

Rev. 13

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

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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 [136, 237]. This was achieved through the controlled additions of vanadium (V), Nb and nitrogen (N) to become Grade 91. Later, the carbon **concentration** in Grade 91 **steel** 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 [320] 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 for applications up to 649 °C (1200 °F) and Division 2 for applications up to 482 °C (900 °F)** [4]. 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 1/4Cr-1Mo (Grade 22) and even **stainless steels**.

Grade 91 steel **exhibits** good corrosion resistance to sulfidation and oxidation. However, because this high strength material could have **a** relatively high weld hardness, the use of this alloy, especially in refinery environments where hydrogen sulfide is present, **is not recommended**. **In addition**, the negligible economic benefits **generally** do not justify **their** use **in** low pressure applications.

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

1 Scope

This report is applicable only to 9Cr-1Mo-V (Grade 91) steel, which is the most commonly used grade of 9Cr high-strength steels in the oil refining and petrochemical industries compared to other grades, including 9Cr-1Mo-1W-Cb (Grade 911), 9Cr-2W (Grade 92), and 9Cr-3W-3Co-Nd-B (Grade 93). Grade 92 and Grade 911 steels have been used in the power generation industry but are generally not used in the oil refining or petrochemical industry. Grade 93 steel is newer and has rarely been used in practical applications to date. Therefore, these steels were excluded from this study. However, some data on these steels were included for comparison with the Grade 91 steel.

This report provides a brief overview of the industrial applications of Grade 91 steel. Revisions to ASME design rules are highlighted. With an emphasis on Grade 91 steel, this report covers the basic material and metallurgical properties, including a summary of the physical and mechanical properties, corrosion resistance, and oxidation resistance, indicating possible corrosion and/or mechanical failure mechanisms and how to avoid them. Appropriate heat treatment of the base metal and welds is also provided.

Discussions on the guidelines and rationale for the specifications for Grade 91 steel base metals and welding consumables are provided. Special considerations for the successful fabrication of Grade 91 steel, including welding, heat treatment, and nondestructive testing, are also provided.

Experiences of using Grade 91 steel in the oil refining and petrochemical industries are summarized. Research and trials on materials and fabrication of Grade 91 steel heavy-walled pressure vessels are also reviewed.

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

Weldment	Weld deposit, base metal heat affected zones and adjacent base metal zones subject to residual stresses from welding.
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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
ESR	electro-slag re-melting

ESW	electro-slag welding
FATT	fracture appearance transition temperature
FCAW	flux core arc welding
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HAZ	heat affected zone
HBW	Brinell hardness number using tungsten ball indenter
HV	Vickers hardness number
L.M.P.	Larson-Miller parameter $T \times (C + \log t)$ (C = constant (typically, 20 or 22)), T = temperature in Kevin, t = time in hour)
MT	magnetic particle testing
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
VT	visual testing
UT	ultrasonic testing
WPS	welding procedure specification

2.3 Symbols

A_{c1}	temperature at which austenite begins to form during heating
A_{c3}	temperature at which transformation of ferrite to austenite is completed during heating
	chromium equivalent
M_s	start temperature of martensitic transformation
M_f	finish temperature of martensitic transformation
σ	creep-rupture strength

3 Industrial Application

Figure 1 shows the typical temperatures and pressures at which the Grade 91 steel is used. Grade 91 steel has primarily been used to make pipes and tubes for steam services, typically in coal- and natural-gas-fired power plants, since the mid 1980s [5, 6]. This steel is currently used for steam services in oil refineries and petrochemical plants. Grade 91 steel is sometimes used for process services in refineries, such as feed heater tubes. Owing to its inherently high hardness, the use of steel in wet H₂S service is generally not recommended.

However, there is limited experience in using Grade 91 steel in pressure vessels. The use of Grade 91 steel for heavy-walled hydroprocessing reactors was discussed at the API task group meetings in the late 2010s, although such applications have not yet been achieved.

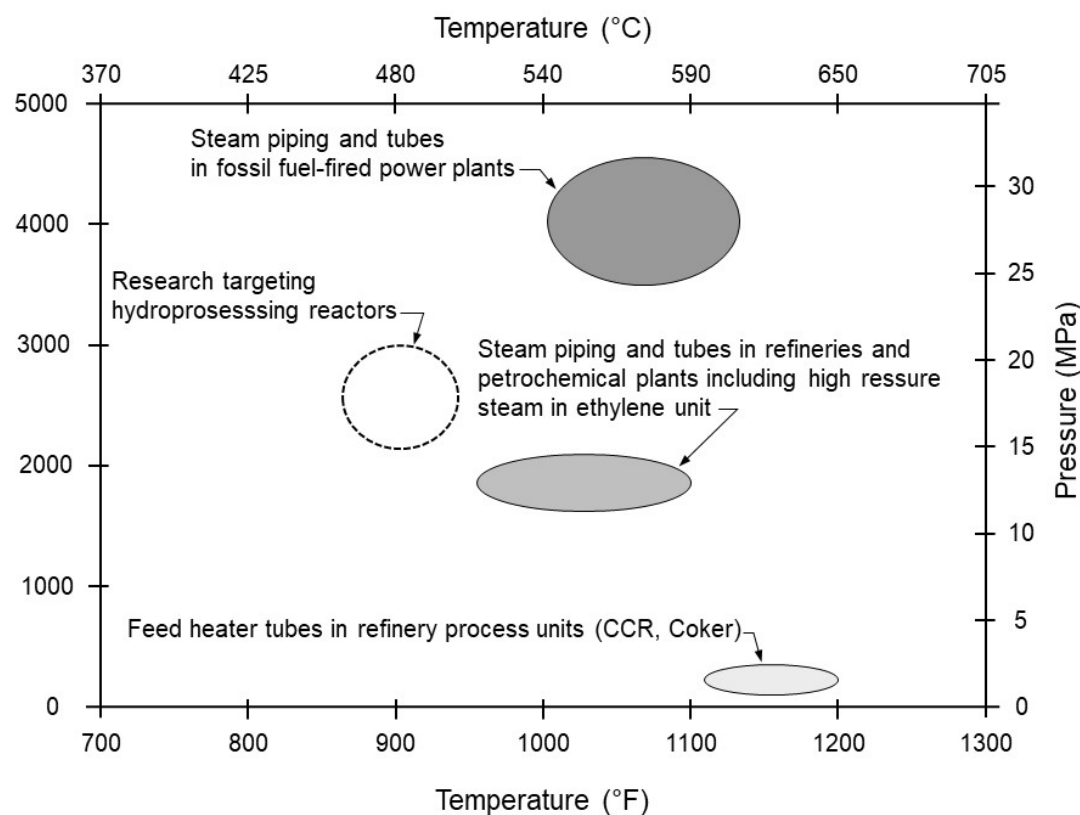


Figure 1—Typical temperatures and pressures at which Grade 91 steel is used

4 Design Considerations

4.1 Allowable Stresses

Before 2019, Grade 91 steel had two sets of allowable stresses in the creep temperature range, depending on whether the thickness exceeded 75 mm (3 in) [7]. In 2019, both sets of allowable stresses were reduced, and a combined set of allowable stresses was defined [8]. These values were then assigned to the current Grade 91 Type 1 steel [4], which has a chemical composition previously specified for Grade 91. In parallel, another set of allowable stresses was approved in CC2864-1 [9] for a controlled chemical composition, which is now known as Type 2 (refer to Section 5.2). It should be noted that the Type 2 chemical composition affects design temperatures at or above 538 °C (1000 °F), offering 1–7 % higher allowable values compared to those for the Type 1 chemical composition.

Figure 2 shows the allowable stress values above 482 °C (900 °F) based on ASME specification SA-335 P91 defined in Table 1A of ASME Section II, Part D in the 2017 [7] and 2021 [10] editions. As of this writing, these revisions have been incorporated into ASME B31.1-2022 [11] but not into ASME B31.3-2022 [12].

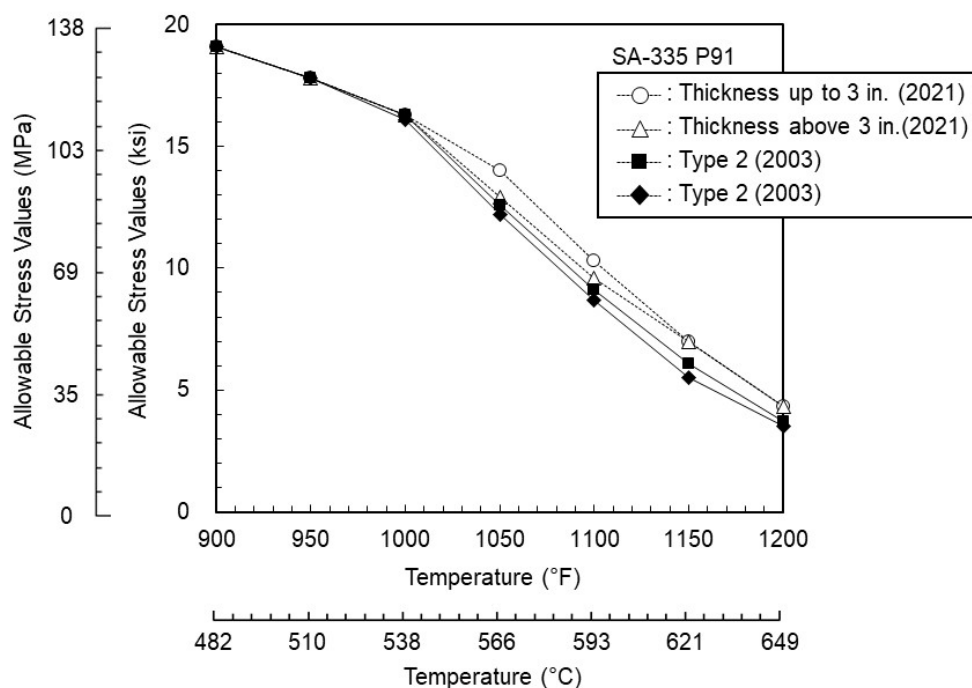


Figure 2—Allowable stress values above 482 °C (900 °F) for SA-335 P91 defined in Table 1A of ASME Section II, Part D in 2017 [7] and 2021 [10] editions

4.2 Weld Joint Strength Reduction Factor

The cross-weld creep-rupture strengths of various alloy steels have been shown to be inferior to those of the base metal [13]. For that reason, the weld joint strength reduction factor (WJSRF), which is the ratio of the strength of the welds to that of the base metal, is employed in the design to consider the reduction in the creep strength of the welds. WJSRF is to address the inherent material properties of welds at elevated temperatures.

ASME B31.1 [11] and B31.3 [12] mandate the application of WJSRF in the design of longitudinal or spiral welds in piping. Similarly, ASME Section I [14] defines it for longitudinal welds of cylindrical or hemispherical components. ASME codes that provide WJSRF values do not explicitly require application of these WJSRFs to circumferential welds. **Figure 3** shows the weld joint strength reduction factor for Grade 91 steel. These factors are not specified in ASME Section VIII Divisions 1 and 2 [15, 16].

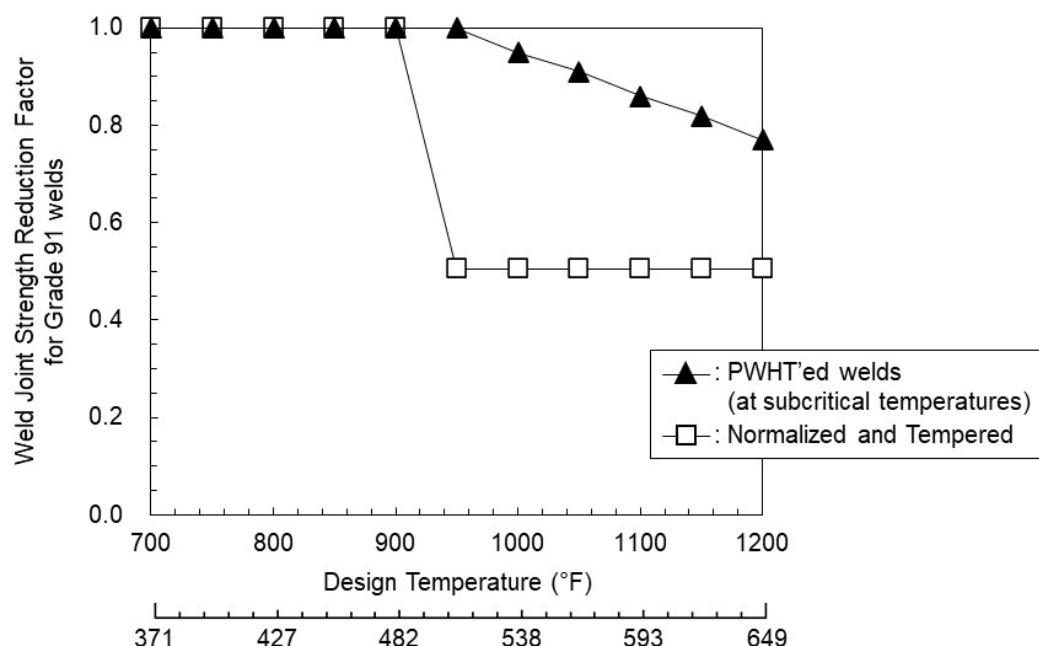


Figure 3—Weld joint strength reduction factors for Grade 91 steel as specified in ASME B31.1 [11], B31.3 [12], and Section I [14]

5 Chemical, Physical, Mechanical and Metallurgical Properties

5.1 General

In order to clarify the advantages of using the **Grade 91 steel**, the chemical composition, physical, mechanical and metallurgical properties including allowable stress and design stress intensity values are summarized in the following sections. Comparisons with **other relevant alloy steels** are also provided in some cases. **Table 1** lists ASME material specifications for conventional **9Cr-1Mo (Grade 9)**, **Grade 91** and other **9Cr high strength** steel plates, forgings, fittings, pipe, and tubes [17]. The relevant **Code Cases (CCs)** [18–25] are also included.

5.2 Chemical Composition of Base Metal

Table 2 gives the chemical composition of **Grade 9**, **Grade 91** and other **9Cr high-strength steels** listed in ASME Section II, Part A [172] and the relevant CCs [21, 23]. This list applies to all product forms of **these steels**. The main difference between **Grade 91** and **Grade 9 steel** is the controlled addition of vanadium (V), **niobium (Nb)** and nitrogen (N). In addition, the carbon **concentration** of Grade 91 material is limited to a range from 0.08 % to 0.12 %, compared with **Grade 9 steel**, which limits carbon **concentration** to 0.15 % maximum.

ASME material specifications define two sets of chemical compositions for Grade 91 steel wrought products. Type 1 specifies the control of 14 elements, whereas Type 2 specifies 20 elements. Type 2 specifies narrower ranges for manganese (Mn), sulfur (S), silicon (Si), nickel (Ni), N, and aluminum (Al). It also specifies maximum limits for boron (B), tungsten (W), copper (Cu), tin (Sn), antimony (Sb), and arsenic (As), which are not included in the Type 1 specifications. In addition to the control of individual elements, a minimum N:Al ratio of 4 is adopted for Type 2 [26]. These additional restrictions for Type 2 steels are related to the higher allowable stresses assigned to Type 2 steels above 510 °C (950 °F). **Figure 4** shows the relationship between the levels of Ni and Al present in ex-service Grade 91 steels [27].

The Type 2 chemical composition was obtained through statistical analysis of the base metal creep data and is therefore not intended for weld metals.

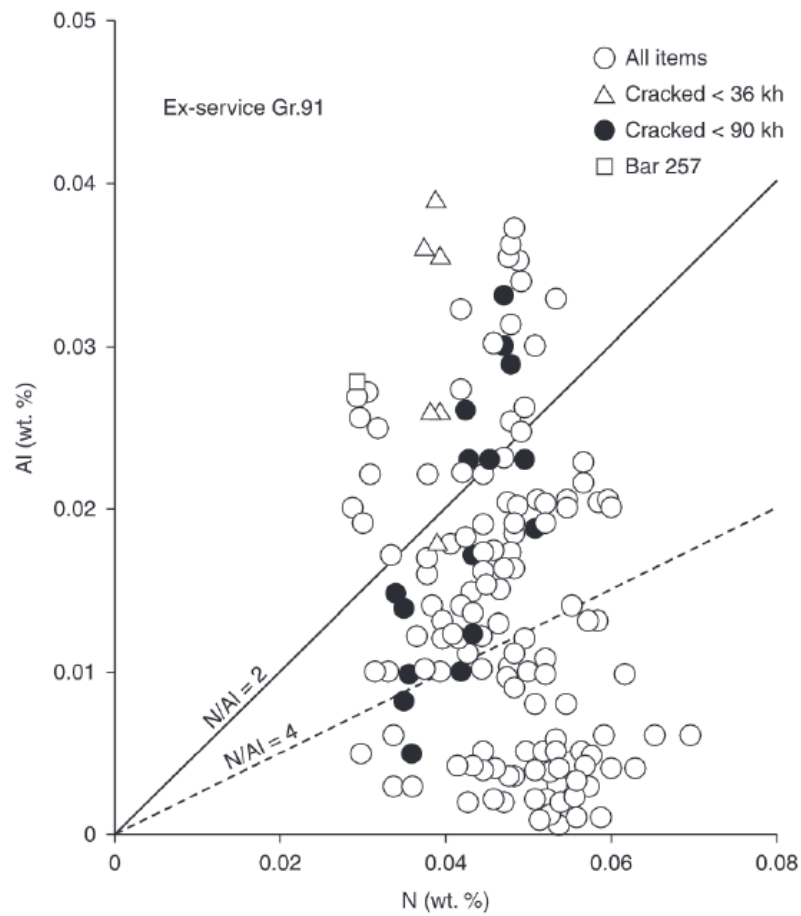


Figure 4—Relationship between Al and N present in ex-service Grade 91 steels (data points represented with solid symbols experienced Type IV (refer to Section 6.7) cracking during service)

Table 1—Specifications and Code Cases for Grade 91 and other 9Cr high-strength steels

ASME Specification or Code Case	Title
SA-182 (Grades F91, 911, 92 and 93) [17]	Standard Specification for Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service
SA-213 (Grades T91, 911, 92 and 93) [17]	Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes
SA-234 (Grades WP91, 911 and 92) [17]	Standard Specification for Piping Fittings of Wrought Carbon Steel and Alloy Steel for Moderate and Elevated Temperature Service
SA-335 (Grades P91, 911 and 92) [17]	Standard Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service
SA-336 (Grades F91, 911 and 92) [17]	Standard Specification for Alloy Steel Forgings for Pressure and High Temperature Parts
SA-369 (Grades FP91 and 92) [17]	Standard Specification for Carbon and Ferritic Alloy Steel Forged and Bored Pipe for High-Temperature Service
SA-387 (Grade 91) [17]	Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum
SA-691 (Grade 91) [17]	Standard Specification for Carbon and Alloy Steel Pipe, Electric-Fusion-Welded for High-Pressure Service at High Temperatures
CC1943-1 (Grade 91) [18]	Seamless Modified 9Cr-1Mo, Section I
CC1973-2 (Grade 91) [19]	9Cr-1Mo-V Material, Section VIII, Division 2
CC 2179-11 (Grade 92) [20]	9Cr-2W, UNS K92460 Material, Section I, Section VIII, Division 1
CC 2327-3 (Grade 911) [21]	9Cr-1Mo-1W-Cb Material, Section I
CC 2815-1 (Grade 91) [22]	Use of SA-336/SA-336M Class F91 for Class 2, Section VIII, Division 2
CC 2839-2 (Grade 93) [23]	9Cr-3W-3Co-Nd-B Material, Section I
CC 2864-3 (Grade 91 Type 2) [24]	9Cr-1Mo-V Material, Section I
B31 Case 215 (Grade 91 Types 1 and 2) [25]	9Cr-1Mo-V Material Compositions, ASME B31.1

