	—	168 (24.3)	167 (24.2)	161 (23.3)	161 (23.3)	161 (23.3)	158 (22.9	156 (22.6)	152 (22.1)	148 (21.4)	142 (20.6)	135 (19.6)	113 [a c] (16.4) [a c]	76 [a c] (11.0) [a c]	51 [a c] (7.4) [a c]	34 [a c] (5.0) [a c]	23 [a c] (3.3) [a c]	15 [a c] (2.2) [a c]	10 [a c] (1.5) [a c]
9Cr-1Mo-V	Seamless Tubes Seamless Pipe Forged and Bored Pipe Fittings Forgings Plate	SA-213 SA-335 SA-369 SA-234 SA-182/336 SA-387	T91 P91 FP91 WP91 F91 91	≤ 7.6 (3.0)	168 (24.3)	168 (24.3)	168 (24.3)	167 (24.2)	166 (24.1)	163 (23.7)	161 (23.4)	158 (22.9)	153 (22.2)	147 (21.3)	140 (20.3)	132 (19.1)	123 (17.8)	112 (16.3)	97 [a] (14.0) [a]	71 [a] (10.3) [a]	48 [a] (7.0) [a]	30 [a] (4.3) [a]
	Seamless Tubes Forged and Bored Pipe Fittings Seamless Pipe Forgings Plate	SA-213 SA-369 SA-234 SA-335 SA-182/336 SA-387	T91 FP91 WP91 P91 F91 91	> 7.6 (3.0)	168 (24.3)	168 (24.3)	168 (24.3)	167 (24.2)	166 (24.1)	163 (23.7)	161 (23.4)	158 (22.9)	153 (22.2)	147 (21.3)	140 (20.3)	132 (19.1)	123 (17.8)	112 (16.3)	97 [a] (12.9) [a]	71 [a] (9.6) [a]	48 [a] (7.0) [a]	30 [a] (4.3) [a]
9Cr-2W CC 2179-3	Forgings Forged Pipe	SA-182 SA-369	9Cr-2W	—	177 (25.7)	177 (25.7)	174 (25.3)	169 (24.5)	164 (23.8)	160 (23.2)	157 (22.8)	154 (22.4)	151 (21.9)	148 (21.4)	143 (20.8)	139 (20.1)	132 (19.2)	126 (18.3)	114 (16.6)	90 (13.0)	68 (9.8)	—
	Pipe Tube	SA-335 SA-213	9Cr-2W	—	177 (25.7)	177 (25.7)	174 (25.3)	169 (24.5)	164 (23.8)	160 (23.2)	157 (22.8)	154 (22.4)	151 (21.9)	148 (21.4)	143 (20.8)	139 (20.1)	132 (19.2)	126 (18.3)	119 (17.2)	94 (13.6)	70 (10.2)	48 (6.9)
9Cr-1Mo-1W-1Cb CC 2327 (only for ASME Section I)	Seamless Tubes Seamless Pipe Forged and Bored Pipe Fittings Forgings Plate	CC 2327	9Cr-1Mo-1W-1Cb	—	177 (25.7)	177 (25.7)	173 (25.1)	166 (24.1)	163 (23.6)	160 (23.2)	159 (23.0)	157 (22.7)	154 (22.3)	150 (21.7)	145 (21.0)	139 (20.1)	131 (19.0)	122 (17.7)	103 (14.9)	79 (11.4)	46 (6.7)	—
16Cr-12 Ni-2Mo	Seamless Tubes Seamless Pipe Fittings Plates	SA-213 SA-376 SA-403 SA-240	TP316H TP316H 316H 316H	—	138 (20.0)	138 (20.0)	138 (20.0)	133 (19.3)	124 (18.0)	145 (17.0)	114 (16.6)	112 (16.3)	111 (16.1)	110 (15.9)	108 (15.7)	108 (15.6)	106 (15.4)	105 (15.3)	104 (15.1)	85 [a d] (12.4) [a d]	68 [a d] (9.8) [a d]	51 [a d] (7.4) [a d]

[a] Minimum post weld heat treatment of the Grade 91 shall be 704 °C (1300 °F) and the allowable stresses for temperatures of 566 °C (1050 °F) and above are values obtained from time-dependent properties.

[b] Allowable stresses for temperatures of 482 °C (900 °F) and above are values obtained from time-dependent properties.

[c] Allowable stresses for temperatures of 510 °C (950 °F) and above are values obtained from time-dependent properties.

[d] Allowable stresses for temperatures of 593 °C (1100 °F) and above are values obtained from time-dependent properties.

Table 8—Design Stress Intensity Values "S_m" in ASME Section III, Division 2, for 9Cr-1Mo-V Steel in Comparison with 2 1/4 Cr-1Mo, 2 1/4 Cr-1Mo-V, 9Cr-1Mo Steels and 316 H Stainless Steel

Nominal Composition and/ or Code Case	Product Form	Specification	Grade	Maximum Metal Temperatures °C (°F)											
				–29 to 38 (–20 to 100)	93 (200)	149 (300)	204 (400)	260 (500)	316 (600)	343 (650)	371 (700)	399 (750)	427 (800)	454 (850)	482 (900)
				Maximum Allowable Stress MPa (ksi)											
2 1/4 Cr-1Mo	Seamless Tubes Seamless Pipe Forgings Fittings	SA-213 SA-335 SA-336 SA-234	T22P22 F22 22 WP22	138 (20.0)	128 (18.5)	125 (18.1)	123 (17.9)	123 (17.9)	123 (17.9)	123 (17.9)	123 (17.9)	123 (17.9)	123 (17.8)	100 (14.5)	88 (12.8)
	Forgings Plate	SA-182 SA-387	F22 22 Class 2	172 (25.0)	172 (25.0)	169 (24.5)	166 (24.1)	165 (23.9)	164 (23.8)	163 (23.6)	161 (23.4)	159 (23.0)	155 (22.5)	150 (21.8)	117 (17.0)
2 1/4 Cr-1Mo-V	Forgings Forgings Forgings	SA-182 SA-336 SA-541	F22V F22V 22V	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	190 (27.6)	187 (27.1)	183 (26.5)	179 (25.6)	174 (25.2)	169 (24.5)	163 (23.6)
	Plates Plates	SA-542 SA-832	D 22V	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	190 (27.6)	187 (27.1)	183 (26.5)	179 (25.9)	174 (25.2)	169 (24.5)	163 (23.6)
9Cr-1Mo	Seamless Tubes Seamless Pipe Fittings	SA-213 SA-335 SA-234	T9 P9 WP9	138 (20.0)	138 (20.0)	120 (17.4)	119 (17.2)	118 (17.1)	116 (16.8)	114 (16.6)	112 (16.3)	—	—	—	—
	Forgings Forgings	SA-182 SA-336	F9 F9	195 (28.3)	195 (28.3)	190 (27.5)	188 (27.2)	187 (27.1)	185 (26.8)	181 (26.3)	174 (25.3)	—	—	—	—
9Cr-1Mo-V	Seamless Tubes Seamless Pipe Forgings Plate	SA-213 SA-335 SA-182 SA-387	T91 P91 FP91 91	195 (28.3)	195 (28.3)	195 (28.3)	194 (28.2)	194 (28.1)	191 (27.7)	188 (27.3)	184 (26.7)	—	—	—	—
9Cr-1Mo-V CC 1973-2	Seamless Tubes Seamless Pipe Forgings Plate	SA-213 SA-335 SA-182 SA-387	T91 P91 F91 91	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	195 (28.3)	190 (27.6)	187 (27.1)	183 (26.5)	179 (25.9)	174 (25.2)	169 (24.5)	163 (23.6)
16Cr-12Ni-2Mo	Seamless Tubes Seamless Pipe	SA-213 SA-312	TP316H TP316H	138 (20.0)	138 (20.0)	138 (20.0)	133 (19.3)	124 (18.0)	117 (17.0)	115 (16.7)	112 (16.3)	111 (16.1)	110 (15.9)	—	—

The effect of aging on CVN specimens from a commercial ESR heat for times up to 5000 hours at temperatures from 482 °C (900 °F) to 649 °C (1200 °F) was investigated. Aging caused a maximum shift in the transition temperature of about 40 °C (72 °F) [from to 40 °C (to 40 °F) to 0 °C (32 °F)] [39].

3.5.4 Creep Rupture Properties

Two of the major attributes of the 9Cr-1Mo-V are its excellent creep rupture strength and its retention of long term rupture ductility. It offers significantly improved elevated temperature strength properties over those of 2 $^1/_4$ Cr-1Mo or standard 9Cr-1Mo steels as shown in Figure 12 [39].