Table 2—Chemical composition (heat analysis) of Grade 9, Grade 91 and other 9Cr high-strength steels

Product Form	Spec. or CC	Grade, Type	UNS Designation	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	Nb	Ti	N	Al	B	Other elements
Forgings	SA-182 [17]	F9	K90941	0.15	0.30–0.60	0.030	0.030	0.50–1.00	—	—	8.0–10.0	0.90–1.10	—	—	—	—	—	—	—
		F91 Type 1	K90901	0.08–0.12	0.30–0.60	0.020	0.010	0.20–0.50	0.40	—	8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	0.01	0.03–0.07	0.02	—	Zr: 0.01 max.
		F91 Type 2	K90901	0.08–0.12	0.30– <u>0.50</u>	0.020	<u>0.005</u>	0.20– <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0–9.5	0.85–1.05	0.18–0.25	0.060–0.10	0.01	<u>0.035–0.070</u>	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		F911	K91061	0.09–0.13	0.30–0.60	0.020	0.010	0.10–0.50	0.40	—	8.5–9.5	0.90–1.10	0.18–0.25	0.060–0.10	0.01	0.04–0.09	0.02	0.0003–0.006	Zr: 0.01 max. W: 0.90–1.10
		F92	K92460	0.07–0.13	0.30–0.60	0.020	0.010	0.50	0.40	—	8.50–9.50	0.30–0.60	0.15–0.25	0.04–0.09	0.01	0.030–0.070	0.02	0.001–0.006	Zr: 0.01 max. W: 1.50–2.00
		F93	K91350	0.05–0.10	0.20–0.70	0.020	0.008	0.05–0.50	0.20	—	8.50–9.50	—	0.15–0.30	0.05–0.12	—	0.005–0.015	0.030	0.007–0.015	Co: 2.5–3.5 W: 2.5–3.5 Nd: 0.010–0.06 O: 0.0050 max.
Seamless Tubes	SA-213 [17]	T9	K90941	0.15	0.30–0.60	0.025	0.025	0.25–1.00	—	—	8.00–10.00	0.90–1.10	—	—	—	—	—	—	—
		T91 Type 1	K90901	0.07–0.14	0.30–0.60	0.020	0.010	0.20–0.50	0.40	—	8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	0.01	0.030–0.070	0.02	—	Zr: 0.01 max.
		T91 Type 2	K90901	<u>0.08–0.12</u>	0.30– <u>0.50</u>	0.020	<u>0.005</u>	0.20– <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	0.01	<u>0.035–0.070</u>	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		T911	K91061	0.09–0.13	0.30–0.60	0.020	0.010	0.10–0.50	0.40	—	8.5–9.5	0.90–1.10	0.18–0.25	0.06–0.10	0.01	0.040–0.090	0.02	0.0003–0.006	Zr: 0.01 max. W: 0.90–1.10
		T92	K92460	0.07–0.13	0.30–0.60	0.020	0.010	0.50	0.40	—	8.5–9.5	0.30–0.60	0.15–0.25	0.04–0.09	0.01	0.030–0.070	0.02	0.001–0.006	Zr: 0.01 max. W: 1.5–2.00
		T93	K91350	0.05–0.10	0.20–0.70	0.020	0.008	0.05–0.50	0.20	—	8.50–9.50	—	0.15–0.30	Nb + Ta: 0.05–0.12	—	0.005–0.015	0.030	0.007–0.015	Co: 2.5–3.5 W: 2.5–3.5 Nd: 0.010–0.060 O: 0.0050 max.
Pipe Fittings	SA-234 [17]	WP9	K90941	0.15	0.30–0.60	0.030	0.030	1.00 max.	—	—	8.0–10.0	0.90–1.10	—	—	—	—	—	—	—
		WP91 Type 1	K90901	0.08–0.12	0.30–0.60	0.020	0.010	0.20–0.50	0.40	—	8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	0.01	0.03–0.07	0.02	—	Zr: 0.01 max.
		WP91 Type 2	K90901	0.08–0.12	0.30– <u>0.50</u>	0.020	<u>0.005</u>	0.20– <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0–9.5	0.85–1.05	0.18–0.25	0.06–0.10	0.01	<u>0.035–0.070</u>	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		WP911	K91061	0.09–0.13	0.30–0.60	0.020	0.010	0.10–0.50	0.40	—	8.5–9.5	0.90–1.10	0.18–0.25	0.060–0.10	0.01	0.04–0.09	0.02	0.0003–0.006	Zr: 0.01 max. W: 0.90–1.10
		WP92	K92460	0.07–0.13	0.30–0.60	0.020	0.010	0.50	0.40	—	8.50–9.50	0.30–0.60	0.15–0.25	0.04–0.09	0.01	0.030–0.070	0.02	0.001–0.006	Zr: 0.01 max. W: 1.50–2.00
Seamless Pipe	SA-335 [17]	P9	K90941	0.15	0.30–0.60	0.025	0.025	0.25–1.00	—	—	8.00–10.00	0.90–1.10	—	—	—	—	—	—	—
		P91 Type 1	K90901	0.08–0.12	0.30–0.60	0.020	0.010	0.20–0.50	0.40	—	8.00–9.50	0.85–1.05	0.18–0.25	0.06–0.10	0.01	0.030–0.070	0.02	—	Zr: 0.01 max.
		P91 Type 2	K90901	0.08–0.12	0.30– <u>0.50</u>	0.020	<u>0.005</u>	0.20– <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.00–9.50	0.85–1.05	0.18–0.25	0.06–0.10	0.01	<u>0.035–0.070</u>	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		P911	K91061	0.09–0.12	0.30–0.60	0.020	0.010	0.10–0.50	0.40	—	8.5–9.5	0.90–1.10	0.18–0.25	0.060–0.10	0.01	0.04–0.09	0.02	0.0003–0.006	Zr: 0.01 max. W: 0.90–1.10
		P92	K92460	0.07–0.13	0.30–0.60	0.020	0.010	0.50 max.	0.40	—	8.50–9.50	0.30–0.60	0.15–0.25	0.04–0.09	0.01	0.03–0.07	0.02	0.001–0.006	Zr: 0.01 max. W: 1.50–2.00

Table 2—Continued

Product Form	Spec. or CC	Grade, Type	UNS Designation	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	Nb	Ti	N	Al	B	Other elements
Forgings	SA-336 [17]	F9	K90941	0.15	0.30 – 0.60	0.025	0.025	0.50 – 1.00	—	—	8.0 – 10.0	0.90 – 1.10	—	—		—	—	—	—
		F91 Type 1	K90901	0.08–0.12	0.30 – 0.60	0.025	0.025	0.20 – 0.50	0.40	—	8.0 – 9.5	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	0.03 – 0.07	0.02	—	Zr: 0.01 max.
		F91 Type 2	K90901	0.08 – 0.12	0.30 – <u>0.50</u>	0.020	<u>0.005</u>	0.20 – <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0 – 9.5	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	<u>0.035</u> – 0.070	0.02	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		F911	K91061	0.09 – 0.13	0.30 – 0.60	0.020	0.010	0.10 – 0.50	0.40	—	8.5 – 9.5	0.90 – 1.10	0.18 – 0.25	0.06 – 0.10	0.01	0.04 – 0.09	0.02	0.0003 – 0.006	Zr: 0.01 max. W: 0.90 – 1.10
		F92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max.	0.40	—	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.01	0.030 – 0.070	0.02	0.001 – 0.006	Zr: 0.01 max. W: 1.50 – 2.00
Forged & Bored Pipe	SA-369 [17]	FP9	K90941	0.15	0.30 – 0.60	0.030	0.030	0.50 – 1.00	—	—	8.0 – 10.00	0.90 – 1.10	—	—		—	—	—	—
		FP91 Type 1	K90901	0.08–0.12	0.30 – 0.60	0.025	0.025	0.20 – 0.50	0.40	—	8.0 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	0.03 – 0.07	0.02	—	Zr: 0.01 max.
		FP91 Type 2	K90901	0.08 – 0.12	0.30 – <u>0.50</u>	0.020	<u>0.005</u>	0.20 – <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	<u>0.035</u> – 0.070	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
		FP92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50 max.	0.40	—	8.50 – 9.50	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.01	0.030 – 0.070	0.02	0.001 – 0.006	Zr: 0.01 max. W: 1.50 – 2.00
Plate	SA-387 [17]	9	K90941	0.15.	0.30 – 0.60	0.025	0.025	1.00 max.	—	—	8.00 – 10.00	0.90 – 1.10	0.40 max.	—		—	—	—	—
		91 Type 1	K90901	0.08–0.12	0.30 – 0.60	0.020	0.010	0.20 – 0.50	0.40	—	8.00 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	0.030 – 0.070	0.02	—	Zr: 0.01 max.
		91 Type 2	K90901	0.08 – 0.12	0.30 – <u>0.50</u>	0.020	<u>0.005</u>	0.20 – <u>0.40</u>	<u>0.20</u>	<u>0.10</u>	8.0 – 9.50	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	0.01	<u>0.035</u> – 0.070	<u>0.020</u>	<u>0.001</u>	Zr: 0.01 max. W: <u>0.05 max.</u> Sn: <u>0.010 max.</u> Sb: <u>0.003 max.</u> As: <u>0.010 max.</u> N/Al: <u>4.0 min.</u>
	SA-1017 [17]	911	K91061	0.09 – 0.13	0.30 – 0.60	0.020	0.010	0.10 – 0.50	0.40	—	8.5 – 9.5	0.90 – 1.10	0.18 – 0.25	0.06 – 0.10	0.01	0.04 – 0.09	0.02	0.0003 – 0.006	Zr: 0.01 max. W: 0.90 – 1.10
		92	K92460	0.07 – 0.13	0.30 – 0.60	0.020	0.010	0.50	0.40	—	8.5 – 9.5	0.30 – 0.60	0.15 – 0.25	0.04 – 0.09	0.01	0.030 – 0.070	0.02	0.001 – 0.006	Zr: 0.01 max. W: 1.50 – 2.00
CC2327-3 [21]		Grade 911	K92460	0.09 – 0.13	0.30 – 0.60	0.020	0.010	0.10 – 0.50	0.40	—	8.5 – 9.5	0.90 – 1.10	0.18 – 0.25	0.060 – 0.100	0.01	0.040 – 0.090	0.02	0.0003 – 0.006	Zr: 0.01 max. W: 0.90 – 1.10
CC2839-2 [23]		Grade 93	K91350	0.05 – 0.10	0.20 – 0.70	0.020	0.008	0.05 – 0.50	0.20	—	8.50 – 9.50	—	0.15 – 0.30	Nb + Ta: 0.05 – 0.12	—	0.005 – 0.015	0.030	0.007 – 0.0015	Co: 2.5 – 3.5 W: 2.5 – 3.5 Nd: 0.010–0.060 O: 0.0050 max.

5.3 Physical Properties

Table 3 provides the physical properties used for design purposes. **Figures 5** and **6** compare the thermal conductivity and mean coefficient of linear expansion versus temperature for **Grade 91**, 2 1/4 Cr-1Mo (**Grade 22**) steels and 304H SS [28]. The **Grade 91** steel has higher thermal conductivity than **Type 304H SS** but lower than **Grade 22** steel. The **Grade 91** steel has a lower mean coefficient of linear expansion than **Type 304H SS** and **Grade 22** steel. **Figure 7** shows the modulus of elasticity of Grade 91 steel vs. temperature [2838].

Table 3—Physical properties of Grade 91 steel vs. temperature

Temperature °C (°F)	Modulus of Elasticity GPa (10 ² ksi)	Thermal Conductivity W/m K (Btu/ft ² hr °F/in.)	Coefficient of L. Expansion Between Room Temperature and Indicated Temperature 10 ⁻⁶ /°K (10 ⁻⁶ /°F)	Specific Heat Capacity J/Kg °K (Btu/lb °F)	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)	—

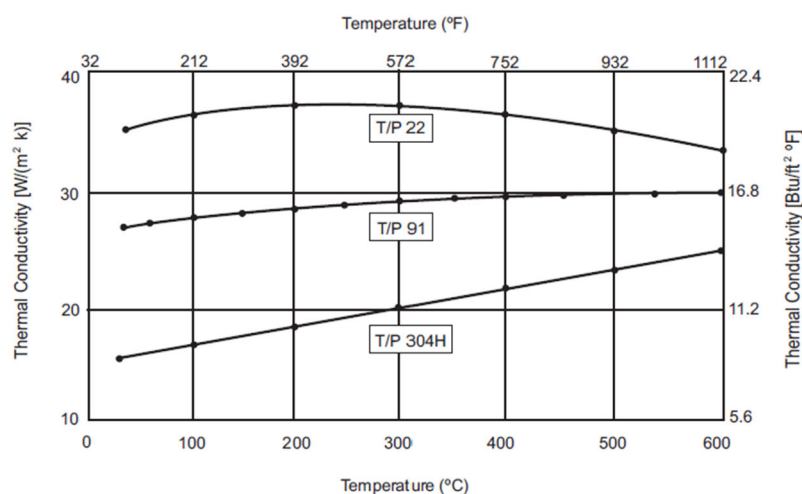


Figure 5—Thermal conductivity

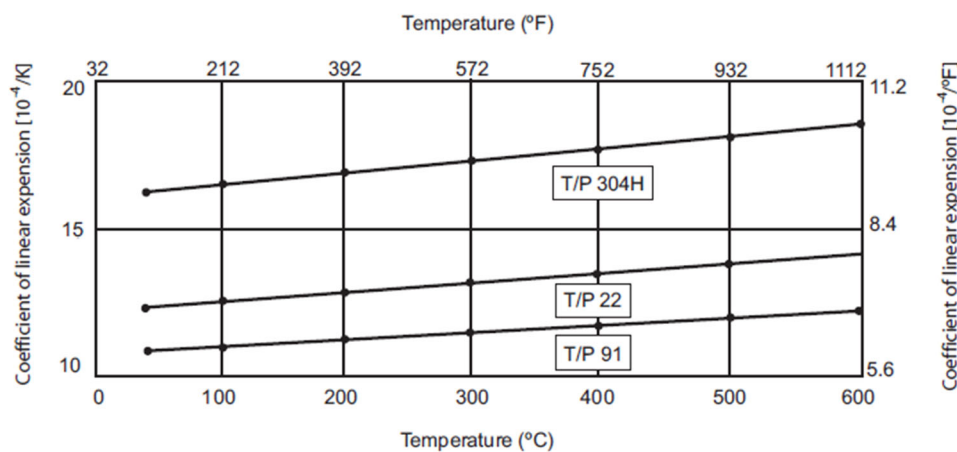


Figure 6—Mean coefficient of linear expansion

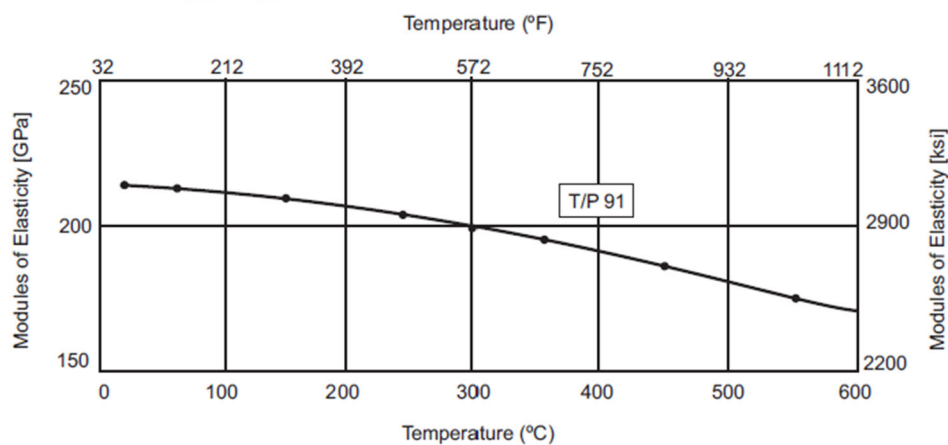


Figure 7—Modulus of elasticity vs. temperature

5.4 Metallurgical Properties

5.4.1 Transformation Data

Grade 91 steel is a deep hardening steel. **Figure 8** shows the Jominy end quench HRC hardness test results for 101.6 mm (4 in.) long bars of Grade 91 and 22 steels of approximately the same carbon concentration [2939, 3040]. A metallurgical investigation showed that the critical cooling rate to obtain 100 % Martensite is about 0.2 °C/s (0.36 °F/s) [2939]. Depending on the chemical composition, the Ac₁ was found to be as low as 785 °C (1445 °F) with most values between 800 °C (1470 °F) and 830 °C (1530 °F). The Ac₃ temperature was found to be in the range of 890 °C (1635 °F) and 940 °C (1725 °F) [2838]. **Figure 9** shows the relationship between the Ni + Mn concentration and Ac₁ in Grade 91 steel [237]. Weld metal generally contains a higher concentration of Ni + Mn than wrought products, leading to a lower Ac₁. Therefore, it is important that the Ac₁ of weld metal is not exceeded during PWHT (refer to Section 8.3.12).

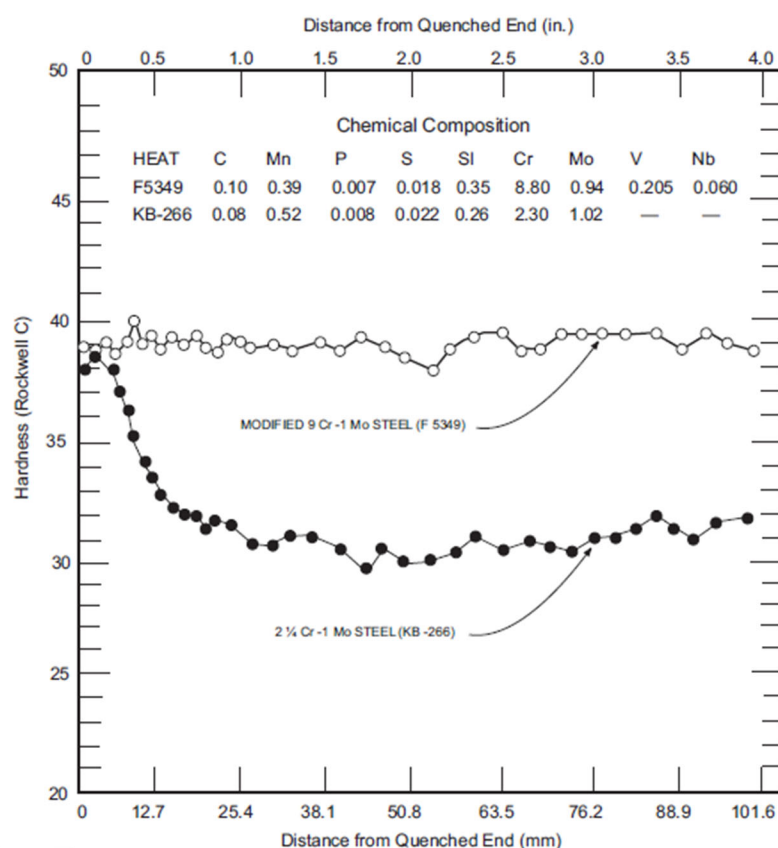


Figure 8—Deep hardening behavior of Grade 91 steel

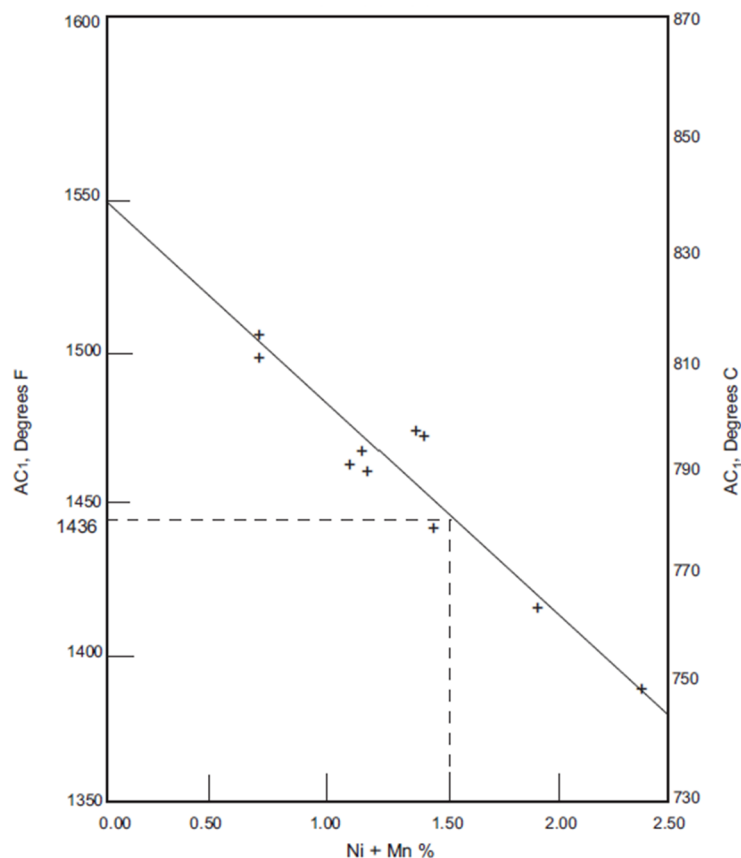


Figure 9—Effect of Ni + Mn concentration on Ac1 (data was obtained using Grade 91 weld metals)

5.4.2 Martensite Formation

Figure 10 shows the CCT diagram for Grade 91 steel [3144]. The steel is typically used in normalized and tempered (N + T) condition as indicated in **Table 4**. By cooling from the austenitizing temperature to room temperature, the structure of this steel transforms (over a wide area of cooling rates) nearly completely to martensite [2838].

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 (750 °F) and 210 °C (410 °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 are about 340 °C (640 °F) and 150 °C (300 °F), respectively. It can be assumed conservatively that the M_f lies above 100 °C (210 °F) [642], which also varies with prior austenite grain size [2838].

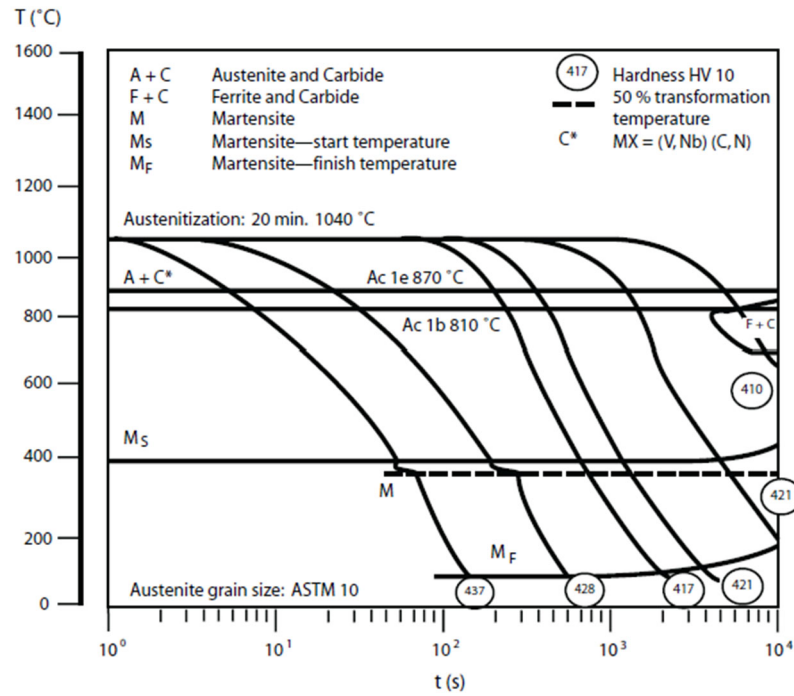


Figure 10—CCT diagram of Grade 91 steel

Table 4—Heat treatment and mechanical properties of Grade 9, Grade 91, and other 9Cr high strength steels

Spec. or CC	Grade, Type	Heat Treatment Type	Austenitizing Temperature °C (°F)	Tempering Temperature °C (°F)	Tensile Strength MPa (ksi)	Minimum Yield Strength MPa (ksi)	Minimum Elongation in 50 mm (2 in.) or 4D %	Minimum Reduction of Area %	Hardness
SA-182 [17]	F9	Annealed or N + T	955 (1750) min.	If N + T: 675 (1250) min.	585 (85) min.	380 (55)	20	40	179 – 217 HBW
	F91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 (90) min.	415 (60)	20	40	190 – 248 HBW
	F911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 (90) min.	440 (64)	18	40	187 – 248 HBW
	F92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 (90) min.	440 (64)	20	45	269 HBW max.
	F93	N + T	1070 – 1170 (1960 – 2140)	750 – 790 (1380 – 1455)	620 (90) min.	440 (64)	19	40	250 HBW max.
SA-213 [17]	T9	Full or isothermal annealed, or N + T	—	If N + T: 675 (1250)	415 (60) min.	205 (30)	30	—	179 HBW max. 190 HV max.
	T91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	585 (85) min.	415 (60)	20	—	190 – 250 HBW 196 – 265 HV
	T911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 (90) min.	440 (64)	20	—	250 HBW max. 260 HV max.
	T92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 (90) min.	440 (64)	20	—	250 HBW max. 265 HV max.
	T93	N + T	1070 – 1170 (1960 – 2140)	750 – 790 (1380 – 1455)	620 (90) min.	440 (64)	19	—	250 HBW max. 265 HV max.
SA-234 [17]	WP9	Full or isothermal annealed, or N + T	—	If N + T: 675 (1250) min.	CL 1: 415 (60) min. CL 3: 520 (75) min.	CL 1: 205 (30) CL 3: 310 (45)	22	—	217 HBW max.
	WP91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	590 – 760 (85 – 110)	415 (60)	20	—	190 – 250 HBW
	WP911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 – 840 (90 – 120)	440 (64)	20	—	248 HBW max.
	WP92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 – 840 (90 – 120)	440 (64)	20	—	269 HBW max.
SA-335 [17]	P9	Full-annealed, isothermal annealed, or N + T	—	If N + T: 675 (1250) min.	415 (60) min.	205 (30)	30	—	—
	P91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	585 (85) min.	415 (60)	20	—	190 – 250 HBW 196 – 265 HV
	P911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 (90) min.	440 (64)	20	—	250 HBW max. 265 HV max.
	P92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 (90) min.	440 (64)	20	—	250 HBW max. 265 HV max.
SA-336 [17]	F9	Annealed or N + T	—	If N + T: 675 (1250) min.	585 – 760 (85 – 110)	380 (55)	20	40	—
	F91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 – 760 (90 – 110)	415 (60)	20	40	—
	F911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 – 830 (90 – 120)	440 (64)	20	40	—
	F92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 – 830 (90 – 120)	440 (64)	20	45	—

Table 4—Continued

Spec. or CC	Grade, Type	Heat Treatment Type	Austenitizing Temperature °C (°F)	Tempering Temperature °C (°F)	Tensile Strength MPa (ksi)	Minimum Yield Strength MPa (ksi)	Minimum Elongation in 50 mm (2 in.) or 4D %	Minimum Reduction of Area %	Hardness
SA-369 [17]	FP9	Full-annealed or N + T	—	If N + T: 680 (1250) min.	415 (60)	210 (30)	22	—	—
	FP91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	585 (85)	415 (60)	20	—	—
	F92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 (90)	440 (64)	20	—	—
SA-387 [17]	9	Annealed or N + T	—	If N + T: 675 (1250) min.	515 – 690 (75 – 100)	310 (45)	18	40	—
	91 Types 1 & 2	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	585 – 760 (85 – 110)	415 (60)	18	—	—
SA-1017 [17]	911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 – 840 (90 – 120)	440 (64)	18	—	—
	92	N + T	1040 – 1080 (1900 – 1975)	730 – 800 (1350 – 1470)	620 – 840 (90 – 120)	440 (64)	20	—	—
CC2327-3 [21]	Grade 911	N + T	1040 – 1080 (1900 – 1975)	740 – 780 (1365 – 1435)	620 (90)	440 (64)	20	—	238 HBW max. 250 HV max.
CC2839-2 [23]	Grade 93	N + T	1070 – 1170 (1960 – 2140)	750 – 790 (1380 – 1455)	620 (90)	440 (64)	19	—	250 HBW max.

5.4.3 Heat Treatment of Base Metal

5.4.3.1 General

Normalizing and tempering heat treatment is specified for Grade 91 steels, while Grade 9 steel may be annealed instead. To achieve an acceptable combination of strength and ductility in Grade 91 steel, it is normalized at temperatures of 1040 to 1080 °C (1900 to 1980 °F), followed by air cooling and tempering at temperatures of 730 to 800 °C (1350 to 1470 °F). As listed in **Table 4**, these temperature ranges are currently specified for all product forms of Grade 91 steels, although higher normalizing temperatures of up to 1095 °C (2000 °F) and lower tempering temperatures reaching 730 °C (1350 °F) were allowed in older edition of the standards.

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 in Grade 91 steels. Owing to the presence of these precipitates, Grade 91 steels offer excellent creep-rupture strength. Typical microstructure after normalizing and tempering is shown in **Figure 11** [32].

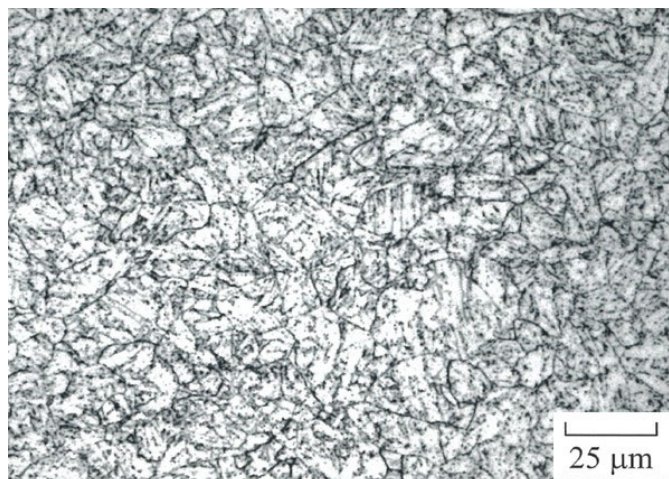


Figure 11—Typical microstructure of Grade 91 steel after normalizing and tempering

5.4.3.2 Normalizing

Figure 12 shows the grain coarsening behavior of Grade 91 steel obtained after normalizing at various temperatures between 930 and 1120 °C (1700 to 2050 °F) [2939]. The steel resistant to extensive grain coarsening even when held at temperatures near 1066 °C (1950 °F) for 8 hours. Grain coarsening is minimal at temperatures up to 1120 °C (2050 °F) when held for 1 hour. Excessively high normalizing temperatures or long soaking times lead to coarsening of austenite grains, resulting in inadequate toughness. Conversely, excessively low normalizing temperatures or short soaking times lead to low creep strength.

5.4.3.3 Tempering

Although tempering at temperatures of 730 to 800 °C (1350 to 1470 °F) is permitted in the latest ASME Grade 91 material specification, purchase specifications for Grade 91 steels typically recommend tempering temperatures in the range of 760 to 780 °C (1400 to 1440 °F) to balance the tensile, creep, and impact properties. A higher tempering temperature improves the low-temperature toughness, but slightly degrades tensile properties (tensile strength, yield strength, and elongation percentage) [33]. Thus, normalizing and tempering heat treatment conditions for Grade 91 steels have been established by targeting creep properties rather than the low-temperature toughness.

It is important to assure that the tempering temperature does not exceed 790 °C (1450 °F) to avoid getting into the two-phase region, i.e. exceeding A_{c1} . 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 [642].

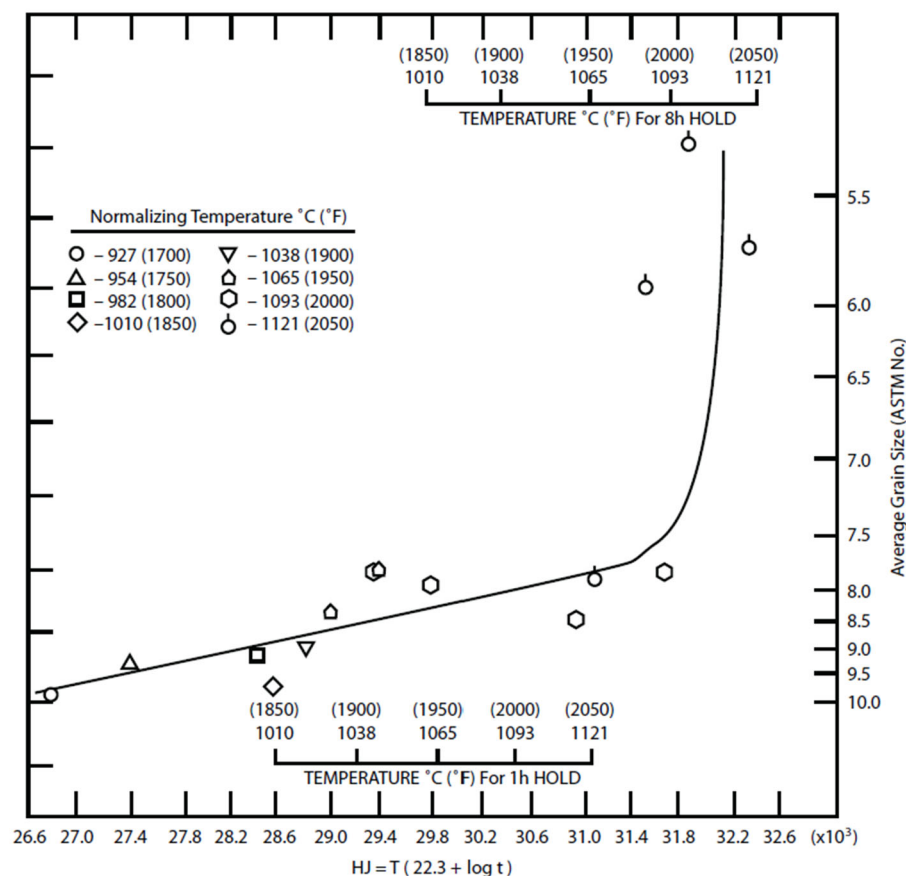


Figure 12—Grain coarsening behavior of Grade 91 steel

5.5 Mechanical Properties

5.5.1 General

The mechanical properties of **Grade 9, Grade 91, and other 9Cr high-strength steel** 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 of **base and weld metals** is given below.

5.5.2 Tensile Strength

5.5.2.1 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 **Grade 91** steel 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 13** [2939]. 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.

5.5.2.2 ASME Temperature Limits and Use Restrictions

Table 5 lists the maximum temperatures for the use of **Grade 91 steel and other 9Cr high-strength steels** specified in various ASME codes and CCs. The maximum temperature for **Grade 91 steels** is 649 °C (1200 °F) except for in **ASME Section VIII, Division 2, Class 1**, where use of **Grade 91 steel** is not permitted above 482 °C (900 °F).

Previously, CC 1973-2 [19] existed to permit the use of Grade 91 steels for ASME Section VIII, Division 2; however, it has now been incorporated into the code.

In ASME Section VIII, Divisions 1 and 2, limited material specifications are allowed. The use of allowable stress values assigned to Grade 91 Type 2 steel, which are higher than those assigned to Grade 91 Type 1 steel, is not permitted [4].