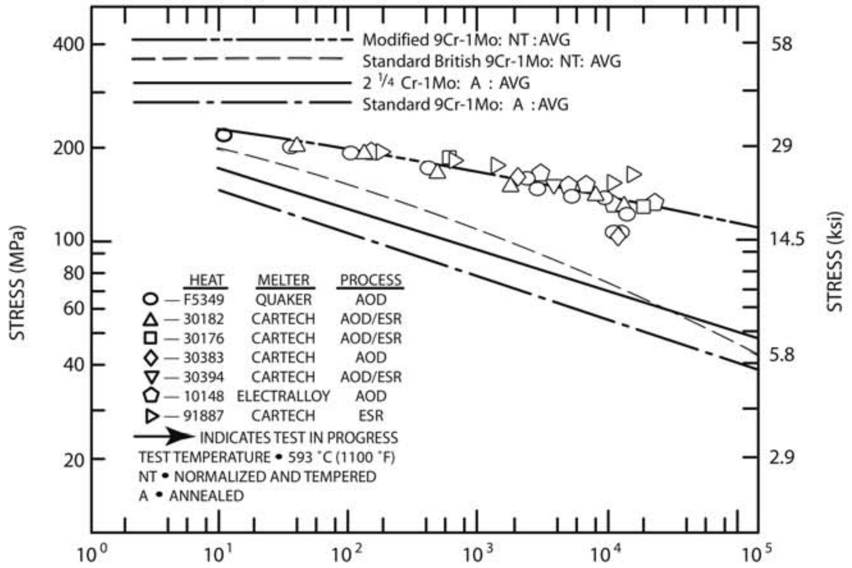

Figure 12—Stress Rupture Strength of Commercial Heats of N + T Grade 91 Alloy Steel at 593 °C (1100 °F)

Grade 91 steel has been investigated over the years in many laboratories all over the world. Table 9 shows the creep rupture values for ASTM A 213 [26], Grade T91 steel [38]:

Table 9—Creep Rupture of ASTM A 213 Grade T91 Steel

Temperature °C (°F)	σ_R 10,000 h MPa (ksi)	σ_a 10,000 h MPa (ksi)
500 (930)	175 (25)	164 (24)
525 (980)	160 (23)	153 (22)
550 (1020)	150 (22)	141 (20)
575 (1070)	142 (21)	124 (18)
600 (1110)	125 (18)	98 (14)
625 (1160)	98 (14)	68 (10)

A comparison of the creep rupture behavior of weldments of Grade 91 steel to base material at 649 °C (1200 °F) is illustrated in Figure 13 [36].

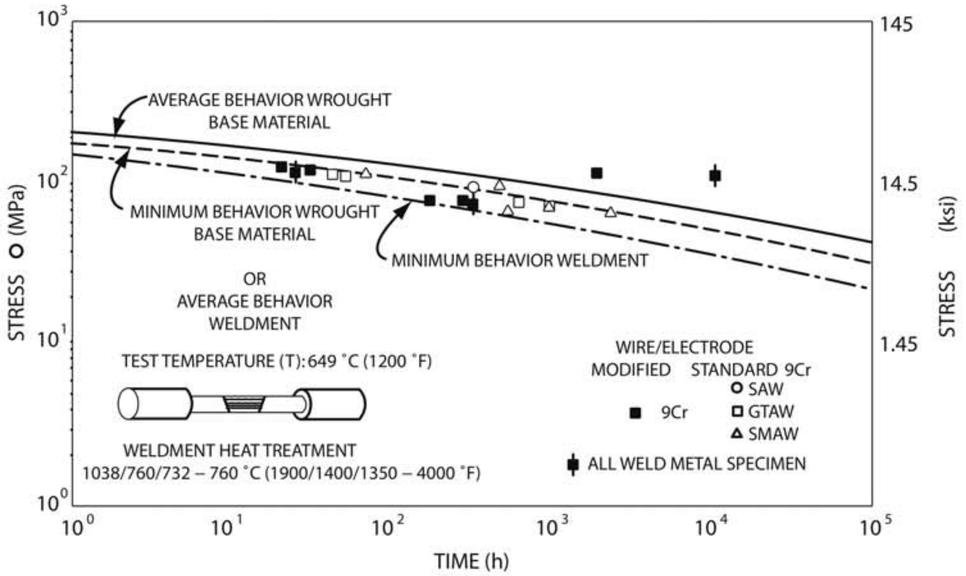

Figure 13—Comparison of Creep Rupture Strength of Grade 91 Steel Weldments to Base Metal

3.5.5 Base Metal Hardness

As shown in Table 4, ASME Specifications SA-182, SA-213, and SA-234 specify either maximum limits or ranges for acceptable base metal Brinell hardness. Depending on the specification, the Grade 91 steels have a higher HBN than for standard 9Cr-1Mo steels with the maximum ranging from 238 to 250 HBW. The ASME hardness limit for the standard 9Cr-1Mo steels is lower and ranges from 179 to 217 HBW. In wet H_2S service, the maximum allowable hardness for Grade 91 steel base metal per NACE MR0103-2005 [33] is 248 HBW.

However, lower hardness (~160 HBW to 180 HBW) for P91 piping spools have been reported. Such low hardness values suggest that improper heat treatment had occurred either during manufacturing and/or fabrication (bending, etc.). Therefore, when base metal hardness is below 190 HBW, further investigation is warranted.

4 Metallurgy and Environmental Related Failure Mechanisms

4.1 Oxidation and Sulfidation Resistance

The oxidation resistance and sulfidation resistance of Grade 91 is equivalent to that of the standard 9Cr-1Mo Grade. In air, the oxidation resistance of Grade 91 is excellent even at 949 °C (1200 °F). In steam service, the oxidation resistance of Grade 91 is similar to that of 2 $^1/_4$ Cr-1Mo. Sulfidation resistance of Grade 91 is equivalent to that of Grade 9Cr-1Mo steel and is superior to the lower Cr-Mo alloys. In H_2-H_2S services (e.g. hydro-treating equipment) SS cladding may be necessary in order to assure resistance to corrosion. [46]

4.2 Wet Hydrogen Sulfide Cracking

Grade 91 may be susceptible to sulfide stress corrosion cracking (SSC) in aqueous sulfide conditions because of high HAZ and weld hardness values. The Grade 91 steel was subjected to detailed mechanical property assessment, sulfide stress corrosion cracking susceptibility and fracture toughness testing. Results showed that hardness of welds exceeded the range normally used in wet H_2S service for Cr-Mo steels, the weld and HAZ toughness were low, and sulfide cracking susceptibility was very high. Furthermore once cracked, the crack growth rate is increased significantly in wet H_2S environment. PWHT at temperatures near the transformation temperature, reduces hardness but some hardness values still exceeded the maximum hardness limit of 248 BHW specified in NACE MR0103 [33] for 9Cr-1Mo-V steel [33, 47]. Therefore, the possible use of Grade 91 alloy steel in wet H_2S service should be carefully evaluated and only done with careful control of weld and HAZ hardness. This includes services that may form wet H_2S exposures during turnarounds and upset conditions.

4.3 Hydrogen Attack Resistance

Hydrogen attack is an elevated temperature phenomenon where dissolved hydrogen diffuses in the steel and reacts with the carbon or carbides in the steel to form methane. This formation can occur at the surface (surface decarburization) or at locations within the metal such as at fissures or grain boundaries, which is known as internal decarburization. The limits for the use of carbon and Cr-Mo steels in high temperature and high-pressure hydrogen service are set by API RP 941 [1]. Grade 91 steel is not susceptible to high temperature hydrogen attack [46, 48]. It is not included in API RP 941 but will be more resistant than the highest Cr alloy (6Cr-$^1/_2$ Mo) shown in API RP 941, Figure 1.

4.4 Hydrogen Embrittlement, Hydrogen Diffusivity and Trapping

Hydrogen embrittlement as described here can occur below 149 °C (300 °F) due to atomic hydrogen, which diffuses into steel at high temperature, high pressure gaseous hydrogen typical in hydroprocessing reactor systems. Due to higher hydrogen solubility at higher temperatures, the hydrogen concentration in the wall may build up especially in thicker components to a level such that hydrogen cracking can occur when the equipment is cooled too rapidly to permit the hydrogen to diffuse out of the steel. The vanadium-modified steels tend to demonstrate a low susceptibility to hydrogen embrittlement, as the finely dispersed vanadium and Nb carbide precipitates within the alloy tend to trap the hydrogen within the steel [46, 48, 49, 50].

4.5 Temper Embrittlement

Both Grade 9 and Grade 91 steels exhibit almost no susceptibility to temper embrittlement (TE).

TE occurs when certain alloy steels are held within or cooled slowly through the embrittling temperature range of 371 °C to 554 °C (700 °F to 1030 °F). TE is manifested by an increase in the ductile to brittle transition temperature (DBTT). Embrittlement occurs in Cr-Mo alloy steels when impurities such as P, Sb, Sn, and As segregate at the prior austenitic grain boundaries and the material is stressed. The alloying elements Mn and Si also act to enhance TE in combination with the impurity or tramp elements listed above. Step cooling heat treatments had an insignificant effect on absorbed impact energy in CVN impact testing. [51].

4.6 Type IV Cracking

Steels with properties enhanced by heat treatment commonly develop a drop in hardness in the outer extremity of the HAZ due to over-tempering at temperatures below the lower critical transformation temperature and/or micro-structural changes in the inter-critical temperature range. This purported “soft zone” exhibits stress rupture strength below that of the unaffected base metal in cross-weld tests resulting in reduction in the creep life of the welded joint. Type IV cracking is the generic name assigned to this phenomenon [52, 53].

Hardness traverses for SMAW, SAW and GMAW of P-91 steel weldments following four hours of tempering at 745 °C (1375 °F) are shown in Figure 14. This figure shows the soft zone, where the Vickers hardness is approximately 190 to 195. The hardness is in the range of 205 to 220 in the unaffected base metal [52].

At high stress levels, the 9Cr-1Mo-V steel may suffer Type IV cracking due to presence of such soft zone of reduced creep rupture strength [40, 53]. The cross-weld creep strength at 600 °C (1112 °F) of T91/P91 weldments that contained Type IV fine-grained HAZ, showed about 20 % loss when compared to the base material [54].

One method for ensuring satisfactory service performance with Grade 91 steel is to avoid stress concentration/risers and to limit the applied axial stress or bending moments across the welded joint [54, 55]. Use of additional safety factor in the design, such as 20 % reduction in allowable stress has been suggested when the principal stress is acting in cross-weld direction [38]. However, the whole the issue of how to avoid Type IV cracking is still under investigation by the industry.

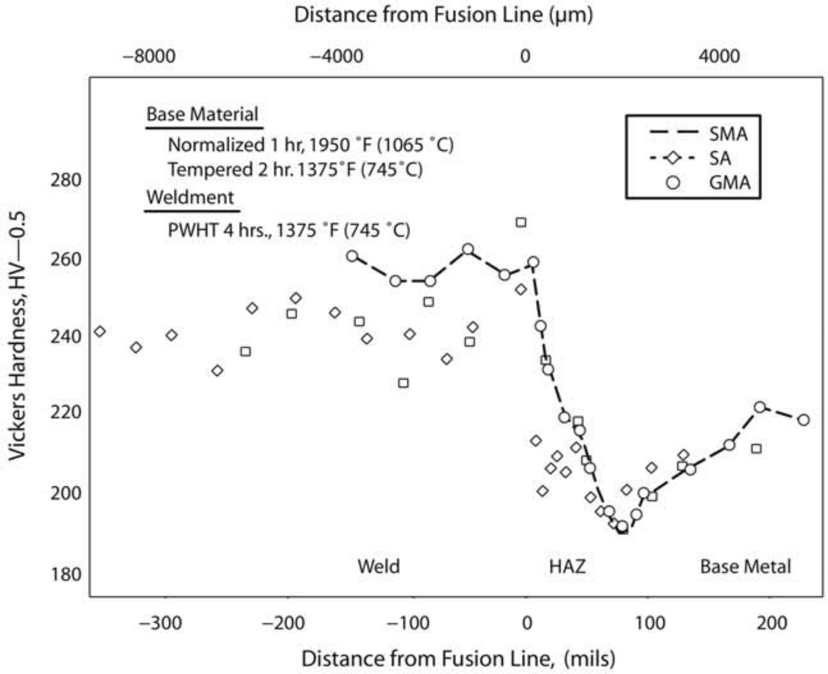

Figure 14—Hardness Profile of Grade 91 Weldment with Type IV Soft Zone

5 Material Requirements

5.1 Base Metal

Table 1 lists specifications and CCs that are applicable to Grade 91 steel. In addition, most users require that base material be impact tested after heat treatment and they meet the acceptance average impact requirements of 33.9 J (25 ft-lbs) with no single value less than 21.7 J (16 ft-lbs) at 21 °C (70 °F). If Grade 91 alloy steel is intended for use in wet H_2S service, the requirements of NACE MR0103 [33] are typically specified.

5.2 Welding Consumables

5.2.1 Welding Consumable Specifications

The following 9Cr-1Mo-V (B9) welding consumables are specified in AWS and ASME specifications:

- SMAW: E9015-B9, E9016-B9 or E9018-B9 per A/SFA-5.5 [28];
- GTAW: ER90S-B9 per A/SFA-5.28 [30];
- SAW: EB9 as per A/SFA-5.23 [29];
- FCAW: E91T1-B9 per A/SFA 5.29 [31].

Table 10 shows chemical composition of B9 welding consumables for Grade 91 alloy steels.

Table 10—Compositional Specifications of 9Cr-1Mo-V Steels Weld Consumables

Elements	P/T 91 Pipe/Tube	ER90S-B9 A/SFA 5.28	E901X-B9 A/SFA 5.5	EB9 A/SFA 5.23	E91T1-1 A/SFA 5.29
C	0.08 to 0.12	0.07 to 0.13	0.08 to 0.13	0.07 to 0.13	0.07 to 0.13
Mn [a]	0.30 to 0.60	1.25 maximum	1.25 maximum	1.25 maximum	1.25 maximum
P, maximum	0.020	0.010	0.010	0.01	0.020
S, maximum	0.010	0.010	0.010	0.01	0.015
Si	0.20 to 0.50	0.15 to 0.30	0.30 maximum	0.30 maximum	0.50 maximum
Cr	8.00 to 9.50	8.00 to 9.50	8.00 to 10.50	8.00 to 10.00	8.0 to 10.5
Mo	0.85 to 1.05	0.80 to 1.10	0.85 to 1.20	0.80 to 1.10	0.85 to 1.20
Ni a	0.40 maximum	1.00 maximum	1.00 maximum	1.00 maximum	0.40 to 1.00
V	0.18 to 0.25	0.15 to 0.25	0.15 to 0.30	0.15 to 0.25	0.15 to 0.30
N	0.03 to 0.07	0.03 to 0.07	0.02 to 0.07	0.03 to 0.07	0.02 to 0.07
Nb	0.06 to 0.10	0.02 to 0.10	0.02 to 0.10	0.02 to 0.10	0.02 to 0.10
Cu, maximum	—	0.20	0.25	0.10	0.25
Al, maximum	0.04	0.04	0.04	0.04	0.04

[a] Ni + Mn = 1.5 % maximum. Other values for corrosive service are given in 5.2.4.

5.2.2 Role of Alloying Elements

Welding consumables are made to meet the minimum requirements of Grade 91 base metal. A study on the effect of single elements including optimum content of nitrogen, nickel, manganese, and Nb indicates nitrogen has an important influence on creep rupture strength by forming carbonitrides. However, nitrogen lowers toughness due to the formation of nitrides with other elements. Nitrogen also increases yield and tensile strength, but lowers ductility. Typical nitrogen maximum content is 0.04 %. Manganese and nickel have influence on strength properties. Nickel increases toughness, but the Ni + Mn content should be controlled as discussed in 5.2.3.3. Nb is required to maintain creep properties. Nb lowers toughness, but a maximum Nb content of 0.05 % is typical, above which dramatic loss of CVN would result [37, 56]. Silicon content greater than 0.15 % decreases toughness but provides molten pool deoxidation and prevents porosity. Typically, a maximum Si content of 0.2 % to 0.3 % is acceptable. Carbon decreases toughness but 0.08 % minimum content is required for creep strength. Vanadium is required to maintain creep properties, however, content greater than 0.25 % significantly lowers toughness. A maximum vanadium content of 0.20 % is typical [37, 38].

5.2.3 Chemical Composition and Residual Elements

5.2.3.1 Chromium Equivalent (Cr_{eq})

To obtain a proper balance between facture toughness, creep-rupture strength and resistance to long-term embrittlement, the alloy composition and residual elements are typically controlled to provide a single-phase microstructure and avoid residual delta ferrite. Delta ferrite reduces toughness and creep resistance. By keeping the chromium equivalent (Cr_{eq}) below 10, the tendency to form delta ferrite is reduced. Even materials with Cr_{eq} between 10 and 12 exhibited adequate toughness when the delta ferrite does not exceed 5 %. The chromium equivalent is estimated by the following formula [37] (all elements in wt %):

$$Cr_{eq} = \mathrm{Cr} + 6\mathrm{Si} + 4\mathrm{Mo} + 1.5\mathrm{W} + 11\mathrm{V} + 5\mathrm{Nb} + 9\mathrm{Ti} + 12\mathrm{Al} – 40\mathrm{C} – 30\mathrm{N} – 4\mathrm{Ni} – 2\mathrm{Mn} – 1\mathrm{Cu}.$$

5.2.3.2 Residual Elements

In order to minimize crater cracking or undesirable grain boundary phenomena, low residual element weld filler metal are typically used. For this reason, X-bar greater than 15 is usually specified for all welding processes except FCAW [37]. Although some manufacturers of FCAW filler metal can meet this specification, typically X-bar greater than 25 is acceptable as FCAW is usually allowed by users for less critical welds such as welding nonpressure containing components. X-bar or factor is calculated from the Bruscato formula as follows:

$$\text{X-bar} = (10\text{P} + 5\text{Sb} + 4\text{Sn} + \text{As})/100$$

where

P, Sb, Sn, and As are in ppm.