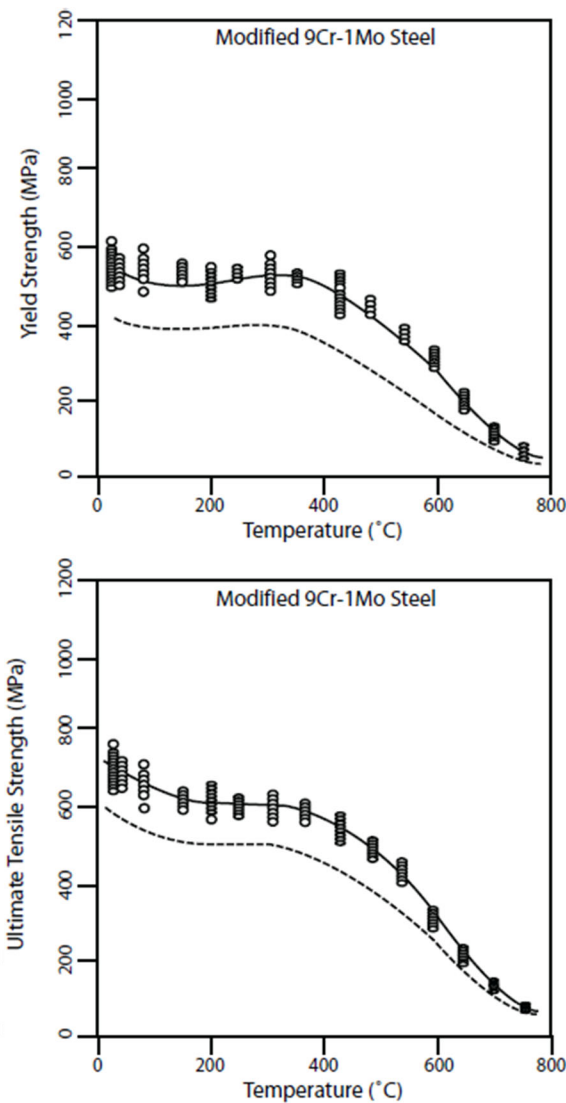


Figure 13—Yield (0.2 %) and ultimate tensile strengths vs. temperature for Grade 91 steel

Table 5—ASME Code and CCs maximum allowable temperatures for Grade 91 and other 9Cr high strength steels

ASME Code or CC	Nominal Composition	Spec. or CC	Grade	Type	Maximum Temperature °C (°F)
ASME Section II, Part D for Section I, Table 1A [4]	9Cr-1Mo-V	SA-182 / 336, -213, -234, -335, -369, -387 Cl.2	F91, T91, WP91, P9, FP91, 91	1, 2	649 (1200)
ASME Section II, Part D for Section VIII, Division 1, Table 1A [4]	9Cr-1Mo-V	SA-182 / 336, -213, -335, -387 Cl.2	F91, T91, P91, 91	1	649 (1200)
		SA-234, -369	WP91, FP91	1	Not permitted
		SA-182 / 336, -213, -234, -335, -369, -387 Cl.2	F91, T91, WP91, P91, FP9, 91	2	Not permitted
ASME Section II, Part D for Section VIII, Division 2 Class 1, Table 2A [4]	9Cr-1Mo-V	SA-182 / 336, -213, -335, -387 Cl.2	F91, T91, P91, 91	1	482 (900)
ASME Section II, Part D for Section VIII, Division 2 Class 2, Table 5A [4]	9Cr-1Mo-V	SA-182 / 336, -213, -335, -387 Cl.2	F91, T91, P91, 91	1	649 (1200)
ASME 31.1, Table A-2 [11]	9Cr-1Mo-V	ASTM A182/336, A213, A234, A335, A369, A387 Cl.2 / 691	F91, T91, WP91, P9, FP91, 91	1, 2	649 (1200)
ASME 31.3, Table A-1 [12]	9Cr-1Mo-V	ASTM A182, A234, A335, A387 Cl. 2 / 691	F91, WP91, P91, 91	—	649 (1200)
CC2327-3 [21] for Section I	9Cr-1Mo-1W-Cb	SA-182/ 336, -213, -234, -335, -369, -1017	F911, T911, WP911, P911, FP911, 911	—	621 (1150)
CC2179-11 [20] for Section I, and Section VIII, Division 1	9Cr-2W	SA-182 / 336, 213, 234, 335, 369, 1017	F92, T92, WP92, P92, FP91, 92	—	649 (1200)
CC2839-2 [23] for Section I	9Cr-3W-3Co-Nd-B	SA-182, 213, 335	F93, T93, P93	—	649 (1200)

5.5.2.3 ASME Maximum Allowable Stress

Table 6 lists the maximum allowable stress values of ASME Section I and Section VIII, Division 1 for various product forms of Grade 91 steels [4]. **Table 6** also includes the corresponding values for Grade 22, V-modified 2 1/4 Cr-1Mo-V (Grade 22V), Grade 9, austenitic stainless steels, and other 9Cr high-strength steels. Although Grade 91 Type 2 steel has higher allowable stress values than Grade 91 Type 1 steel, the Type 2 steel is not covered in ASME Section VIII, Division 1 and is allowed only in ASME Section I (and B31.1 [11]) [4].

Figure 14 shows a comparison of the maximum allowable stress values of Section I and ASME Section VIII, Division 1 [4], taking seamless tube product as an example, for Grades 22 and 91 steels and Type 347H SS. The allowable stress values for Grade 91 steel are the highest among these steels up to approximately 540 °C (1000 °F), while the values for Type 347H SS are higher above that temperature.

Allowable stress values for Grade 91 steel are 40 % higher than those for Grade 22 steel up to approximately 480 °C (900 °F). Above this temperature, the allowable stress ratio ($S_{\text{Grade 91}} / S_{\text{Grade 22}}$) increase significantly; the ratio exceeds 200% at 540 °C (1000 °F) and reaches 260% at 650 °C (1200 °F).

Comparing Grade 91 to Type 347H SS, the allowable stress values for Grade 91 steel are higher at temperatures below approximately 540 °C (1000 °F). In this temperature range, the difference in allowable stress values decreases with increasing temperature and eventually reverses. Above about 540 °C (1000 °F), the allowable stresses for Types 316H are greater.

Tables 7 and 8 list the maximum allowable stress values of ASME Section VIII, Division 2, Classes 1 and 2 [4]. These tables cover the various product forms of Grade 91 steel. ASME Section VIII, Division 2, Class 1 provides the allowable stress up to 480 °C (900 °F), whereas Class 2 provides the allowable stress up to 650 °C (1200 °F).

Figure 15 shows a comparison of the maximum allowable stress values for Section VIII, Division 2, Class 2, taking plate products as an example, for Grades 91 and 22V. The use of 2 1/4 Cr-1Mo-V steel is limited to 480 °C (900 °F), while 9Cr-1Mo-V has maximum allowable stress values up to 649 °C (1200 °F). There is a negligible difference in allowable stress values for Grade 91 and Grade 22V steel up to 430 °C (800 °F). Above this temperature, the allowable stress values for Grade 91 steel are higher than those for Grade 22V steel, and the difference reaches approximately 30 % at 480 °C (900 °F).

Nominal Composition	Product Form	Spec. or CC	Grade	Maximum Metal Temperatures (°F)																	
				100	200	300	400	500	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200
				Maximum Allowable Stress (ksi) ^a																	
2 1/4 Cr-1Mo	Forgings Smls. Tube Smls. Pipe Forged & Bored Pipe Pipe Fittings Plate	SA-182 / 336 SA-213 SA-335 SA-369 SA-234 SA-387	F22 Cl.1 T22 P22 FP22 WP22 Cl. 1 22 C1. 1	17.1	17.1	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	16.6	13.6	10.8	8	5.7	3.8	2.4	1.4
	Forgings Plate	SA-182 / 336 SA-387	F22 Cl. 3 22 Cl. 2	21.4	21.4	20.9	20.6	20.5	20.4	20.2	20	19.7	19.3	18.7	15.8	11.4	7.8	5.1	3.2	2	1.2
2 1/4 Cr-1Mo -V	Forgings Plate	SA-182 / 336, -541 -542, -832	F22V, 22V D Cl. 4a, 22V	24.3	24.3	24.3	24.3	24.3	23.7	23.2	22.8	22.2	21.6	21.0	20.3	—	—	—	—	—	—
9Cr-1Mo	Forgings	SA-182 / 336	F9	24.3	24.2	23.5	23.4	23.3	22.9	22.6	22.1	21.4	20.6	19.6	16.4	11.0	7.4	5.0	3.3	2.2	1.5
	Smls. Tubes Smls. Pipe Forged & Bored Pipe Pipe Fittings	SA-213 SA-335 SA-369 SA-234	T9 P9 FP9 WP9	17.1	17.1	16.6	16.5	16.4	16.2	15.9	15.6	15.1	14.5	13.8	13.0	10.6	7.4	5.0	3.3	2.2	1.5
9Cr-1Mo-V Type 1	Forgings (Pipe Fittings) ^b	SA-182 / 336 (SA-234) ^b	F91 Type 1 (WP91 Type 1) ^b	25.7	25.7	25.7	25.6	25.5	25.1	24.7	24.2	23.5	22.6	21.5	20.2	18.8	16.1	12.2	8.7	5.7	3.5
	Smls. Tubes Smls Pipe (Forged & Bored Pipe) ^b Plate	SA-213 SA-335 (SA-369) ^b SA-387	T91 Type 1 P91 Type 1 (FP91 Type 1) ^b 91 Type 1 Cl.2	24.3	24.3	24.3	24.2	24.1	23.7	23.4	22.9	22.2	21.3	20.3	19.1	17.8	16.1	12.2	8.7	5.7	3.5
9Cr-1Mo-V Type 2	(Forgings) ^b (Pipe Fittings) ^b	(SA-182 / 336) ^b (SA-234) ^b	(F91 Type 2) ^b (WP91 Type 2) ^b	25.7	25.7	25.7	25.6	25.5	25.1	24.7	24.2	23.5	22.6	21.5	20.2	18.8	16.7	12.6	9.1	6.1	3.7
	(Smls. Tubes) ^b (Smls. Pipe) ^b (Forged & Bored Pipe) ^b (Plate) ^b	(SA-213) ^b (SA-335) ^b (SA-369) ^b (SA-387) ^b	(T91 Type 2) ^b (P91 Type 2) ^b (FP91 Type 2) ^b (91 Type 2 Cl.2) ^b	24.3	24.3	24.3	24.2	24.1	23.7	23.4	22.9	22.2	21.3	20.3	19.1	17.8	16.3	12.6	9.1	6.1	3.7
9Cr-1Mo-1W-1Cb	CC2327-3 for ASME Section I		Grade 911	25.7	25.7	25.1	24.1	23.6	23.2	23.0	22.7	22.3	21.7	21.0	20.1	19.0	17.7	14.4	10.6	7.3	—
9Cr-2W	CC2179-11 for ASME Section I, and Section VIII, Division 1		Grade 92	25.7	25.7	25.3	24.5	23.8	23.2	22.8	22.4	21.9	21.4	20.8	20.1	19.2	18.3	15.4	11.7	8.3	5.3
9Cr-3W-3Co-Nd-B	CC2839-2 for ASME Section I		Grade 93	25.7	25.7	25.1	24.3	23.8	23.3	23.0	22.7	22.2	21.7	21.0	20.2	19.2	19.1	16.9	15.5	12.0	6.5
18Cr-8Ni	Smls. Tube	SA-213	TP304H	20.0	20.0	18.9	18.3	17.5	16.6	16.2	15.8	15.5	15.2	14.9	14.6	14.3	14.0	12.4	9.8	7.7	6.1
16Cr-12Ni-2Mo	Smls. Tube	SA-213	TP316H	20.0	20.0	20.0	19.3	18.0	17.0	16.6	16.3	16.1	15.9	15.7	15.6	15.4	15.3	15.1	12.4	9.8	7.4
18Cr-10Ni-Cb	Smls. Tune	SA-213	TP347H	20.0	20.0	18.8	17.8	17.1	16.9	16.8	16.8	16.8	16.8	16.8	16.7	16.6	16.4	16.2	14.1	10.5	7.9
18Cr-10Ni-Ti	Smls. Pipe (t > 8/3 inch)	SA-376	TP321H	20.0	20.0	19.1	18.7	18.7	18.3	17.9	17.5	17.2	16.9	16.7	16.5	16.4	16.2	12.3	9.1	6.9	

Table 7— Maximum allowable stress values of ASME Section III, Division 2, Class 1 (ASME Section II, Part D, Table 2A) for Grade 91 steel in comparison with Grade 22, Grade 22V and Grade 9 steels

Nominal Composition	Product Form	Spec.	Grade	Maximum Metal Temperatures (°F)											
				100	200	300	400	500	600	650	700	750	800	850	900
				Maximum allowable stress values (ksi) ^a											
2 1/4 Cr-1Mo	Forgings Smls. Tube Smls. Pipe Forged & Bored Pipe Pipe Fittings Plate	SA-182 / 336 SA-213 SA-335 SA-369 SA-234 SA-387	F22 Cl.1 T22 P22 FP22 WP22 Cl. 1 22 C1. 1	20.0	18.7	18.2	18.0	17.9	17.9	17.9	17.9	17.9	17.7	17.1	13.6
	Forgings Plate	SA-182 / 336 SA-387	F22 Cl. 3 22 Cl. 2	25.0	25.0	24.3	24.1	24.0	23.8	23.6	23.4	23.0	22.5	21.9	17.0
2 1/4 Cr-1Mo -V	Forgings Plate	SA-182 / 336, -541 -542, -832	F22V, 22V D Cl. 4a, 22V	28.3	28.3	28.3	28.3	28.3	27.6	27.1	26.5	25.9	25.2	24.5	23.6
9Cr-1Mo	Forgings	SA-182 / 336	F9	28.3	28.3	27.4	27.2	27.1	26.8	26.3	25.8	—	—	—	—
	Smls. Tubes Smls. Pipe Forged & Bored Pipe Pipe Fittings	SA-213 SA-335 SA-369 SA-234	T9 P9 FP9 WP9	20.0	18.1	17.4	17.2	17.1	16.8	16.6	16.3	—	—	—	—
9Cr-1Mo-V	Forgings	SA-182 / 336	F91 Type 1	30.0	30.0	30.0	29.9	29.8	29.3	28.9	28.2	27.4	26.4	25.1	23.6
	Smls. Tubes Smls. Pipe Plate	SA-213 SA-335 SA-387	T91 Type 1 P91 Type 1 91 Cl. 2 Type 1	28.3	28.3	28.3	28.2	28.1	27.7	27.3	26.7	25.9	24.9	23.7	22.3

^a Maximum allowable stress values in **bold** are based on successful experience in service.

Table 8—Maximum allowable stress values of ASME Section III, Division 2, Class 2 (ASME Section II, Part D, Table 5A) for Grade 91 steel in comparison with Grade 22, Grade 22V and Grade 9 steels

Nominal Composition	Product Form	Spec.	Grade	Maximum Metal Temperatures (°F)																	
				100	200	300	400	500	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200
				Maximum allowable stress values (ksi) ^a																	
2 1/4 Cr-1Mo	Forgings Smls. Tube Smls. Pipe Forged & Bored Pipe Pipe Fittings Plate	SA-182 / 336 SA-213 SA-335 SA-369 SA-234 SA-387	F22 Cl.1 T22 P22 FP22 WP22 Cl. 1 22 C1. 1	20.0	18.7	18.2	18.0	17.9	17.9	17.9	17.9	17.9	17.7	17.1	13.6	10.8	8.0	5.7	3.8	2.4	1.4
	Forgings Plate	SA-182 / 336 SA-387	F22 Cl. 3 22 Cl.2	30.0	27.5	26.2	25.4	24.8	24.3	24.0	23.7	23.3	22.9	21.9	17.0	11.4	7.8	5.1	3.2	2.0	1.2
2 1/4 Cr-1Mo -V	Forgings Plate	SA-182 / 336, -541 -542, -832	F22V, 22V D Cl. 4a, 22V	35.4	35.4	35.4	35.4	35.4	35.4	35.4	34.9	34.2	33.4	28.9	23.8	—	—	—	—	—	—
9Cr-1Mo	Forgings	SA-182 / 336	F9	35.4	33.1	31.9	31.5	31.3	30.8	30.4	29.9	29.2	28.2	27.1	16.4	11.0	7.4	5.0	3.3	2.2	1.5
	Smls. Tubes Smls. Pipe Forged & Bored Pipe Pipe Fittings	SA-213 SA-335 SA-369 SA-234	T9 P9 FP9 WP9	20.0	18.1	17.4	17.2	17.1	16.8	16.6	16.3	15.9	15.4	14.8	14.1	10.6	7.4	5.0	3.3	2.2	1.5
9Cr-1Mo-V	Forgings	SA-182 / 336	F91 Type 1	37.5	37.3	36.5	36.5	36.5	36.3	36.0	35.4	34.7	33.6	32.3	30.8	25.9	16.1	12.2	8.7	5.7	3.5
	Smls. Tubes Smls. Pipe Plate	SA-213 SA-335 SA-387	T91 Type 1 P91 Type 1 91 Cl. 2 Type 1	35.4	35.4	35.4	35.4	35.4	35.4	35.4	35.4	34.7	33.6	32.3	30.8	25.9	16.1	12.2	8.7	5.7	3.5

^a Maximum allowable stress values shown in *italics* are those obtained from time-dependent properties.

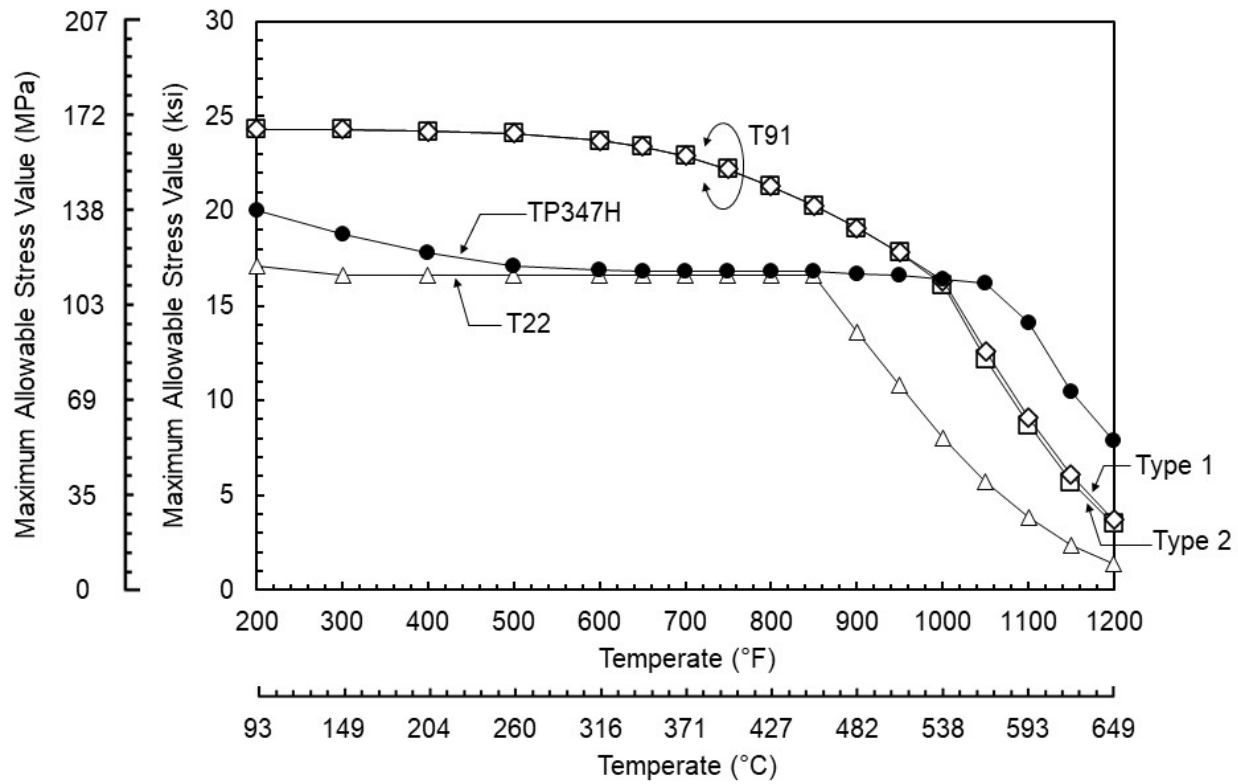


Figure 14—Maximum allowable stress values of Grade 91 steel seamless tubes for Section VIII, Division 1

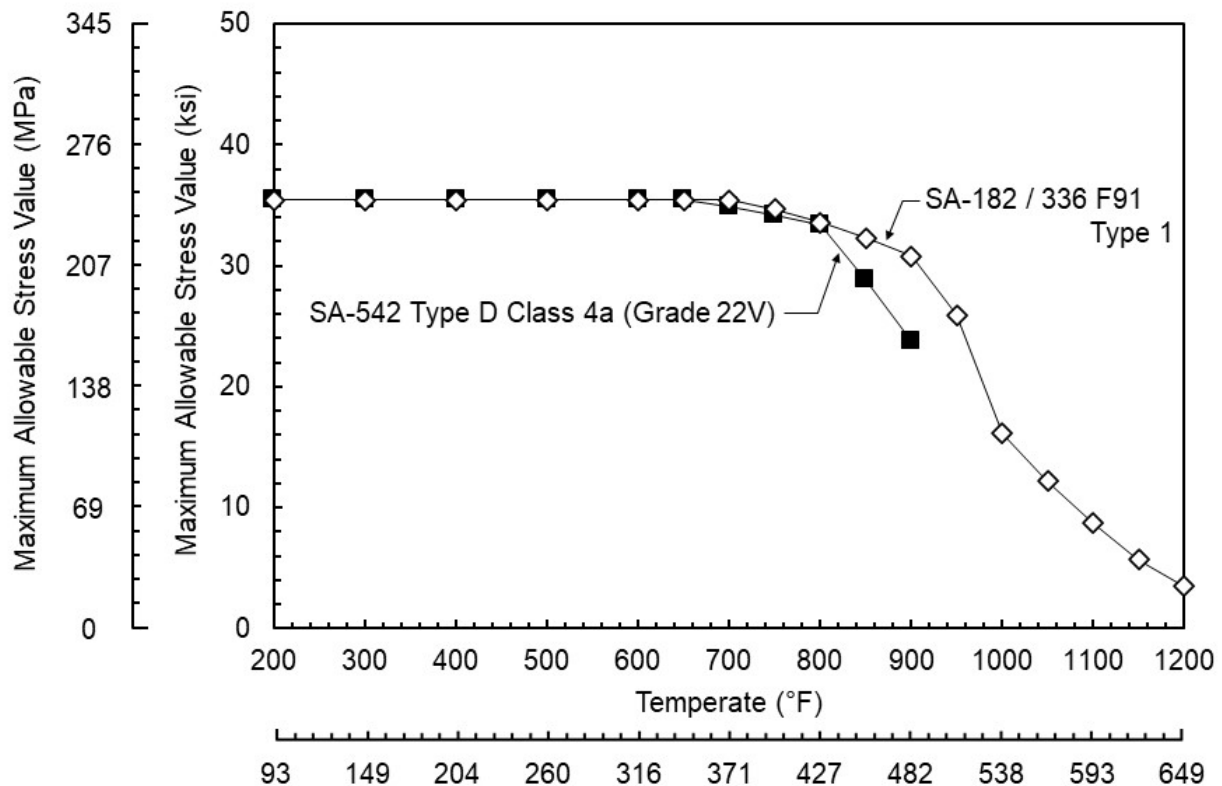


Figure 15—Maximum allowable stress values of Grade 91 and 22V steel plate for Section VIII, Division 2, Class 2

5.5.3 Impact Toughness

5.5.3.1 Impact Toughness of Base Metal

5.5.3.1.1 General

Figure 16 shows typical examples of the Charpy V-notch impact toughness (CVN) for seamless pipes and tubes of Grade 91 steel obtained from various suppliers [33–35]. The wrought products of Grade 91 steel generally show sufficient impact toughness at 0 °C (30 °F). The toughness of Grade 91 steel is affected by the following factors.

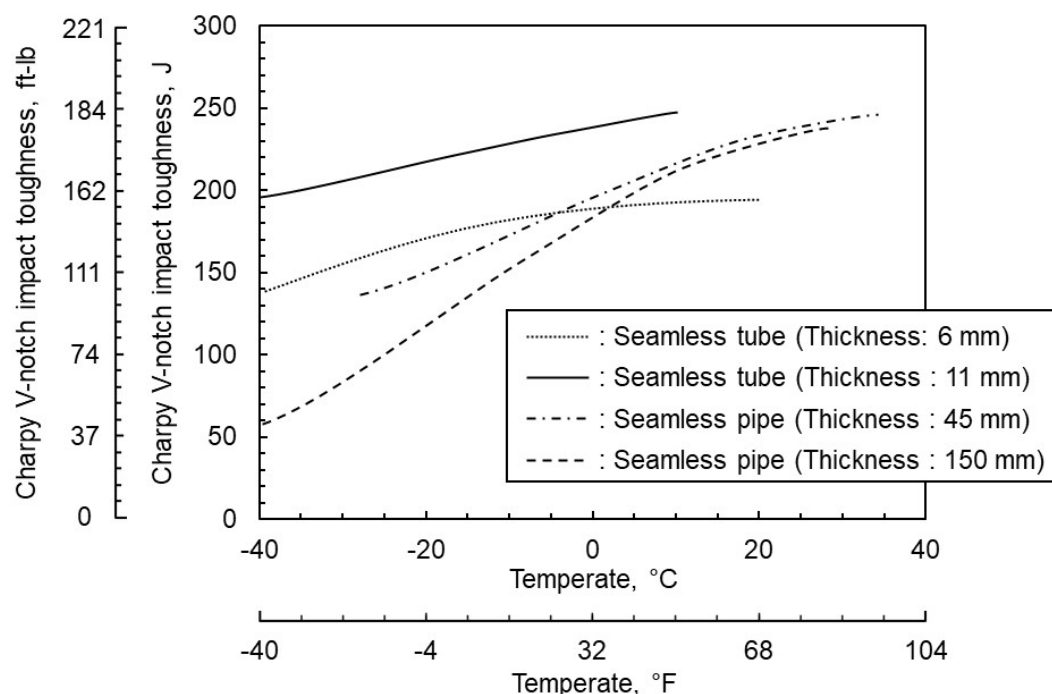


Figure 16—CVN vs. temperature for Grade 91 steel base metal

5.5.3.1.2 Effect of Steel Melting Practice

The CVN has been shown to be related to the employed melting practice [2939]. It is also sensitive to inclusion size and shape. Melting practices, which achieve low sulfur and phosphorous levels and produce favorable 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.

5.5.3.1.2 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” [3645]. Aging is a different phenomenon than TE mentioned in Section 6.6. Aging is related to the coarsening of carbides or the formation of Laves phase [37]. 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 (1020 °F to 1110 °F) with some reduction in strength and hardness at 650 °C to 700 °C (1200 °F to 1290 °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 (1020 °F to 1110 °F). Normalizing temperature variations in the range of 1050 °C to 1100 °C (1920 °F to

2010 °F) did not affect the mechanical properties (yield strength, elongation percent and hardness) after aging. This embrittlement is not influenced by phosphorous concentration up to 200 ppm [3645]. Grade 91 steels with high Si concentration tend to show greater embrittlement than steels with low Si concentration [38].

The effect of aging on CVN specimens from a commercial ESR heat for times up to 5000 hours at temperatures from 480 °C (900 °F) to 650 °C (1200 °F) was investigated. Aging caused a maximum shift in the transition temperature of about 40 °C (104 °F) [2939].

5.5.3.2 Impact Toughness of Weld Metal

5.5.3.2.1 Effect of Welding Process

Grade 91 steel weld metals (AWS Classification B91), except for those made with GTAW, exhibit lower CVN impact toughness than the base metal, even after PWHT. Figure 17 shows an example of CVN of SMAW weld metal [29].

SMAW and SAW weld metals generally exhibit acceptable CVN values at room temperature. If the welded components are intended for use at lower temperatures, the welding procedure is carefully established.

Weld metal oxygen concentration is primarily affected by the welding process. CVN toughness generally increases with decreasing oxygen concentration. The effect of oxygen is discussed in Section 7.2.3.5.

5.5.3.2.2 Effect of Welding Technique

Bead shape (thickness) and welding position affect the impact toughness of the weld metal; thinner and wider beads tend to facilitate tempering of the metal previously deposited by subsequent beads. Therefore, weaving and avoiding stringer beads typically leads to higher impact toughness. Contrary to the flat welding position (1G), loss of toughness is normally observed in the vertical (3G) and overhead (4G) positions with SMAW, mostly owing to the bead shape [237].

5.5.3.2.3 Effect of PWHT Temperature and Holding Time

Generally, increases in the PWHT temperature and the holding time facilitate tempering of weld metal as long as PWHT temperature is below Ac1. Figure 18 shows that the influences of PWHT time on impact toughness of Grade 91 steel weld metals produced using SMAW process [237].

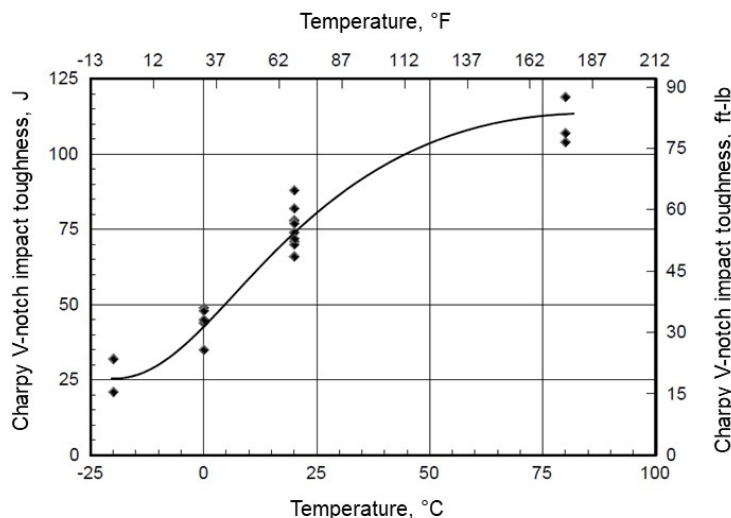


Figure 17—CVN vs. temperature for Grade 91 steel SMAW weld metals after PWHT (755°C (1390 °F) for 3 hours)

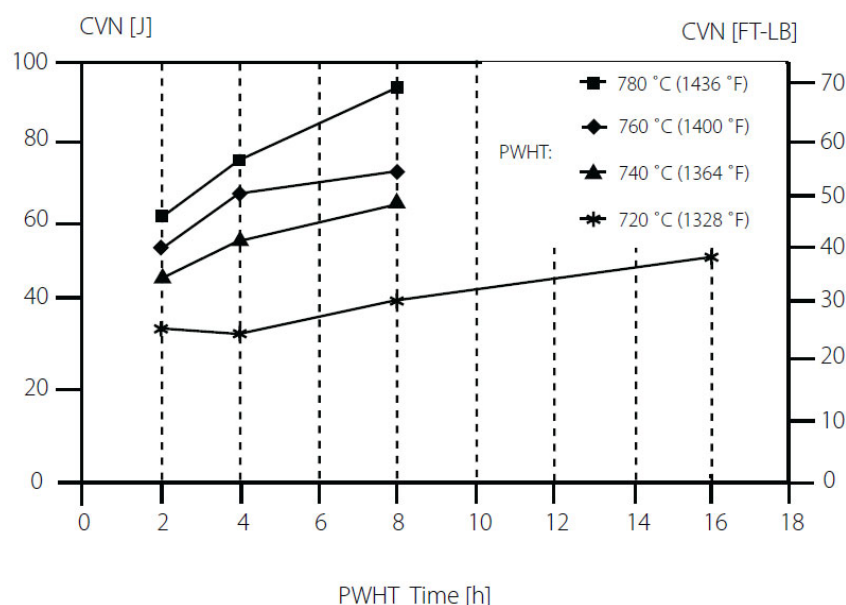


Figure 18—Influence of PWHT time on toughness of Grade 91 weld metal (B91) produced using SMAW

5.5.4 Creep Rupture Properties

5.5.4.1 Creep Rupture Properties of Base Metal

Two of the major attributes of the Grade 91 steels 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 Grade 22 or Grade 9 steels as shown in **Figure 19** [2939]. Grade 91 steel has been investigated over the years in many laboratories all over the world. **Table 9** [2838] shows the creep rupture values for ASTM A 213 T91 steel.

The allowable stresses of Grade 91 steels in the creep regime are usually determined based on the 100,000 h creep-rupture strength. Such long-term creep rupture strengths were initially predicted using short-term creep test data (e.g., up to 10,000 h). However, accumulated creep data has revealed that the 100,000 h creep rupture strength is lower than the predicted value. This has led to multiple revisions of the allowable stress values in the ASME codes (refer to Section 4.1).

The allowable stress values as of this writing are based on the creep data analysis conducted in 2016–2017 [40]. These values have been incorporated into ASME Section II-2023 [4] for Section I, Section VIII, Division 1, and ASME B31.1-2022 [11], but are not yet in ASME B31.3-2022 [12].

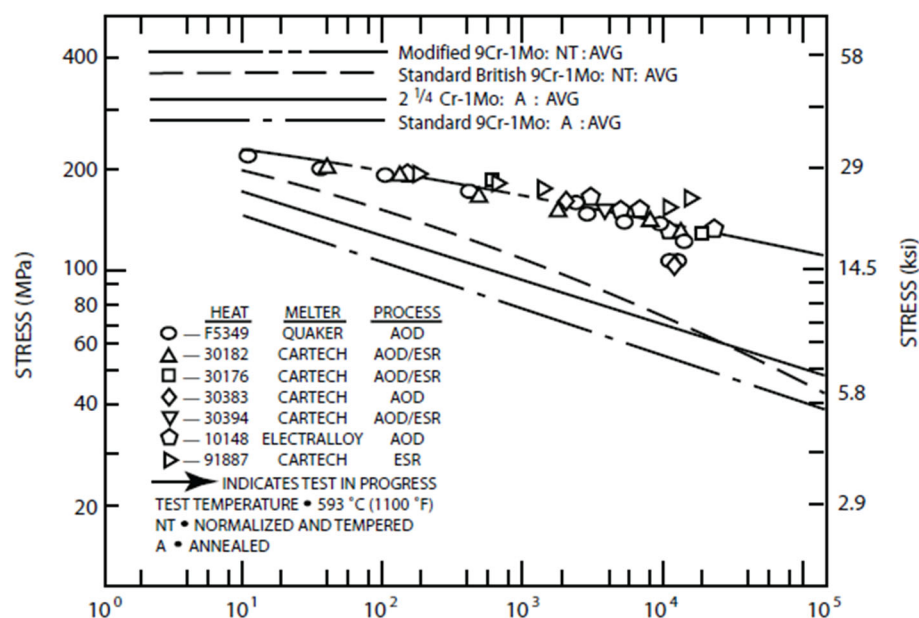


Figure 19—Stress rupture strength of commercial heats of N + T Grade 91 Steel at 593 °C (1100 °F)

Table 9—Creep rupture of ASTM A 213 T91

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)

5.5.4.2 Creep Rupture Properties of Welded Joints

Figure 20 presents a comparison of the creep-rupture strengths of base metals and welded joints of Grade 91 steels [41]. Results indicate that creep-rupture strengths of welded joints after welding heat treatment at subcritical temperatures are lower than the base metal. This phenomenon is known as Type IV cracking (refer to Section 6.7); the fine-grained region in the HAZ of welded Grade 91 steel results in a short-time rupture with low creep elongation. To consider this short-term failure, the WJSRF was specified for longitudinal weld seams in piping (refer to Section 4.2). It should be noted that even if the welds undergo normalizing and tempering, the creep-rupture strengths of the welded joints of Grade 91 steel are still lower than that of the base metal.

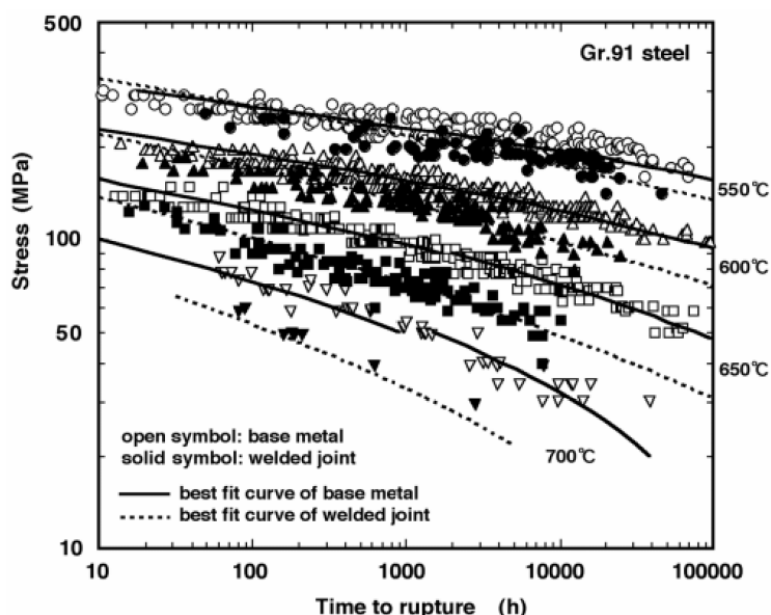


Figure 20—Comparison of creep-rupture strengths of Grade 91 steel welded joints to those of base metal

5.5.5 Hardness

5.5.5.1 Hardness of Base Metal

As summarized in **Table 4**, ASME specifications SA-182, SA-213, SA-234, and SA-335 specify 190–248 (or 250) HBW as the acceptable Brinell hardness for the base metal. ASME specifications SA-336, SA-369, and SA-387 do not specify a hardness range or limit.

Figure 21 shows the effect of the accumulated heat treatment temperature and time during tempering on the Brinell hardness of the base metals. In the untempered conditions, the hardness of the steel exceeds 400 HBW. As the tempering time and temperature increase, the hardness of the steel decreases to below 200 HBW. In the long term, hardness values below 180 HBW is observed. The scatter in hardness for a given value of L.M.P. is about $\pm 10\%$ [42].

Low hardness (~ 160 – 180 HBW) has been reported for Grade 91 steel piping spools [43, 44], suggesting that improper heat treatment occurred during manufacturing and/or fabrication (e.g., bending). Therefore, further investigation is advisable when the base metal hardness is below 190 HBW.

5.5.5.2 Hardness of Welds

Hardness of as-welded Grade 91 steel weld metal and HAZ reaches 400 HV, or higher. **Figures 22** shows that the influences of PWHT temperature and holding time on Vickers hardness of Grade 91 steel weld metals produced using SMAW process [237]. Similarly, **Figure 23 and 24** show the effects of the accumulated PWHT temperature and holding time on Vickers hardness of Grade 91 steel weld metal and the HAZ of the Grade 91 steel welds, respectively [42, 45].