5.2.3.3 Ni + Mn Content

The quantity of Ni + Mn affects the Ac_1 as shown in Figure 5. In order that PWHT temperature does not exceed the lower critical temperature Ac_1, Ni + Mn content is typically limited to 1.5 wt % maximum. This provides safeguard against austenite reformation during PWHT [37]. The 1.5 % maximum limit is typically specified for utility services, e.g. steam generation. When maximum weld metal hardness is a key consideration, e.g. for process services, Ni + Mn content is usually limited to 1.3 wt % maximum. This will allow use of slightly higher PWHT temperature to achieve acceptable weld metal hardness for process conditions. In addition, a balance between the Ni and Mn contents is necessary because Ni increases toughness but reduces the creep strength, while Mn reduces toughness but it is necessary for deoxidation of the molten weld pool [37].

5.2.3.4 Mn/S Ratio

By observing the AWS –B9 0.010 wt % maximum sulfur and phosphorous contents, problems such as crater cracking, maintenance of toughness after PWHT, or undesirable grain boundary effects can be avoided in SMAW, GTAW, and SAW. It has been found through experience that consumables exhibiting manganese-to-sulfur ratios greater than 50 do not exhibit crater cracking phenomena when combined with low phosphorous content [37].

5.2.3.5 Oxygen Content

Low oxygen content is beneficial to achieving satisfactory toughness. The oxygen contents of GTAW, SMAW and FCAW weld deposit are typically 100 ppm, 300 ppm to 700 ppm, and 600 ppm to 1000 ppm respectively [57]. GTAW weld metals gave superb toughness, comparable to that of the base metal, while the toughness of SMAW and SAW markedly decreased due to higher oxygen content [58]. Figure 15 shows the effect of oxygen content on toughness of P91 weldments made by GTAW, GMAW and SAW [37].

5.2.4 Low Hydrogen

Low hydrogen controls are typically specified to be implemented and maintained during fabrication, procurement, use and storage of welding consumables. Use of covered electrodes and fluxes meeting hydrogen criterion H4 [4.0 ml (H_2)/100 g deposited metal] for covered electrodes and H5 for SAW fluxes are advisable. However, due to the higher heat input and inter-pass temperature of SAW process, some users specify higher diffusible hydrogen criterion H8 for SAW fluxes to reduce hydrogen content in the weldment.

5.2.5 Flux

Solid wires of automatic welding processes are typically specified to contain the principal elements required for the deposited weld metal. With this requirement, welds deposited by SAW process do not derive any principal element from the flux, i.e. only neutral fluxes are used. Another typical requirement is that SAW fluxes are not crushed and

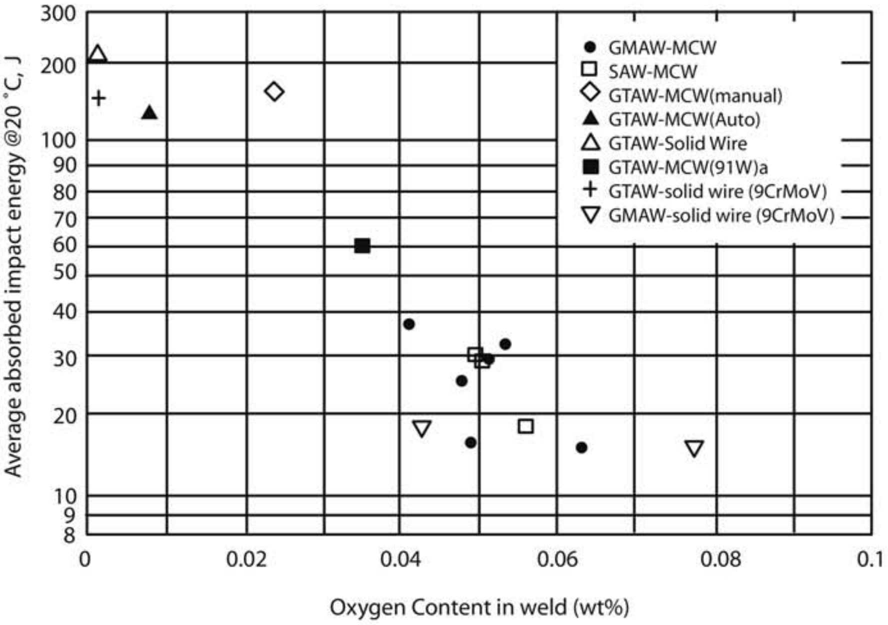

Figure 15—Effect of Oxygen Content on Toughness for Selected Grade 91 Weldments

reused. Also production SAW welds are usually performed using the same brand flux and the same brand or AWS/ ASME classification wire as used for the PQR.

5.2.6 Moisture

Low moisture content is required for used welding consumables. After opening shipping containers of electrodes, fluxes and other welding materials, storage and handling of these welding consumables is typically performed in accordance with manufacturer's recommendations and ASME Section II, Part C [2] in order to avoid moisture pick-up. However, if 9Cr-1Mo-V electrodes or SAW fluxes absorb moisture, re-drying is not advisable and they are typically discarded.

5.2.7 Impact Testing

Early formulation work and later production of E9015-B9 consumables showed that even though chemical composition may be within acceptable ranges, nil ductility could be observed. This was caused by minor and undistinguishable tramp elements that are present in coating minerals. Thus, verifying toughness for coated electrodes is prudent. It is advisable that impact testing in accordance with the fracture toughness section of AWS B4.0 [32] be required for all lots of weld metal. Similar to base metal requirements in 5.1, toughness acceptance criteria for welding consumables is average of 33.9 J (25 ft-lbs) with no value less than 21.7 J (16 ft-lbs) at 21 °C (70 °F) for all welding processes except FCAW. An impact test value of 21.7 J (16 ft-lbs) average is required for FCAW welds, which are typically allowed by users only for less critical applications.

5.2.8 Consumable Composition Testing and Certification

All welding consumables are commonly supplied with certified material test reports (CMTRs). Each filler size, lot, and/ or heat of B9 welding consumables is typically required to have its chemical compositions tested. Actual mechanical and toughness results per lot or heat are also often specified. Consequently, CMTRs are typically required to be submitted by the manufacturer for each heat and lot of supplied B9 welding consumables [37, 59].

6 Fabrication and Welding Requirements

6.1 General Concerns

6.1.1 Weld Hardness

The 9Cr-1Mo-V high strength steels have relatively high weld hardness that makes them unsuitable for various refinery environments, unless measures are taken during fabrication and welding.

6.1.2 Weld Toughness

Achieving toughness in the weld equal to that of base metal has been an elusive goal for all but the GTAW process. Typically, minimum weld toughness requirements are the same as indicated in 5.1 and 5.2.7.

6.1.3 Bending and Loading Stresses

Extreme care must also be observed during lifting, handling, moving, supporting, etc. to avoid applying unnecessary bending stresses or loading to weldments that have not yet received PWHT [37].

6.1.4 Cold Cracking

Preheat and inter-pass temperature control is necessary to avoid cold cracking (hydrogen assisted cracking) as is the use of low hydrogen weld consumables [52], as discussed in 6.4.4 and 5.2.4 respectively.

6.1.5 Hot Cracking

Hot cracking occur at temperatures close to the solidus temperature and is caused by micro-segregation. Such cracks are formed due to low melting point impurity elements, such as sulfur and phosphorous in the steel. Manganese has greater affinity for sulfur than iron and its addition successfully eliminates hot cracking in most cases. Elements that form low melting compounds, such as silicon and Nb contribute to hot cracking. Therefore, with Grade 91 steel, hot cracking can become a problem if the content of such elements is too high. However, laboratory and commercial experience with 9Cr-1Mo-V steel indicates no problem with weld metal solidification cracking [52].