5.5.5.3 Hardness Conversion

It should be noted that the standard hardness conversion table per ASTM E140 for non-austenitic steels does not exactly match the relationship between the Brinell and Vickers hardness in Grade 91 steels. This conversion can instead be in accordance with the following equation [42] :

$$HBW = HV5 \times 0.859 + 21.11$$

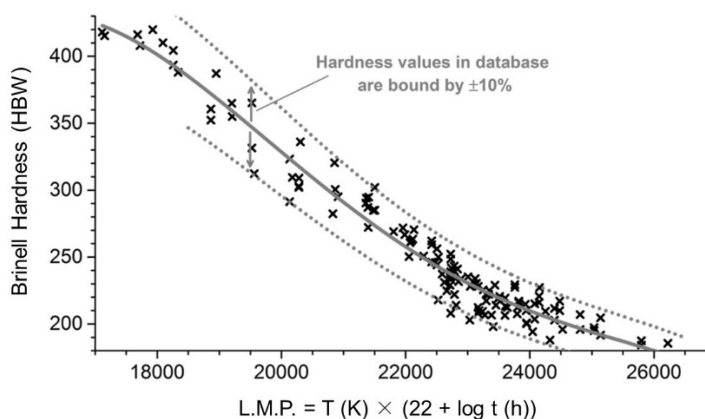


Figure 21—Effect of accumulated heat treatment temperature and time on Brinell hardness of Grade 91 Steel base metal

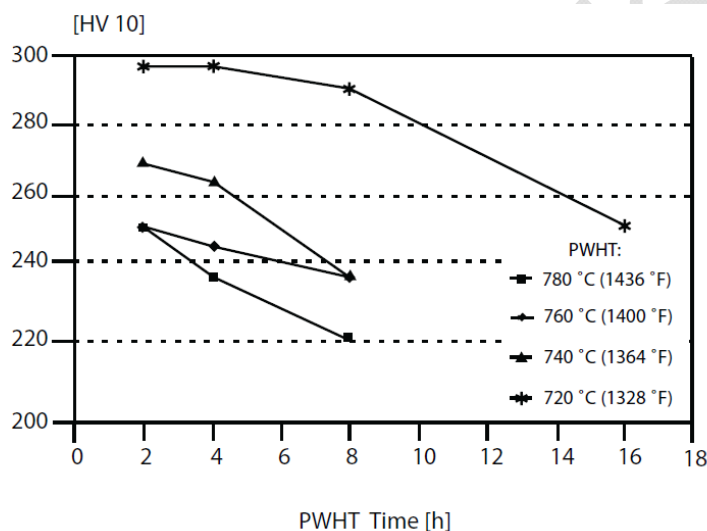


Figure 22—Influence of PWHT temperature on Vickers hardness of Grade 91 weld metal (B91) produced using SMAW

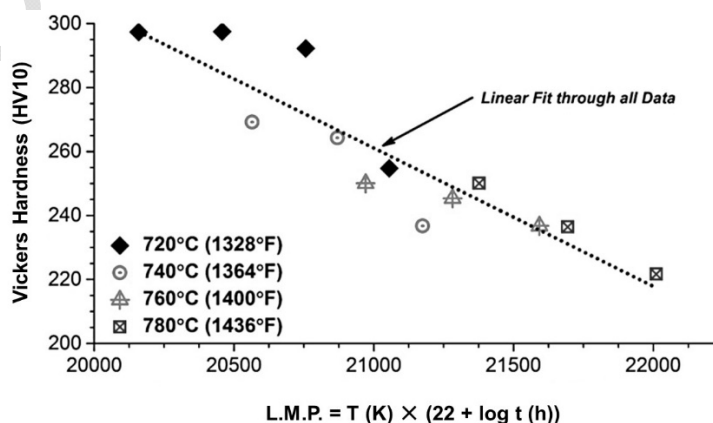


Figure 23—Effect of accumulated PWHT Temperature and holding time on Vickers hardness of Grade 91 steel weld metal (B91) using SMAW

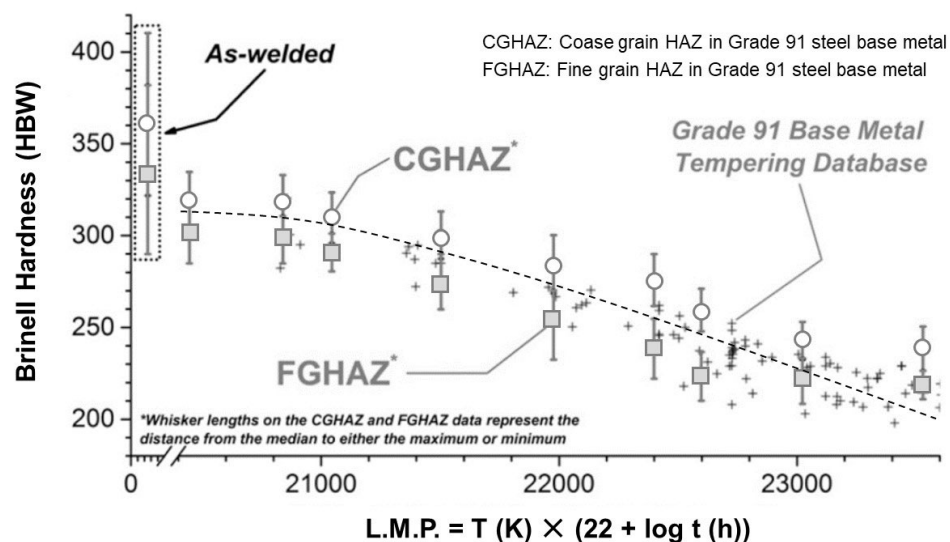


Figure 24—Effect of accumulated PWHT temperature and holding time on Brinell hardness of HAZ in Grade 91 steel base metal

6 Metallurgy and Environmental Related Failure Mechanisms

6.1 Oxidation and Sulfidation Resistance

Oxidation resistance and sulfidation resistance of Grade 91 is equivalent to that of **Grade 9 steel**. In air, oxidation resistance of Grade 91 **steel** is excellent even at 650 °C (1200 °F). In steam service, oxidation resistance of Grade 91 is similar to that of **Grade 22 steel**. Sulfidation resistance of Grade 91 **steel** is equivalent to that of **Grade 9 steel** and is superior to the lower Cr-Mo alloys. In H₂-H₂S services (e.g., hydro-treating equipment) SS cladding may be necessary in order to assure resistance to corrosion [46].

6.2 Carburization Resistance

Carburization resistance of Grade 91 steel is considered to be equivalent to that of **Grade 9 steel**. When Grade 91 steel is exposed to a carburizing environment or carbonaceous material at high temperatures (typically above 595 °C (1100 °F)), carbon is absorbed into the steel, creating a carburized layer. This leads to surface hardening, loss of ductility, embrittlement, spalling, or cracking depending on the depth of carburization. This type of failure typical observed in fired heater tubes. Significant carburization in Grade 91 steel may result in the replacement of components far earlier than the projected creep life originally intended. Carburization occurs not only during service operation but also during heat treatment applied in steel manufacturing process.

6.3 Wet Hydrogen Sulfide Cracking

Grade 91 steel may be susceptible to sulfide stress corrosion cracking (SSC) under aqueous sulfide conditions because of its high HAZ and weld hardness. **Grade 91 steel base metal and welds were post-weld heat-treated at temperatures between 750 °C (1375 °F) and 800 °C (1475 °F) for 2 hours [47].** The specimens were then subjected to Vickers hardness and slow strain-rate tensile tests in air and NACE TM0177 solution. The hardness test results revealed that the weld metal reached 290 HB, suggesting that it is difficult to meet the hardness limit of 248 HV specified by NACE MR0103 [48] after PWHT at normal temperatures. Furthermore, the crack growth rate of the specimens was faster in the NACE TM0177 solution than in the air, implying a low fracture toughness of Grade 91 steel in wet H₂S. Therefore, the use of Grade 91 steel in wet H₂S service is generally avoided. This includes services that may result in wet H₂S exposure during turnaround and upset conditions.

6.4 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 [494]. Grade 91 steel is not susceptible to high temperature hydrogen attack [46, 5048]. 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 [49].

6.5 Hydrogen Embrittlement, Hydrogen Diffusivity and Trapping

Hydrogen embrittlement as described here can occur below 150 °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, 5048, 5149, 5250].

6.6 Temper Embrittlement (TE)

Both Grade 9 and Grade 91 steels exhibit almost no susceptibility to TE. TE occurs when certain alloy steels are held within or cooled slowly through the embrittling temperature range of 370 °C to 550 °C (700 °F to 1030 °F). TE is manifested by an increase in the ductile to 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 testing. [5354].

6.7 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 microstructural 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 [5452, 5553].

Hardness traverses for SMAW, SAW and GMAW of P-91 steel weldments following 4 hours of tempering at 745 °C (1375 °F) are shown in Figure 25. This figure shows the soft zone, where the Vickers hardness is approximately 190 HV to 195 HV. The hardness is in the range of 205 HV to 220 HV in the unaffected base metal [5452].

At high stress levels, the Grade 91 steel may suffer Type IV cracking due to presence of such soft zone of reduced creep-rupture strength [3040, 5553]. The cross-weld creep strength at 600 °C (1110 °F) of T91/P91 weldments that contained Type IV fine-grained HAZ, showed about 20 % loss when compared to the base material [5654].

Power industry data on type IV cracking are likely based on the base materials fabricated before the importance of the N:Al ratio (refer to Section 5.2) was understood and specified for critical piping. Some operators reported that the minimum N:Al ratio, in combination with the 760–780 °C (1400–1440 °F) base metal tempering temperature and 740–760 °C (1360–1400 °F) PWHT temperature, reduced the Type IV cracking probability for refinery and petrochemical services, where typical operating temperatures are lower than in the power industry (refer to Figure 1). Performing Vickers hardness surveys of the HAZ to detect soft zones with a hardness of lower than 200 HV is a control step used by some operators to prevent Type IV cracking.

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 [5654, 5755]. 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 [2838].

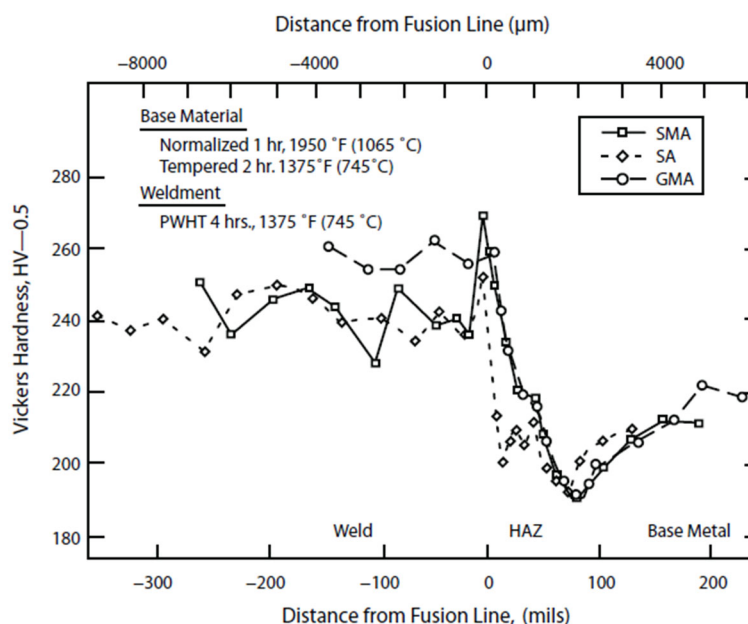


Figure 25—Hardness profile of Grade 91 weldment with Type IV soft zone

6.8 Hydrogen Stress Cracking

Higher-chromium martensitic steels can be susceptible to hydrogen stress cracking when left for prolonged periods in contact with moisture in an untempered condition [58]. Cold formed or welded components awaiting for the subsequent heat treatment are vulnerable to this type of cracking. Historically, hydrogen stress cracking has been reported in 400-series stainless steels, while it has also been found in Grade 91 steels in recent cases, though it has not been widely reported [59]. The cracks are typically found to be intergranular [59]. The reported failures on Grade 91 steels are mostly found in as-welded components within the range of 400–450 HV [60]. In addition to the hardened martensitic structure, the presence of stress (e.g., residual stress in welds) and the humid environment contribute to the occurrence of the cracking. This mechanism is commonly referred to in the power generation industry as “stress corrosion cracking”; for clarity it is called hydrogen stress cracking here. The dissolved hydrogen associated with this mechanism is generated by the corrosion reaction from contact with water and is not associated with a particular hydrogen-charging ion (e.g., H_2S or CN). It is also not associated with elevated temperature hydrogen or hydrogen charged into the steel during welding.

6.9 Creep-Fatigue

Creep-fatigue is an accumulation of damage due to both creep and fatigue (generally low cycle) at elevated temperatures. Consequently, the service life of the components subjected to creep-fatigue can be significantly less than that expected from pure creep or fatigue. The degree of interaction between the creep and fatigue varies with the stress, temperature, duration of the hold time (the amount of time in a cycle where the stress is held constant during fatigue loading), frequency of loading, and ductility of the material. Creep-fatigue on Grade 91 steel has been a concern for components which are subjected to load cycles during start-up and shutdown.

6.10 Steam Oxidation

Steels undergo oxidation in high-temperature steam environments with high oxide scale growth rates, which results in the exfoliation of these scales. This exposes fresh metal and further increases the oxidation rate. Moreover, these spalled oxides may damage downstream components. For Grade 91 steel, exfoliation can occur above approximately 550 °C (1020 °F). The time required for exfoliation decreases as temperature increases [61].

For boiler superheaters steam oxidation of Grade 91 steel tubing can cause premature failures as shown in **Figure 26** because the insulating oxide scale at the tube ID on the steam side can result in tube metal temperatures exceeding the design temperature. Failures have been experienced within 4 years at 600 °C (1110 °F). Chemical cleaning of the boiler tubing by removing the heavy oxide scale can prevent these failures.



Figure 26—Grade 91 steel boiler superheater tube (T91) that failed due to overheating in 4 years

7 Material Requirements

7.1 Base Metal

Table 1 lists specifications and CCs that are applicable to Grade 91 steel. As discussed in Section 5.2, the ASME material specifications define two sets of chemical compositions for Grade 91 steel wrought products (i.e., Types 1 and 2). Type 2 offers 1–7 % higher allowable stress values at or above 540 °C (1000 °F) compared to those for Type 1 (refer to Section 4.1). Using Grade 91 steels with the Type 2 chemical composition has been becoming more common for steam piping and tube in fossil fuel-fired power plants since the service temperature are normally well above 540 °C (1000 °F). Owner/operator or designer can define which type should be used.

Typically, impact testing is not conducted for Grade 91 steel base metal. However, when the minimum metal temperature is lower than room temperature, it is recommended to verify whether the material has sufficient impact toughness at that temperature. The lowest temperature is often achieved during pressure testing, and if there is a concern regarding the impact toughness of the material at ambient temperature or the temperature of the test media (e.g., water), it is advisable to consider prewarming the system before pressure testing.

7.2 Welding Consumables

7.2.1 Welding Consumable Specifications

The most common chemical compositional designation for Grade 91 steel welding consumables is B91, although B9 was used in older editions. Since 2020 edition of AWS A5.28 [62], B91C and B91CMn has been added. The B91C and B91CMn welding consumables offer improved creep strength, and oxidation and corrosion resistance at elevated temperatures, mainly with modified Nb and V concentrations and a higher limit for Ni + Mn concentrations [62].

The B91 designation requires a maximum Ni + Mn concentration of 1.40 %. As discussed in the following section (refer to Section 7.2.3.3), it is common to reduce further the Ni + Mn concentration in the filler metal or weld deposit. Therefore, to identify the Ni + Mn limit, supplemental designators (1.2) and (1.0) may be used: the B91 (1.2)

designation requires a maximum Ni + Mn concentration of 1.20 %, whereas the B91 (1.0) designation requires a maximum Ni + Mn concentration of 1.00 %.

As of this writing the following classification are defined in AWS and ASME specifications:

SMAW: E9015-B91, E9016-B91 or E9018-B91 per A/SFA-5.5 [6328];

GTAW: ER90S-B91, -B91C, -B91CMn per A/SFA-5.28 [6430];

GMAW (solid wire): ER90S-B91, -B91C, -B91CMn per A/SFA-5.28 [64];

GMAW (composite wire): E90C-B91 per A/SFA-5.28 [64];

SAW: EB91-B91 as per A/SFA-5.23 [6529];

FCAW : E91T1-B91 per A/SFA 5.29 [6634].

Table 10 shows chemical compositions of B91 welding consumables. Chemical composition of pipe product, SA-355 P91 Type 1, is also included in the table for comparison.

Table 10—Compositional specifications of Grade 91 steel welding consumables (B91)

Elements	SMAW Weld metal	GTAW / GMAW Solid wire			GMAW Weld metal from composite wire	SAW Weld metal	FCAW Weld metal	Reference
	E901X-B91 A/SFA-5.5	ER90S-B91 A/SFA-5.28	ER90S-B91C A/SFA-5.28	ER90S-B91CMn A/SFA-5.28	E90C-B91 A/SFA-5.28	B91 A/SFA-5.23	B91 A/SFA-5.29	SA-335 P91 Type 1 ^b
C	0.08 – 0.13	0.07 – 0.13	0.05 – 0.12	0.05 – 0.12	0.08 – 0.13	0.08 – 0.13	0.08 – 0.13	0.08 – 0.12
Mn	1.20 max. ^a	1.20 max. ^a	0.50 – 1.25	1.20 – 1.90	1.20 max. ^a	1.20 max. ^a	1.20 max. ^a	0.30 – 0.60
Si	0.30 max.	0.15 – 0.50	0.50 max.	0.10 – 1.90	0.50 max.	0.80 max.	0.50 max.	0.20 – 0.50
P	0.01 max.	0.010 max.	0.015 max.	0.015 max.	0.020 max.	0.010 max.	0.020 max.	0.020 max.
S	0.01 max.	0.010 max.	0.015 max.	0.015 max.	0.015 max.	0.010 max.	0.015 max.	0.010 max.
Ni	0.80 max. ^a	0.80 max. ^a	0.10 – 0.80	0.20 – 1.00	0.80 max. ^a	0.80 max. ^a	0.80 max. ^a	0.40 max.
Cr	8.0 – 10.5	8.0 – 10.5	8.0 – 10.5	8.0 – 10.5	8.00 – 10.50	8.0 – 10.5	8.0 – 10.5	8.00 – 9.50
Mo	0.85 – 1.20	0.85 – 1.20	0.80 – 1.20	0.80 – 1.20	0.85 – 1.20	0.85 – 1.20	0.85 – 1.20	0.85 – 1.05
V	0.15 – 0.30	0.15 – 0.30	0.10 – 0.35	0.15 – 0.30	0.15 – 0.30	0.15 – 0.25	0.15 – 0.30	0.18 – 0.25
Cu	0.25 max.	0.20 max.	0.40 max.	0.40 max.	0.20 max.	0.25 max.	0.25 max.	–
Al	0.04 max.	0.04 max.	–	–	0.04 max.	0.04 max.	0.04 max.	0.02 max.
Nb	0.02 – 0.10	0.02 – 0.10	0.01 – 0.08	0.01 – 0.08	0.02 – 0.10	0.02 – 0.10	0.02 – 0.10	0.06 – 0.10
N	0.02 – 0.07	0.03 – 0.07	0.01 – 0.05	0.01 – 0.05	0.03 – 0.07	0.02 – 0.07	0.02 – 0.07	0.030 – 0.070

^a Mn + Ni shall be 1.40 % maximum.
^b Heat Analysis

7.2.2 Role of Alloying Elements

Welding consumables are designed so that the mechanical property of the weld metal satisfies the minimum requirements of Grade 91 base metal. A study on the effect of single elements including optimum concentration 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 concentration is 0.04 %. Manganese and nickel have influence on strength properties. Nickel increases toughness, but the Ni + Mn concentration should be controlled as discussed in Section 7.2.3.3. Nb is required to maintain creep-rupture strength. Nb lowers toughness, but a maximum Nb concentration of 0.05 % is typical, above which dramatic loss of CVN would result [237, 6756]. Silicon concentration greater than 0.15 % decreases toughness but provides molten

pool deoxidation and **increases weld metal fluidity**, preventing porosity. Typically, a maximum Si **concentration** of 0.2 % to 0.3 % is acceptable. Carbon decreases toughness but 0.08 % minimum **concentration** is required for creep strength. Vanadium is required to maintain creep properties, however, **concentration** greater than 0.25 % significantly lowers toughness. A maximum vanadium **concentration** of 0.20 % is typical [237, 2838].