6.1.6 Reheat Cracking

Reheat cracking, also referred to as stress relief cracking or post weld heat treatment cracking, is intergranular cracking in the HAZ or in the weld metal that occurs during the exposure of weldments to the elevated temperature necessary for PWHT or during service at high temperature. This type of cracking exhibits low rupture ductility and is caused by the combination of matrix strengthening as a result of carbide precipitation, embrittlement of the grain boundaries as a result of residual segregation, and both internal residual stress due to welding and externally applied stress. Higher phosphorous content (e.g. 0.014 %) in Grade 91 steel reduces rupture ductility. Therefore, careful control of the content of residual elements such as phosphorous (< 0.010 %) is recommended. The reduction in area (RA) is used as a measure of rupture ductility and 20 % RA may be used as the demarcation for susceptibility to reheat cracking [52]. However, laboratory investigators and commercial fabricators have reported no instances of reheat cracking in Grade 91 alloy steel and reheat cracking has not been reported to be a problem [52, 56].

6.2 Cold Bending

Cold bending is typically performed after post weld heat treatment because 9Cr-1Mo-V steels in the as welded condition are very hard. The degree of cold working is usually limited to 17 % maximum (wall thickness reduction), if steels are applied at creep range temperatures. Most users would require that cold worked 9Cr-1Mo-V steels be normalized and tempered if the steels are applied in the creep range and the degree of cold working exceeds 17 %. Cold deformation requires heat treatment by most codes for deformation greater than 5 % [38].

6.3 Hot Bending

The optimum hot forming temperature of Grade 91 alloy pipe or tube lies from 850 °C to 1100 °C (1560 °F to 2010 °F). Forming operations such as forging and upsetting are performed in the upper part of the temperature range between 950 °C and 1100 °C (1740 °F and 2010 °F), while hot bending and stretching are carried out in the lower part of this temperature range. For induction bending, it is recommended to carry out a qualification test to determine the optimum bending parameters (temperature, speed, etc.) [38].

Hot bending of pipe is typically carried out using computer aided induction heated bending machines. After hot bending above critical temperatures, the material is typically receives a complete post bending heat treatment (PBHT) consisting of normalizing at 1050 °C (1922 °F), followed by air cooling and tempering at 750 °C (1382 °F) again followed by air cooling [38]. Such heat treatment is performed for the entire component. Localized heat treatment is considered to be ineffective. The product will retain the same properties as specified (including creep properties) only after proper and full post bending heat treatment. Heat treatments deviating from this practice, such as tempering only rather than full PBHT can result in premature failure [38].

When warm thermal straightening is implemented, caution must be observed to not encroach on the lower critical (Ac_1) temperature of the material, otherwise full normalizing and tempering heat treatment will be required.

6.4 Welding

6.4.1 Welding Processes

6.4.1.1 SMAW, GTAW, and SAW

SMAW and GTAW are the most commonly used welding processes in the fabrication of 9Cr-1Mo-V steels, but productivity is limited. Use of automatic SAW and the use of a combination of these processes are acceptable.

In most cases, acceptable mechanical properties are achievable with SMAW, provided that the electrode formulation is consistent with –B9 composition and sufficient welder skill is available [37].

Weld metal deposited with GTAW typically exhibits far greater toughness than weld metal deposited using flux and slag systems [37]. One-sided butt joints in 9Cr-1Mo-V steel are typically welded with the GTAW process and the interior side is purged with inert gas to a 4 % maximum oxygen atmosphere. The inert gas is usually held for the first two layers of weld metal. Root passes with other processes are usually back-gouged to sound metal.

SAW of Grade 91 steel is readily accomplished by the use of automatic, machine or semi-automatic processes using both constant current or constant voltage power sources [37].

6.4.1.2 FCAW

Flux core arc welding (FCAW) may be used if approved by the purchaser. FCAW is often approved for less-critical applications. When used, FCAW is usually required to have external shielding gas and all vertical welding is typically made with an uphill progression. If FCAW is permitted for pressure-containing welds, it is typically not allowed for root passes of one-sided butt welds and is required to be of spray or globular transfer. All areas to be welded are typically required to be cleaned to bright metal prior to welding and each pass is also cleaned completely prior to deposit of subsequent passes.

6.4.1.3 GMAW

The composition of –B9 solid wire GMAW welding consumable is lean on deoxidizers, which is important for proper operation and results. Because of this, the wetting action is reduced and the preponderance for lack of fusion type defects and oxide inclusion content affects the ability to perform successful GMAW welding. Some fabricators have qualified GMAW, but few have implemented it into production because of its operator specific characteristic and inability to perform in a reproducible manner [37]. Therefore, typically most users do not allow use of GMAW for welding Grade 91 steel.

6.4.1.4 Oxy-fuel Gas Welding (OFW) and Electroslag Welding (ESW)

OFW and ESW processes are typically not used for 9Cr-1Mo-V alloy steels.

6.4.2 General Welding Requirements

6.4.2.1 Use of Filler Metal

All welds, including tack welds, are made with filler metal. Tack welds are made with the same type of electrodes or filler wire that is used for the root pass. The filler metals are to match the chemistry of the base metals.

6.4.2.2 Storage and Handling of Welding Consumables

As indicated in 5.2.6, after opening shipping containers of electrodes, fluxes and other welding materials, storage and handling of these welding consumables is typically performed in accordance with manufacturer's recommendations and ASME Section II, Part C [2] in order to avoid moisture pick-up. However, if 9Cr-1Mo-V electrodes or SAW fluxes absorb moisture, re-drying is not advisable and typically they are discarded.

6.4.2.3 Back Purging and Shielding Gas

The back purging and shielding gases for GTAW are typically 100 % welding grade argon or nitrogen. The use of 5 % oxygen in the argon shielding gas may be used as specified in ASME Section II, Part C, SFA–5.28 [28], Table 3 for mechanical testing of 9Cr-1Mo-V filler metal (ER90S–B9). Welding grade gases are specified to be 99.998 % pure.

The shielding gas for FCAW usually consists of 100 % CO_2 or Ar–CO_2 (80 % –20 % or 75 % –25 %) [37].

Root passes of welds in piping; tubing or other components require back purging until at least the root and one hot pass have been deposited.

6.4.2.4 Welding Technique, Bead Shape and Position Effects on Weld Toughness

Bead shape and welding position have a significant effect on toughness. Thin wide beads that permit some degree of tempering from heat of welding induce grain refinement on previously deposited metal. Thicker bead cross-sections minimize this effect. Weaving and avoiding stringer beads tempers the previously deposited weld metal and increase its toughness. Contrary to flat welding position (1G), loss of toughness is normally observed in the vertical (3G) and overhead (4G) positions with SMAW, mostly due to the bead shape in the weldment [37].

6.4.2.5 Heat Input

The maximum heat input for SMAW and GTAW manual procedures typically does not exceed 1.2 kJ/mm (30 kJ/in.). For FCAW (gas shielded) and SAW, the maximum heat input is usually limited to 2.2 kJ/mm maximum (55 kJ/in. max).

6.4.2.6 Interruptions

Any interruption of the welding should be avoided until at least 10 mm ($^3/_8$ in.) weld metal or 25 % to 30 % of the groove thickness has been deposited with weld metal. If interruption occurs and the welds cool below the preheat temperature, the welds are typically wrapped with insulation to promote slow cooling until preheated again, however, additional NDE testing is typically done due to risk of problems on interrupted welds.

6.4.3 Welding Procedure Specification (WPS) and Qualification

6.4.3.1 General

Prior to the start of fabrication, WPSs are typically qualified to ASME Section IX [5] and to the additional requirements of this document. Base metal used for welding procedure qualification is typically of the same ASME material, steel making process, chemical composition, heat treatment and mechanical properties as specified for production.

A change in welding consumable brand, AWS/ASME classification, manufacturer, or its hydrogen content, if applicable, are typically considered as essential variables. Similarly, PWHT temperature and holding time are essential variables within the limits of ± 14 °C (± 25 °F) and ± 1 hour respectively.

The P-number per ASME Section IX for Grade 91 steels is P5B, Group 2.

6.4.3.2 Traverse Micro-hardness Testing

The traverse micro-hardness testing of PQR's welded joint is typically performed at a depth of 1.6 mm ($^1/_{16}$ in.) below the surface of each side and also at $^1/_2$ T. NACE RP0472 [34], Figure 2 and Figure 3, show such traverse hardness test locations for butt and fillet welds respectively. Hardness of 248 HV10 maximum is acceptable for items intended for process units and 260 – 270 HV10 maximum for items used in utility services.

The welding process influences the hardness of B9 weldments. SMAW produces the lowest hardness. SAW welds have somewhat higher hardness. GTAW and FCAW exhibit the highest hardness. Actual results suggest that 248 HV10 maximum may be only achievable with SMAW and SAW. GTAW and FCAW typically exhibit 260 – 270 HV10 micro-hardness.

6.4.3.3 Impact Testing

Similar to impact testing recommended for the base metal and the welding consumables given in 5.1 and 5.2.6, impact testing of base metal, HAZ and weld metal of PQR's welded coupons is also performed. The recommended acceptance toughness criteria are the same as specified in 5.2.6 for welding consumables.

6.4.3.4 Purchaser's Approval

The WPSs and their supporting PQRs are typically submitted to the purchaser for review and approval prior to the start of fabrication.

6.4.4 Preheat and Inter-pass Temperatures

6.4.4.1 Preheat

Preheating is typically performed at 200 °C (400 °F) minimum for all welding processes except GTAW. Lower preheat temperature of 149 °C (300 °F) is acceptable for root pass and thin wall components where GTAW is utilized [37, 42]. Other references indicated the need for higher preheat temperature in the range of 200 °C to 250 °C (392 °F to 482 °F) to prevent cracking in Grade 91 welds with the lower temperatures are appropriate for thinner sections and the higher temperatures are applicable to thicker sections [60, 61]. The metal temperature is typically maintained at the preheat temperature until the weld is completed. It is prudent to use electrical resistance or electrical induction to provide better temperature control and heat distribution for preheating [42].

6.4.4.2 Inter-pass Temperature

Typical inter-pass temperature is in the range of 200 °C to 300 °C (~400 °F to 600 °F). However, for many applications a higher inter-pass temperature is acceptable with an upper limit of 370 °C (700 °F) maximum [37, 42]. Inter-pass temperature also depends on the welding process. Inter-pass temperature of 250 °C to 350 °C (482 °F to

662 °F) is recommended for GTAW and SMAW. However for SAW, inter-pass temperature of 200 °C to 250 °C (392 °F to 482 °F) is recommended [43]. The inter-pass temperature range is typically more controlled for highly constrained welds. For higher Si and C contents close to their maximum composition limit of 0.50 % and 0.12 % respectively, lower inter-pass temperatures are used to prevent the possibility of hot cracking.

6.4.4.3 Cooling for Transformation

As indicated in Figure 6, the temperature Mf is relatively low. Therefore, it must be emphasized that it is necessary to cool welds to below 93 °C (200 °F) before performing a PWHT. This cooling step is required in order to maximize austenite transformation to martensite. Austenite that is not transformed to martensite before PWHT will transform to martensite upon cooling from PWHT temperature and will lead to high weld hardness.

Failure to recognize the low Mf temperature has resulted in excessive hardness above the specified maximum in many of the early attempts to weld Grade 91 steel. This is one of the more important concepts and a critical step for proper fabrication of 9Cr-1Mo-V alloy steel.

6.4.5 Dehydrogenation Heat Treatment (DHT)

If welds are to be cooled down to ambient after welding and before PWHT, a postweld bake-out may be of critical importance, especially for thick-walled components when presence of residual hydrogen is of concern. One example of postweld back-out process includes soaking the weld joint and at least 75 mm (3 in.) on each side of the weld, at 320 °C (~600 °F) for a minimum of 20 minutes or 60 minutes for thin and thick-wall components respectively. Then the weldment is wrapped with insulation and allowed to cool below 93 °C (200 °F). This process facilitates hydrogen diffusion from the weld joint [37, 42].

6.4.6 Postweld Heat Treatment (PWHT)

All 9Cr-1Mo-V welds require PWHT, regardless of wall thickness or diameter. The appropriate PWHT develops a tempered martensitic structure. Precipitation of V/Nb rich carbonitrides along uniform distribution of fine lath boundaries and at dislocations is the basis for superior creep rupture strength of Grade 91 steel. Over tempering during PWHT will result in loss of creep-rupture properties, while under tempering will lead to high weld hardness from untempered martensite.

6.4.6.1 PWHT Temperature

Satisfactory tempering normally does not begin to occur until temperature exceeds 732 °C (1350 °F). Therefore, most successful welding operations typically require PWHT at least in the range of 746 °C to 760 °C (1375 °F to 1400 °F). Temperature excursions and gradient are typically considered in establishing PWHT temperature to avoid exceeding the desired temperature range. Thermal gradient of 28 °C to 56 °C (50 °F to 100 °F) on large bore, heavy-walled piping and vessels is not unusual.

It is important that the Ac_1 of the weld metal is not exceeded during PWHT to avoid getting into the two phase region. Therefore, the PWHT temperature is typically specified below the Ac_1 of the filler metal by approximately 14 °C to 28 °C (25 °F to 50 °F) [43]. For Grade 91 steel, the Ac_1 is a function of Ni + Mn content of the filler metal, as indicated in Figure 5 and as discussed in 6.2.3 [38]. In order to achieve reasonable weld hardness, the PWHT temperature for Grade 91 is specified as high as possible and typically it is kept below 788 °C (1450 °F) [43]. It should be noted that this PWHT temperature exceeds the tempering temperature of Grade 91 base metal indicated in 4.3.3 by 8 °C to 28 °C (14 °F to 50 °F), but this is not considered to be detrimental and cause of concern as achieving adequate weld hardness is more critical for Grade 91 steel weldments.

For less corrosive environments, such as in utility services, higher hardness is typically allowed, that can be achieved by PWHT at relatively lower temperatures. Meanwhile for process corrosive services, the hardness limits are lower that requires performing PWHT at slightly higher temperatures. Typical PWHT temperatures for such services are given below:

6.4.6.1.1 PWHT Temperature for Utility Services

All welds in utility services require PWHT at 760 °C ± 14 °C (1400 °F ± 25 °F) minimum, regardless of wall thickness or diameter.

6.4.6.1.2 PWHT Temperature for Process Services

All welds in process services require PWHT at 775 °C ± 10 °C (1427 °F ± 18 °F), regardless of wall thickness or diameter.

6.4.6.1.3 PWHT Holding Time

PWHT performed at 760 °C ± 14 °C (1400 °F ± 25 °F) for utility services is typically performed for at least one hour for wall thickness less than 13 mm ($^1/_2$ in.). For wall thickness greater than 13 mm ($^1/_2$ in.), PWHT holding time is about two hours. For wall thickness greater than 50 mm (2 in.), PWHT holding time is minimum two hours, plus one hour for each additional 25 mm (1 in.) [42].

For process services and in order to meet the above mentioned hardness requirements, the holding time is typically six hours minimum. To avoid over-tempering and softening thin wall material [e.g. < 12.7 mm (< $^1/_2$ in.)], shorter minimum holding time is usually established during pre-production welding procedure qualification. It is good practice to determine PWHT holding time based on testing of welding procedure qualification.

6.4.6.1.4 Heating and Cooling Rates

For Grade 91 steel, typical heating rate above 400 °C (750 °F) is 100 °C/hr to 150 °C/hr (180 °F/hr to 270 °F/hr). The cooling rate from PWHT temperature to 400 °C (750 °F) is normally controlled to 150 °C to 200 °C/hr (270 °F/hr to 360 °F/hr) maximum. The weld is then cooled down to ambient temperature in still air [38].

6.4.6.1.5 Application of PWHT

For successful PWHT, it is essential for P/T91 steel welds be uniformly heated through wall thickness and around the periphery of the weld using electric heating elements or induction heating bands, and the insulation and/or thermocouples are properly located, installed and shielded. Redundant and multiple thermocouples are frequently installed. Moreover, temperature gradients between weldments and adjacent base metal are to be considered and controlled to avoid harmful thermal stresses during PWHT.

6.4.6.1.6 Effect of PWHT Temperature and Holding Time on Toughness

The influence of the PWHT temperature and holding time on the toughness of matching filler metal to P91 material is shown on Figure 16. For example, increasing the PWHT temperature from 720 °C (1328 °F) to 780 °C (1463 °F) more than doubled the absorbed energy. Furthermore, increasing the holding time at this PWHT temperature from two hours to eight hours increased the absorbed energy from about 60 J to 90 J (44 ft-lbs to 66 ft-lbs). As shown in Figure 16, this PWHT temperature provides the desired weld metal toughness listed in 5.2.7. However, caution is normally observed to not exceed Ac_1 of the weld metal for the reasons described.

6.4.7 Hardness Testing of Production Welds

6.4.7.1 Extent of Production Hardness Testing

Typically production hardness testing of weld deposit and HAZ is performed using a portable Telebrineller hardness tester or equivalent. At least one test is done at 3 m (10 ft) intervals on each longitudinal and circumferential weld and all nozzle welds. For piping, all welds are usually hardness tested. Whenever possible, the production welds are tested on the process side. When this is not practical, testing can be done on the external surface.