7.2.3 Chemical Composition and Residual Elements

7.2.3.1 Chromium Equivalent (Cr_{eq})

To obtain a proper balance between fracture toughness, creep-rupture strength and resistance to aging 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 [237] (all elements in wt. %):

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

7.2.3.2 Residual Elements

In order to minimize crater cracking or other forms of solidification cracking, low residual element weld filler metal are used. The phosphorous (P) and sulfur (S) concentrations in the Grade 91 steel weld metal are typically reduced to 0.010 % or less. Although X-bar with max. 15 is sometimes specified in purchaser specifications, the steel exhibits almost no susceptibility to TE. X-bar is calculated from the Bruscati [68] formula as follows:

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

where

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

It should be noted that, as discussed in Section 5.2, the Type 2 chemical composition for base materials is not related to weld metals.

7.2.3.3 Ni + Mn Concentration

The quantity of Ni + Mn affects the Ac_1 as shown in **Figure 9**. In order that **weld metal does not transform from ferrite (martensite) to austenite during PWHT**, the Ni + Mn **concentration** is typically limited to 1.2 % maximum. 1.0 % maximum is alternatively specified by some owner/operators. This provides an additional safeguard against austenite reformation during PWHT [237]. In addition, a balance between the Ni and Mn concentrations 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 [237]. Unlike the Ni or Mn concentration, a Co concentration of up to 0.80 % has little influence on the Ac_1 of the weld metal [69].

7.2.3.4 Mn/S Ratio

By observing 0.01 % or 0.010 % maximum sulfur and phosphorous **concentration specified in AWS B91 designation [63–65]**, problems such as crater cracking, maintenance of toughness after PWHT, or undesirable grain boundary effects can be avoided in SMAW, GMAW (solid wire), 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 **concentration** [237].

7.2.3.5 Oxygen Concentration

Low oxygen **concentration** is beneficial to achieving satisfactory toughness. The oxygen **concentrations** of GTAW, SMAW and FCAW weld deposit are typically **less than** 100 ppm, 300 ppm to 700 ppm, and 600 ppm to 1000 ppm,

respectively [3957]. 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 concentration [3958]. **Figure 27** shows the effect of oxygen concentration on toughness of P91 weldments made by GTAW, GMAW and SAW [237].

7.2.4 Low Hydrogen

Controlling hydrogen levels in weld metal throughout procurement and use and storage of welding consumables is of critical importance for successful fabrication. The diffusible hydrogen level of H4 is typically specified for SMAW electrodes, while H5 is often allowed for SAW fluxes and FCAW wires. Considering the use of the heat input and inter-pass temperature of the SAW process, some users allow a higher diffusible hydrogen criterion of H8 for SAW fluxes.

The diffusible hydrogen level is classified by the consumable manufacturer in accordance with AWS 4.3 [70] and is generally shown on the material certificate of the consumables.

7.2.5 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 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.

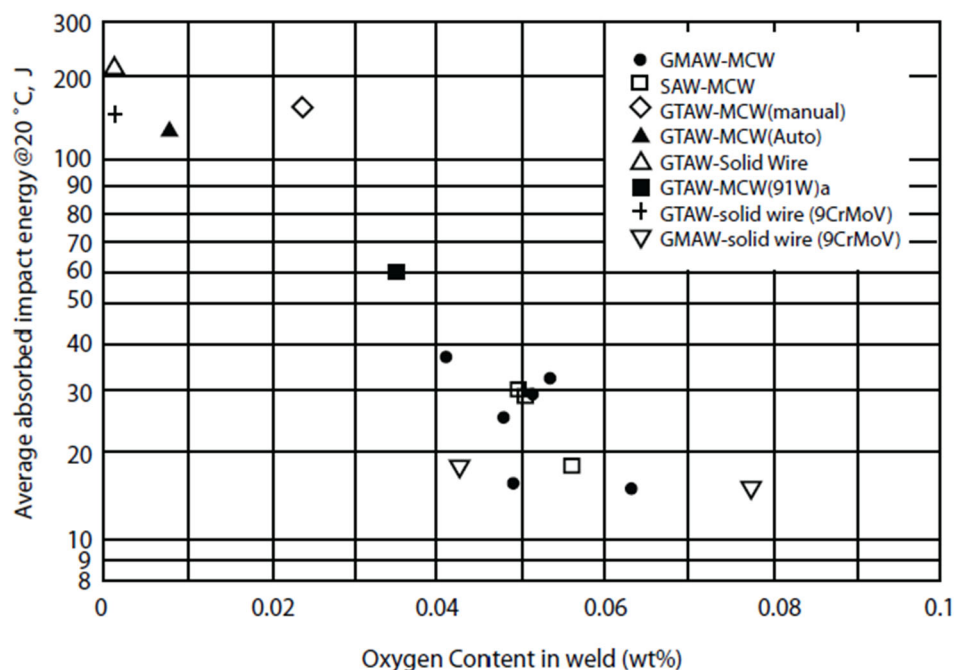


Figure 27—Effect of oxygen concentration on toughness for Grade 91 weld metals

7.2.6 Impact Testing

An average CVN of 27 J (20 ft-lb) or 34 J (25 ft-lb), with no values less than 22 (16 ft-lb) at room temperature or the minimum metal temperature is sometimes required; these requirements are typically not observed for less critical applications.

As discussed in Section 7.3.5, obtaining this level of toughness in welded metals is sometimes challenging, particularly in flux-type welding processes. Furthermore, early formulation work and later production of E9015-B91

consumables showed that even though the chemical composition may be within acceptable ranges, no ductility could be observed. This was caused by the minor and indistinguishable tramp elements present in the coating minerals. Thus, verifying the toughness of the welding consumables for flux-type welding processes is prudent.

Extra care is required to select the welding process and consumable brands if the impact test temperature is lower than the room temperature.

7.2.7 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 B91 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 B91 welding consumables [237, 7159].

8 Special Considerations during Fabrication and Welding

8.1 General Concerns

8.1.1 Hardness

Grade 91 steels have relatively high hardness in the HAZ or weld metal, reaching 400 HV or higher in the as-welded condition, making them unsuitable for application in hydrogen-inducing environments (e.g., wet H₂S services).

8.1.2 Toughness

Achieving toughness in the weld metal equal to that of the base metal has been an elusive goal for all but the GTAW process. Typical toughness requirements are discussed in Sections 7.1 (base metal) and 7.2.6 (welding consumables).

8.1.3 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 [237].

8.1.4 Weld Cracking

8.1.4.1 Cold Cracking

Preheat is necessary to avoid cold cracking (hydrogen assisted cracking) as is the use of low hydrogen weld consumables [5452], as discussed in Sections 8.3.8 and 7.2.4, respectively. DHT is also effective in avoiding cold cracking, particularly for thick-walled components or in cases where flux-type processes are used.

8.1.4.2 Hot Cracking

Hot cracking occurs 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 concentration of such elements is too high. Excessive heat input or excessively high interpass temperatures also lead to hot cracking [72], although the fabricators generally do not experience hot cracking, except for crater cracking.

8.1.4.3 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 **concentration** (e.g. 0.014 %) in Grade 91 steel reduces rupture ductility. Therefore, careful control of the **concentration** 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 [5452]. Laboratory investigators and commercial fabricators have reported no instances of reheat cracking in Grade 91 steel and reheat cracking has not been reported to be a problem [5452, 6756].

8.2 Bending

8.2.1 Cold Bending

When the cold forming (defined herein as bending at a temperature below 705 °C (1,300 °F)) strains of Grade 91 steels exceed a certain limit, the creep-rupture strength decreases drastically [73]. Thus, the application of a post-cold-bending heat treatment (i.e., stress relief at a temperature below A_{c1} or normalizing and tempering) can be considered, depending on the forming strain and the service temperature, and if the components are used in the creep range.

Previously, threshold values for such practices were found to depend on manufacturer or fabricator, although commonly, heat treatment had been omitted when the forming strain did not exceed 5 % [28]. Efforts have devoted to establishing a common requirement for post-cold-bending heat treatment. **Table 11** lists the established requirements specified in ASME Section I, Table PG-20 [14].

When cold bending is performed on Grade 91 steel weldments, PWHT is typically completed before the bending operation because the as-welded weldment has high hardness.

Table 11—Post-cold forming heat treatment requirements for Grade 91 steel

Forming strain, ϵ (%)	Design Temperature, T	
	540 °C (1000 °F) < T ≤ 600 °C (1115 °F)	600 °C (1115 °F) ≤ T < 620 °C (1200 °F)
$\epsilon \leq 5$	Not required	Not required
$5 < \epsilon \leq 20$	Stress Relief ^a	Stress Relief ^a
$20 < \epsilon \leq 25$		
$25 < \epsilon$	Normalizing and Tempering	Normalizing and Tempering
^a 730 °C (1350 °F) – 785 °C (1445 °F) for 1 h/25 mm (1 h/1 in.) or 30 min. minimum.		

8.2.2 Hot Bending

The optimum hot **forming** (defined herein as bending at or above 705 °C (1,300 °F)) temperature of Grade 91 steel 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, **bending** speed, **applicable pipe or tube diameter and thickness range**, etc.) [2838].

Hot bending of pipe **and tubes** is typically carried out using computer aided induction heated bending machines. After hot bending above critical temperatures, the material typically receives a complete post bending heat treatment consisting of **normalizing and tempering as discussed in Section 5.4.3** [2838]. 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 **post bending heat treatment** can result in premature failure **where creep is a major damage mechanism** [2838].

When warm thermal straightening is implemented, caution must be observed to not encroach on the lower critical (A_{c1}) temperature of the material, otherwise normalizing and tempering heat treatment will be required.

8.3 Welding

8.3.1 Introduction

This section reviews the industrial knowledge and practices involved in the welding of Grade 91 steels. The recommended requirements are provided in Annex F of API RP 582 [74].

8.3.2 Use of Filler Material

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 materials are to **meet the specifications listed in Section 7.2.1**.

8.3.3 Storage and Handling of 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 [752] in order to avoid moisture pick-up. **If SMAW electrodes or SAW fluxes are unintentionally exposed to a humid environment, re-drying is not advisable, and they are typically discarded.**

8.3.4 Welding Processes

8.3.4.1 SMAW, GTAW and SAW

SMAW and GTAW are the most commonly used welding processes for the fabrication of Grade 91 steels; however, their productivity is limited. SAW and combinations of these processes have **also been used for the fabrication of thick-walled or large-diameter components**.

Typically, the diameter of the welding wire or rod is limited to a maximum of 3.2 mm for GTAW and SAW, and to a maximum of 4.0 mm for SMAW in order to avoid excessive heat input. In most cases, acceptable mechanical properties are obtained using these processes.

8.3.4.2 FCAW

FCAW with external gas shielding are typically used for the fabrication of thick-walled piping in steam generation applications for fill and cap pass only. The use of FCAW often requires specific approval from the owner/operators.

Most commercial wires used for Grade 91 steel are of the rutile (TiO_2) type (T1 wires), which offer the capability of all-position welding. However, this type of wire produces a weld metal with a relatively high oxygen concentration, resulting in a lower impact toughness than other processes, as discussed in Section 7.2.3.5. **Figure 28** shows an example of CVN for FCAW [76]. In most cases, obtaining sufficient CVN toughness below room temperature is challenging.

Lime-fluoride (also referred to as basic) type wires (T5 wires) produces weld metal with low sulfur and oxygen concentrations, leading to higher impact toughness, although lime-fluoride type wires usually offer less welding operability compared to rutile type wires. If the impact test temperature is lower than room temperature, use of the lime-fluoride type wires can be considered.

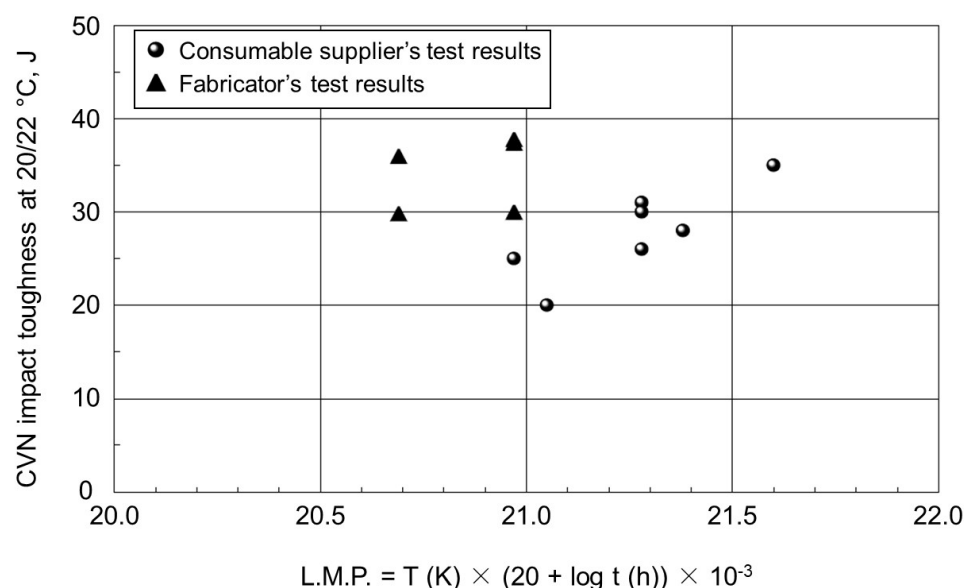


Figure 28—CVN Impact Toughness vs. L.M.P. of PWHT condition for Grade 91 FCAW weld metals (B91)

8.3.4.3 GMAW

Two types of wires are available for GMAW: solid and composite (metal-cored) wires. The former is classified as ER90S-B91, whereas the latter is classified as E90C-B91.

The GMAW process is prone to a lack of fusion or oxide inclusions when it is used for fill pass welding because the maximum acceptable levels of deoxidizing elements (e.g., Si and Mn) in the B91 consumables, which are essential for promoting the wetting action (improved fluidity) of the weld pool, are lower for B91 than for the other Cr-Mo consumables.

Thus, the GMAW process has not been widely applied for filling or cap passes of butt joints, although skilled welders or dedicated settings of automatic welding equipment can manage these problems.

Some fabricators use modified short-circuit GMAW for the root pass of circumferential pipes or tube welding, where the diameter is typically 6 inches or larger. The Si concentration of the wire is key to achieving acceptable side wall fusion; a Si concentration of 0.35 % is typically required for the wire.

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

OFW and ESW processes are not used for Grade 91 steels.

8.3.5 Back Purging and Shielding Gas

The back purging and shielding gases for GTAW are typically 100 % Ar.

The shielding gas for FCAW is usually Ar-CO₂ (up to 25 % CO₂). The CO₂ percentage is sometime limited to a 20 % maximum.

The shielding gas for GMAW is typically consists of Ar-O₂ (up to 5 % O₂) or Ar-CO₂ (up to 20 % CO₂).

Root passes of single-sided open root joints generally require back purging until at least the root and one hot pass or 6 mm (1/4") have been deposited except for cases where the use of short-circuit GMAW without back purging has been agreed by the manufacturer and the owner/operator. The purity of the back purging and shielding gases is controlled in accordance with AWS A5.32 (identical to ASME SFA-5.32) [77].

8.3.6 Welding Procedure Specification (WPS) and Qualification

8.3.6.1 General

WPSs and PQRs are typically qualified according to ASME Section IX. The P-number for Grade 91 steel is P-No. 15E as per ASME Section IX, whereas it was P-No. 5B, Group 2 in older editions.

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

Other than code requirements, essential variables for procedure qualification are often additionally defined by purchaser. A change in welding consumable brand, AWS/ASME classification, manufacturer, or its diffusible hydrogen designation are typically considered as essential variables.

Some owners/operators also regard PWHT temperature and holding time as essential variables within the limits of $\pm 15^\circ\text{C}$ ($\pm 25^\circ\text{F}$) and ± 1 h, respectively. Another good practice for addressing different PWHT conditions is to define the minimum and maximum PWHT conditions; by qualifying both, any PWHT condition from the minimum up to the maximum can be accordingly accepted.

8.3.6.2 Hardness Testing

Hardness testing is commonly included in welding procedure qualification. Vickers hardness surveys are typically performed on the cross-sectional surface of the procedure qualification test coupon after PWHT as guided in Annex C of NACE MR0103 [48].

A maximum hardness of 290 HV is most commonly specified, whereas a lower maximum hardness of 270 HV is sometimes selected for non-wet H₂S process service [78]. These maximum hardness limits are based on successful experience; no sufficient technical background has been documented. An EPRI publication targeting the power industry recommends case-by-case assessments rather than defining a general hardness limit [42]. Although some studies mentioned the use of a maximum hardness 248 HV [78], 248 HBW [79] or 241 HBW [46] for wet H₂S service, Grade 91 steel is typically not recommended for wet H₂S service.

In addition to the maximum hardness, a minimum hardness 195 HV [80] or 200 HV [42, 78] is sometimes specified. As discussed in Section 6.7, some operators impose the minimum hardness requirement in combination with the minimum N:Al ratio to reduce the type IV cracking probability in the soft HAZ.

However, as depicted in **Figure 25**, lower hardness values tend to be observed on the outer side of the HAZ (i.e., the fine-grained HAZ) in the Grade 91 steel welds. The Vickers hardness survey in accordance with Annex C of NACE MR0103 [48] does not intend to detect the hardness in the soft HAZ; NACE MR0103 has intended maximum hardness control. It should also be highlighted that for heavy-walled or multiple-cycle PWHTed components, it may not be feasible to satisfy the abovementioned minimum hardness owing to the longer PWHT holding time. Thus, when the minimum hardness needs to be specified, the manufacturer and the owner/operator can agree upon the criteria and measurement locations.

The hardness criteria discussed in this section is summarized in Table 12.