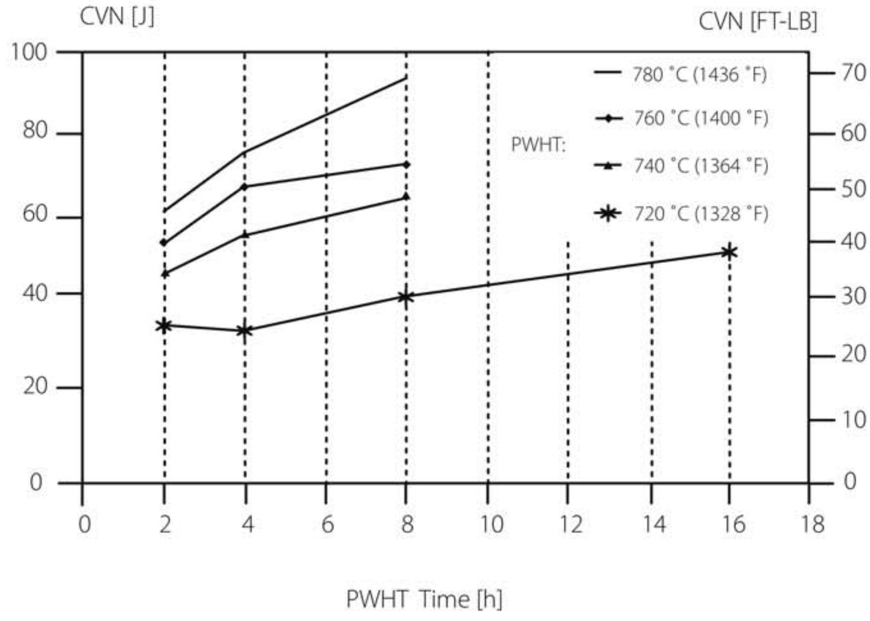

Figure 16—Influence of PWHT Temperature on Toughness of Grade 91 Filler Metal

It is important to indicate that production hardness testing result of HAZ is not quite representative as it is an average of the hardness of HAZ, base and weld metals. Therefore, some users do not require production hardness testing of HAZ especially when the welding procedure qualification (PQR) includes traverse micro-hardness testing as mentioned in paragraph 6.4.3.2.

6.4.7.2 Hardness Requirement

Recommended maximum allowable hardness is 248 HBW for process applications and 275 HBW 300 HBW for utility services. Welds failing the hardness test are typically re-heat treated (no more than two times) or removed, re-welded, heat treated and tested for hardness. Typical hardness (HV10) of P91 SMAW welds as a function of PWHT temperature and holding time is shown in Figure 17 [37].

6.4.8 Dissimilar Metal Welding

6.4.8.1 Joining to Carbon Steel or Low Cr-Mo Steels

Extreme care and planning is typically observed concerning post weld heat treatment of dissimilar metal weldments involving Grade 91. Because of the differing strength and PWHT requirements between the strong Grade 91 and carbon or other Cr-Mo steels, installation of transition piece, buttering and double PWHT are needed at materials change locations to minimize the effect of this strength mismatch, especially in the creep range.

The PWHT temperatures necessary for Grade 91 may exceed lower transformation temperatures for some of the lower strength alloys. In such cases, Grade 91 is oftentimes buttered with 2 $^{1}/_{4}$ Cr-1Mo filler metal or –B3 (or lower) type weld metal. Then PWHT is carried out at Grade 91 temperatures to temper the butter and HAZ of Grade 91 base metal. Then the weld of the buttered Grade 91 to the low alloy is made with the lower strength alloy, followed by a PWHT at temperatures appropriate to the lower alloy to temper the joining weld metal and new HAZ [37].

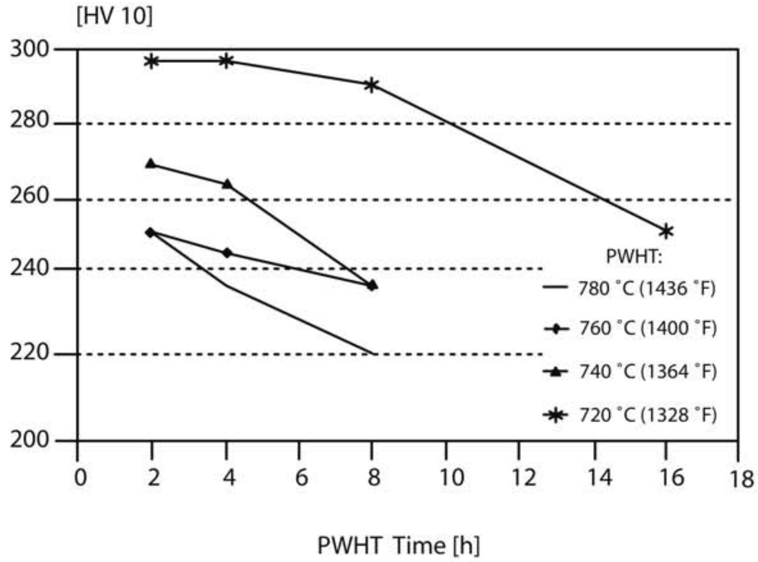

Figure 17—Influence of PWHT Temperature and Holding Time on Hardness of Grade 91 SMAW Weld Metal

6.4.8.2 Joining to Stainless Steel

Transition pieces or multiple buttering/PWHT operations may also be necessary when joining Grade 91 steel with austenitic stainless steels because sensitization may take place if PWHT is applied to stainless steel. In this case, Grade 91 is buttered with Ni-Cr-Fe filler metal, PWHT is performed at P91 PWHT temperature, and the weld to SS is completed using same filler metal. Further PWHT typically is not required [37].

6.4.8.3 Filler Metal Selection

Weld filler metal selection possibilities for dissimilar metal welding are shown in Table 11. When nickel base welding consumables (E/ERNiCrMo-3) are used, it is advisable that the manufacturer confirm that these filler metals will not embrittle at the high PWHT temperature of 9Cr-1Mo-V steel [37].

6.4.8.4 Post Weld Heat Treatment (PWHT)

PWHT temperature guidelines for dissimilar metal welds are included in Table 12 [37, 38].

6.4.9 Nondestructive Examination (NDE) of Production Welds

NDE is performed in accordance with ASME Section V [3] and the acceptable criteria per the applicable code. In general, personnel certified in accordance with ASNT SNT-TC-1A [27] perform NDE. Typically, NDE certifications and procedures are submitted to the purchaser for review and approval prior to the start of fabrication.

NDE includes the following examination methods.

6.4.9.1 Visual Examination (VT)

Visual examination is typically performed on all accessible surfaces of all completed welds.

Table 11—Dissimilar Welding Filler Metal Selection for 9Cr-1Mo-V Steels

P(T)	Material Grade							
	11	22	23	9	91	911	92	SS
91	B2	B3	G, Ni	B8, G	B9, Ni	B9, G	W, G, B9	Ni
911	B2	B3, G	G, B9	B8, G	B9, Ni	G	W, G, B9	Ni
92	B2	B3, G	G, B9	B8, G	B9, G	G, B9	W, G	Ni

Key

G	Nonstandard Composition
B2	1.25Cr-0.5Mo
B3	2.25Cr-1Mo
B8	9Cr-1 Mo
B9	9Cr-1Mo-V
W	Tungsten Modified
B	Boron Modified, etc.
Ni	Nickel Base ENiCrFe-2, ENiCrFe-3, ERNiCr-3
SS	Stainless, 308H, 309H, 316H, 347H, 16-8-2

Table 12—Guideline for PWHT Temperature for Dissimilar Metal Welds

P(T)	Material Grade							
	11	22	23	9	91	911	92	SS
	PWHT Temperature ºC (ºF)							
91	690 ± 14 [a] (1275 ± 25 [a])	732 ± 14 [a] (1350 ± 25 [a])	760 ± 14 [a] (1400 ± 25 [a])	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	670 ± 14 [a] (1400 ± 25 [a])
911	690 ± 14 [a] (1275 ± 25 [a])	732 ± 14 [a] (1350 ± 25 [a])	760 ± 14 [a] (1400 ± 25 [a])	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	670 ± 14 [a] (1400 ± 25 [a])
92	690 ± 14 [a] (1275 ± 25 [a])	732 ± 14 [a] (1350 ± 25 [a])	760 ± 14 [a] (1400 ± 25 [a])	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 (1400 ± 25)	760 ± 14 [a] 1400 ± 25 [a])

[a] Buttering on Cr-Mo steel side is required.

6.4.9.2 Magnetic Particle Examination (MT)

Typically, MT is performed on completed welds, hot root pass welds, back gouged areas (base metal and welds). Locations of weld spatter, arc strike, burns, etc. are usually required to be cleaned by grinding prior to MT.

6.4.9.3 Liquid Penetrant Examination (PT)

In general, PT may replace MT, when examined area is cooled almost to ambient temperature. However, MT is preferred.

6.4.9.4 Ultrasonic Examination (UT)

When 100 % RT is required, critical welds such as nozzles to shell welds are typically examined using UT. In addition, when permitted by the code and purchaser's specifications, UT may be used in lieu of radiography.

6.4.9.5 Radiography (RT)

A 100 % RT testing is commonly specified for full penetration groove welds of all items fabricated from 9Cr-1Mo-V alloy steels. RT of fillet and T-type configurations welds is not practical in most cases, so other NDE methods such as UT are used.

6.4.10 Weld Repairs

The following guidelines are typically practiced for repairs of Grade 91 steels welds.

a) Weld repair procedure is submitted to the purchaser prior to weld repair. This repair procedure to include as a minimum the following information:

- method of excavating defect from weld;
- NDE method used to verify complete defect removal;
- ASME WPS/PQR to be used for weld repair or reference is made to the originally approved welding documents;
- NDE method to be used to verify that the repaired weld is acceptable;
- DHT and/or PWHT procedures to be used.

b) Unacceptable discontinuities are completely removed by chipping, gouging, or grinding to clean, sound metal.

c) The excavated area is examined by magnetic particle or liquid penetrant methods to assure complete removal of defects.

d) Repairs to correct weld defects are made using the same WPS used for the original weld or other previously approved WPS.

e) The repaired area is re-examined using the same examination method and procedure by which the defect was originally detected.

f) Two repair attempts are allowed on any one defective area. No further repair attempt is typically allowed without purchaser/owner's written approval.

g) Any weld repaired area is to be post weld heat treated as indicated on the WPS for Grade 91 base metal.

7 Examples of 9Cr-1Mo-V Applications and Refinery Experiences

7.1 Experiences

NACE REFIN-COR 6.0 Survey [35] for uses of 9Cr-1Mo-V steel in refinery applications is summarized in Table 13.
In addition, Table 14 summarizes cases where Grade P91/T91 materials have been used and the experiences with their use, if available.

7.2 Applications

Grade 91 steel can be considered for steam and other non-H_2S services in refineries. In refinery process units, where H_2S is present, such as in coker, crude and vacuum heaters, Grade 91 has been used with a maximum weld hardness of 235 HBW achievable. However, it seems that the economic benefits for using Grade 91 in low pressure applications are not great enough to justify its use. For heavy wall vessels in H_2S containing services, Grade 91 seems to offer little advantage over the 2 $^1/_4$ Cr-1Mo and 3Cr-1Mo steels (either conventional or V-modified) if it must also be weld overlaid or cladded with SS, considering the wealth of good experience with the 2 $^1/_4$ Cr-1Mo and 3Cr-1Mo steels. However, Grade 91 may be considered for heavy wall equipment in steam and non-H_2S services.

Table 13—Case Histories of Grade 91 Refinery Uses Reported in NACE REFIN-COR

ITEM No.	UNIT	Use or Service
94C5.3-03	Coker	Asked if anyone was using T-91 (modified 9Cr). If so, weld hardness limits may need to be revised from those typically used for conventional 9 Cr. He noted that if you were to use matching filler material for T-91, weld hardness will be high.
94F5.3-14	Coker	Asked whether anyone was considering T-91 steels (vanadium-modified 9Cr-1Mo) for coke drums, in lieu of clad drums.
94F5.3-15	Coker	Responded had considered T-91 when replacing four drums recently. The advantage was to avoid clad cracking by eliminating cladding. However, did not use it, because coke drum cyclic service has some conditions that may cause wet H_2S cracking. Were concerned that T-91 would be susceptible to this problem.
95F5.16-02	General	Have used T-91 for coker furnace tubes. Did not have any problems during fabrication. It was important to use proper preheats.
97F5.8-01	Hydrogen Plant	Asked whether anyone has experience with using P91 (9Cr-1Mo-V) material for inlet header and pigtails. The particular concern was about weldability.
97F5.8-02	Hydrogen Plant	Responded that were problems fabricating P91 for a hydrogen plant. It was heater tubing in a waste heat recovery unit, field fabricated by Far East Contractor. There were hardness problems with the welds, and some delayed hydrogen cracking was experienced in the welds. The welds all had to be ground out and rewelded. There was no problem with similar welds made in the shop rather than the field.
97F5.8-03	Hydrogen Plant	Recently P91 was used for stream super heaters. This was done in the U.S. for a domestic plant with no welding problems after good preparation work.
99F5.2-22	Crude and Vacuum	Starting up a 9Cr furnace in a vacuum unit. The furnace will be running 4 to 5 wt % S bitumen. For some reason, the last two tubes have been specified as T91 tube metallurgy due to velocity concerns. The understanding is that T91 is thought to be more resistant to the higher velocities in a sulfidic corrosion environment. Does anyone have experience with this metallurgy as being more sulfidation-resistant, because he cannot find data to support this claim?
00C5.17-32	General	Asked who has used P91 material in other than steam service.
00C5.17-33	General	Have used P91 in a bitumen furnace in a vacuum heater now in service the last six months.
00C5.17-34	General	Has been considerable discussion on this material, which can be found in REFIN*COR. They have presented a paper on this in the past (98809), which highlighted high hardness and welding problems.
00C5.17-35	General	T91 tubes seen in a catalytic reformer. During an upset they were austenitized and quenched that resulted in very high hardnesses. Yet the tubes are still in service. EPRI has a survey on the use of T91 in industry.
00C5.17-36	General	In a refinery where these tubes were used and the refinery wished they did not have them, as they do not know how to do weld repairs.
2000F5.2-14	Crude and Vacuum	A paper given at CORROSION a few years ago. It was published that there were some issues with high hardness and concern for SSC in a coker heater. API is writing a technical report looking at modified 9Cr and where they can and cannot be used, and fabrication issues. Also, a worldwide survey is being conducted by EPRI on the effects of modified 9Cr on where and how it is used and problems. Asked for a show of hands, has anyone used T91 or P91? The response was 4 or 5 in North America.
2001F5.18-14	General	Asked who uses 91 grades for vessels. Up to now it's been used in high-temperature steam service and some heater tubes. It is being considered for a vessel. They feel they can weld it and ensure HB 237 maximum hardness. There was no response.
2002C5.4-13, 14 & 15	Coker	Reported that in licensed coker units, 9Cr is specified for various exchanger components. 9Cr plate material does not have design allowables in the Code up to the temperatures you need. The heat exchanger fabricators assume you want P91. They have had exchangers go pretty far down the road with P91 in the design to a point that things could not be changed. They imposed a very strict specification on the P91 welding and they met it. They met a 237 max Brinell and they feel this will be fine for service. They probably would not do that intentionally again in the future. It just shows you that we will have to use other alternatives to the 9Cr for those kinds of applications. Comment: If you have the allowable stresses in one product form, you can transfer the allowable stresses from one product form to another product form by CC. Comment: It seems this fabricator did not assume they could do that.

Table 14—Additional Case History for Using Grade P91/T91 Steel

Process Unit	Application	Year Installed	Service	Experience
Coker	Heater Tubes	Before 1995	Feed Heater	No problems during fabrication with good preheat
Coker	Heater Tubes	Before 1996	Feed Heater	Concerned with SSC in future
Hydrogen	Heat Recovery Tubing	Before 1997	Syn Gas/Steam Exchanger	High hardness and delayed hydrogen cracking
Hydrogen	Heat Recovery Tubing	Approximately 2001	Syn Gas/Steam Exchanger	
Vacuum	Bitumen Furnace	1999	Bitumen	
Cat Reformer	Heater Tubes	Before 2000	Feed Heater	Overheated and quenched during operation-high hardness. Still in use.

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[5] ASME *Boiler and Pressure Vessel Code*; *Section IX*, *Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*

[6] ASME SA-182, *Specification for Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service*

[7] ASME SA-213, *Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes*

[8] ASME SA-234, *Specification for Piping Fittings of Wrought Carbon Steel and Alloy for Moderate and High-Temperature Service*

[9] ASME SA-240, *Heat-Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels*

[10] ASME SA-312, *Seamless and Welded Austenitic Stainless Steel Pipe*

[11] ASME SA-335, *Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service*

[12] ASME SA-336, *Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts*

[13] ASME SA-369, *Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service*

[14] ASME SA-376, *Seamless Austenitic Steel Pipe for High-Temperature Central-Station Service*

[15] ASME SA-387, *Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum*

[16] ASME SA-403, *Wrought Austenitic Stainless Steel Piping Fittings*

[17] ASME SA-541, *Quenched and Tempered Carbon and Alloy Steel Forgings for Pressure Vessel Components*

[18] ASME SA-542, *Pressure Vessel Plates, Alloy Steel, Quenched and Tempered, Chromium-Molybdenum and Chromium-Molybdenum-Vanadium*

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