Table 12—Hardness limit for Grade 91 steel welds after PWHT

	Maximum	Minimum
Steam service	290 HV (typical)	195 or 200 HV (in some cases) ^a
Non-wet H ₂ S process service	270 HV (in some cases)	–
Wet H ₂ S service	Use of Grade 91 steel is not recommended	
^a The minimum acceptable hardness and the measurement locations can be agreed upon between the manufacturer and the owner/operator.		

8.3.6.3 Impact Testing

As discussed in Section 7.2.6, some owner/operators impose impact toughness testing at room temperature or the minimum metal temperature for welding procedure qualification. Typically, the acceptance toughness criteria are the same as those mentioned in Section 7.2.6. When impact testing is specified, the weld metal and HAZ are subjected to this test.

8.3.7 Heat Input

Typically, the maximum heat input is limited to 2.0–2.3 kJ/mm (50–58 kJ/in), which helps prevent hot cracking of the weld metal.

8.3.8 Preheat and Interpass Temperatures

8.3.8.1 Preheat

Figure 29 shows a typical temperature profile for welding Grade 91 steel.

Preheating is necessary to prevent cold cracking. ASME B31.1 [11] and B31.3 [12] mandate minimum preheat temperature of 205 °C (400 °F), though lower temperatures had previously been used depending on welding process or wall thickness. It is prudent to use electrical resistance or electrical induction to provide better temperature control and heat distribution during preheating [642].

Typically, the preheating temperature is maintained until the completion of welding or DHT, if applicable. This minimizes the risk of cold cracking and problems due to the as-welded toughness of the weld metal or HAZ. If interruption is unavoidable, refer to Section 8.3.11.

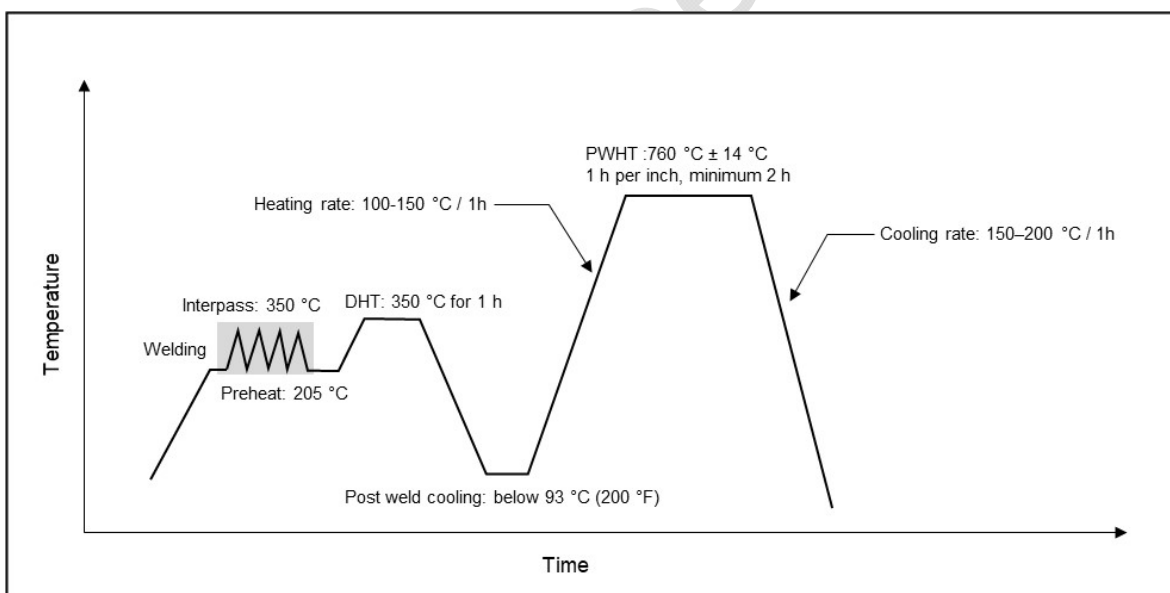


Figure 29—Typical temperature profile for welding Grade 91 steel

8.3.8.2 Interpass Temperature

Imposing an interpass temperature helps control the bead shape and prevents hot cracking in the weld metal. Interpass temperature is in the range of 250 °C to 315 °C (480 °F to 600 °F) is typically applied for GTAW, GMAW, FCAW and SMAW. However, for SAW, the interpass temperature is often limited to 250 °C (482 °F)

Shop and field fabrication rarely faces difficulties in complying with the specified interpass temperature, except for automatic SAW welding, where adequate monitoring is required. For highly constrained joints or filler metals with

Si and C concentrations close to their maximum composition limits of 0.50 % and 0.12 %, respectively, low interpass temperatures will be effective in preventing hot cracking.

8.3.9 Dehydrogenation Heat Treatment (DHT)

It is good practice to carry out DHT (also called “hydrogen bake(-out)”) after completion of the welding, and prior to post weld cooling (refer to Section 8.3.10). DHT is typically performed at 300–350 °C (570–660 °C) with a minimum holding time of 1 hour. Although ASME codes do not mandate DHT, it may be critical to avoid the risk of cold cracking, especially for thick-walled components, where the presence of residual hydrogen is a concern (e.g., where a flux-type welding process is applied).

8.3.10 Post Weld Cooling

As shown in **Figure 10**, the M_f is typically lower than 200 °C (390 °F). Cooling welds to below 95 °C (200 °F) before performing PWHT will maximize austenite-to-martensite transformation.

Austenite that is not transformed to martensite before PWHT will transform to martensite upon cooling from the PWHT temperature, leading to high hardness in the welds. Early attempts to weld Grade 91 steels revealed that a low M_f afforded excessive hardness above the specified maximum, leading to premature failure. Thus, post-weld cooling is considered a critical step in the proper fabrication of Grade 91 steel.

8.3.11 Interruptions

If welding is to be interrupted prior to the completion of welding, a good practice is to deposit at least 10 mm (3/8 in.) of weld metal or fill 25 % to 30 % of the groove thickness prior to the interruption. 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.

8.3.12 Postweld Heat Treatment (PWHT)

8.3.12.1 PWHT Temperature

Satisfactory tempering normally does not begin until the temperature exceeds 730 °C (1350 °F). However, if the PWHT temperature exceeds A_{c1} of the weld metal, the tensile and toughness properties can deteriorate. Therefore, the PWHT temperature should remain below A_{c1} of the weld metal. As discussed in 7.2.3.3 (**Figure 9**), A_{c1} is a function of the Ni + Mn concentration of the filler metal. Refer to 7.2.3.3 for the maximum limit of the Ni + Mn concentration.

PWHT is typically performed at 745–760 °C (1375–1400 °F). ASME Codes (Section I [14], B31.1 [11] and B31.3 [12]) allow PWHT at temperatures as high as 800 °C (1470 °F), where the maximum temperature to be reached during PWHT is lower than the A_{c1} of the filler metal. However, this approach may work only when limited batches of welding consumables are used for fabrication (Refer to **Figures 18** and **20** for the influence of PWHT temperature on the Vickers hardness and CVN, respectively).

8.3.12.2 PWHT Holding Time

ASME Codes (Section I [14], B31.1 [11] and B31.3 [12]) mandate a PWHT holding time of 1 hour per inch, with a minimum holding time of 30 minutes. However, a minimum holding time of 2 hours is typically specified to obtain sufficient weld tempering.

For services where a lower maximum hardness (248–270 HV) is required (see Section 8.3.6.2), determining the PWHT holding time by testing of welding procedure qualification is advisable. The holding time is sometime extended to 6 hours (Refer to **Figures 18** and **20** for the influence of PWHT holding time on the Vickers hardness and CVN, respectively).

8.3.12.3 Heating and Cooling Rates

For Grade 91 steel, typical heating rate above 400 °C (750 °F) is 100 °C/h to 150 °C/h (180 °F/h to 270 °F/h). The cooling rate from PWHT temperature to 400 °C (750 °F) is normally controlled to 150 °C to 200 °C/hr (270 °F/h to 360 °F/h) maximum. The weld is then cooled down to ambient temperature in still air [2838].

8.3.12.4 Temperature control and monitoring, and thermal gradient

It is recognized that the temperature control of Grade 91 steels during PWHT requires extra care compared with that of conventional Cr-Mo steels, such as Grade 11 or 22. As depicted in **Figure 5**, this tendency can be explained based on the thermal conductivity of Grade 91 steels, which lie between those of Type 304 SS and Grade 22 steels.

Proper thermocouple placement is key to conducting PWHT in the desired temperature range. Local PWHT has been done successfully using electrical resistance heating (ceramic pad) elements. In addition to the through-wall thermal gradients that are inevitable during PWHT, precautions are taken to ensure uniform heating for complex shapes and unequal thicknesses, plus any uneven heating effects from environmental conditions, e.g. chimney effects.

Guidelines for the local PWHT for piping and tubing using electric-resistance heating are provided in AWS D10.22 [81], which is now commonly used in Grade 91 steel fabrication specifications.

Redundant and multiple thermocouples are frequently installed.

8.4 Hardness Testing of Production Welds

8.4.1 Test Locations and Frequency

The production hardness is generally measured on the weld metal surface.

The hardness of HAZ is hardly measured accurately during the production hardness testing; the results are not representative, as they are an average of the hardness of the HAZ, base, and weld metals.

For piping, each welded seam is typically subjected to hardness tests. Whenever possible, production welds are tested on the process side. If this is impractical, testing can be performed on an external surface.

8.4.2 Acceptance Criteria

Typical values for acceptance criteria for weld metal are same as those discussed in Section 8.3.6.2 (also refer to Section 5.5.5.3 for hardness conversion, from Vickers to Brinell, vice versa).

8.4.2 Testing Equipment

The most commonly used testing equipment is a testing device employing the Ultrasonic Contact Impedance (UCI) method. Brinell-type portable hardness testers were used in several cases. The rebound method is not commonly used.

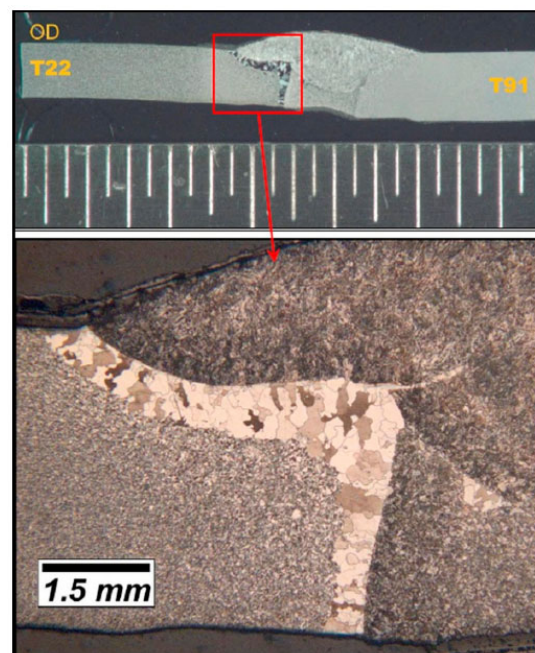
Difficulty in obtaining accurate hardness value through UCI device has been reported [82]. Before measurement, the oxidation scale and underlying decarburization layer are removed. It is advisable to obtain multiple readings at one measurement location and then exclude outliers. Vertical contact of the measuring device is also important for obtaining accurate hardness readings.

8.5 Dissimilar Metal Welding

8.5.1 General

There are three key aspects that must be considered when joining Grade 91 steel and lower alloy steels (e.g., Grade 22 steel) or when joining Grade 91 steel and austenitic stainless steels: difference in base metal thickness owing to

dissimilarities in their allowable stress values, formation of carbon migration zones (carbon-enriched and depleted), either during PWHT or high temperature service, driven by the difference in the Cr content (refer to **Figure 30** for a typical example [83]), and excessive tempering of the lower alloy steel due to the high PWHT temperature imposed by the Grade 91 steel.



Note: This weldment was made using filler metal matching to T91 and underwent PWHT prior to entering the service. The minimum hardness in the carbon-denuded region is ~100 HV 0.5.

Figure 30—Ex-service T22 to T91 weldment operating in a reheater section after 45,000 hours at service temperatures above 565 °C (1050 °F).

8.5.2 Joining to Cr-Mo Steels

Where there is a large difference in the base metal thickness, it is advisable to install a transition piece (**Figure 31**) to reduce stress concentrations and maintain welder-friendly joint configurations and fit-up, rather than joining base metals directly. This configuration is typically observed in thick-walled structures. However, failures have been reported transition pieces where cracks originate from sharp corners on the machined surface as a result of improper surface finishing (tool marks), causing stress risers. Accordingly, when installing a transition piece, the tapered transition point can be rounded.

Carbon migration is a concern because joining dissimilar base metals can result in the formation of a carbon-depleted zone or an over-tempered zone in the lower-Cr alloy steel, which can lead to insufficient creep rupture strength in the weldment. To overcome these problems, the use of a filler metal with an intermediate Cr concentration (e.g., 5Cr-0.5 Mo for joining Grade 91 and 22 steel) is common, although Grade 91 steel filler metal (B91) has been accepted in some cases [84]. Grade 91 steel is often buttered with the filler metal with the intermediate Cr concentration. The thickness of the buttered layer is typically 5–6 mm minimum. PWHT is then performed at Grade 91 temperatures to temper the buttered weld deposit and HAZ of the Grade 91 steel base metal. Welding between the buttered Grade 91 steel and lower-Cr alloy steel is then performed using the same filler metal, followed by PWHT at temperatures appropriate to temper the weld metal and the HAZ of the lower-Cr alloy steel. Temperatures in the range of 700 to 720 °C (1290 to 1330 °F) are typically selected when the weld metal is 5Cr-0.5Mo and the lower-Cr alloy is Grade 22 steel.

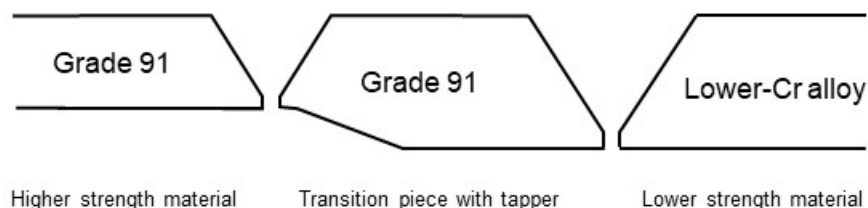


Figure 31—Geometry of the Joint of Grade 91 steel to lower-Cr alloy steel dissimilar metal welding

8.5.3 Joining to Stainless Steels

It is common practice to select Ni-based filler metals over Type 309 filler metals to minimize the formation of carbon migration zones. Because PWHT at Grade 91 temperature on the stainless steel base metal raises concerns related to sensitization, Grade 91 steel is typically buttered with a Ni-based alloy filler metal, and then PWHT is performed at Grade 91 PWHT temperature to temper the buttered weld deposit and HAZ of the Grade 91 steel base metal. Subsequently, the welding between the buttered Grade 91 steel and stainless steel was completed using the same Ni-based filler metal. Further PWHT is not performed.

A catastrophic failure of a dissimilar Type 316 SS to Grade 91 steel weldment has occurred, which was attributed to the presence of an untempered martensitic zone along the fusion line of the Grade 91 steel side. When making butter layers on Grade 91 steel, dilution of the Grade 91 steel base metal with the Ni-based alloy filler metal lowers the A_{c1} temperature along the fusion line. If thickness of the buttered layer is insufficient, the temperature increase during closure welding may facilitate the formation of an untempered martensitic zone. Making butter layers with a sufficient thickness can prevent reheating of the Grade 91 steel above the A_{c1} temperature.

8.6 Nondestructive Examination (NDE) of Production Welds

8.6.1 General

NDE is performed in accordance with ASME Section V [853] and the acceptable criteria per the applicable code. In general, personnel certified in accordance with ASNT SNT-TC-1A [8627] 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.

8.6.2 Visual Examination (VT)

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

8.6.3 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.

8.6.4 Liquid Penetrant Examination (PT)

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

8.6.5 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.

For complex, super high pressure steam systems in petrochemical facilities constructed of heavy wall Grade 91 piping, advanced UT techniques with recordable data, are used during the construction phase for establishing base-line data. This data is beneficial for evaluation of the system integrity after 100,000 hours or 200,000 hours of operation in the creep regime.

8.6.6 Radiography (RT)

A 100 % RT testing is commonly specified for full penetration groove welds of all items fabricated from Grade 91 steels. RT of fillet and T-type configurations welds is not practical in most cases, so other NDE methods such as UT are used.

8.7 Weld Repairs

The recommend requirements are provided in Annex F of API RP 582.

8.8 Pre-commissioning

Grade 91 steel contains 9 % chromium and develops an extremely dense, adherent oxide scale in piping systems. Steam blowing is a common pre-commission step for cleaning steam systems to protect downstream steam turbines from damage caused by oxide scale flakes. Steam blowing of large complex steam systems can be very time consuming, taking many days to weeks unless the pipe IDs are pretreated by bore grinding or grit blasting to remove the mill scale, prior to welding.

9 Examples in using Grade 91 Steels

NACE REFIN-COR 6.0 Survey [8735] for the use of Grade 91 steel in refinery applications is summarized in **Table 12**. In addition, **Table 13** summarizes the cases in which Grade 91 steel has been used and the experiences with its use, if available.

Table 12—Case histories of Grade 91 steel 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 ₂ S 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 13—Additional case history for using Grade 91 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.
Power Former in Refinery	Preheater	Before 2010	Steam	—
CCR	Heater Tubes	Before 2010	Feed Heater	Periodically replaced considering loss of creep ductility due to carburization, but still in service
Ethylene Unit	Convection Tubes	2009	High pressure steam	—
Ethylene Unit	Convection Tubes	Before 2020	High pressure steam	—
CO Boiler	Boiler tubes	Before 2020	High pressure steam	—
Steam Methane Reformer	Super Heater Coils	Before 2020	Steam	—
Tail Gas Treatment Unit	Waste heat boiler	Before 2020	Steam	—
Cogen Unit	—	Before 2020	Steam	—
Olefin Unit	Steam generating component	Under Construction in 2020	High pressure steam	—
Sulfur Recovery Unit Waste Heat Boiler	Superheater Tubes	—	High pressure steam	Creep fatigue failure due to design issues
Cogen Unit	Superheater Tubes	—	High pressure steam	—
Catalytic Reforming Unit	Heater Tubes	1997	Feed Heater (naphtha and hydrogen)	Good service history. No degradation or failures noted
Gas Oil Hydrotreating Unit	Heater Tubes	2004	Treat Gas Heater (hot hydrogen service)	Weld failure during high pressure regulatory hydrotest after 10 years of operation. Failed

				welds weren't properly heat treated during original fabrication.
Olefins Unit	Super high pressure steam system	2000	150 Barg / 540°C super high pressure steam	Good 25 years service w/o issues, except some valves with 17-4PH stems
Olefins Unit	Gas turbine regenerator	2022	Air / turbine exhaust gas	Toughness of 25 mm thick weldments at low MDMT

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10 Progress in Heavy-wall Pressure Vessel Fabrication Technology

10.1 Background

As Grade 91 steel offers excellent resistance to HTHA and high tensile strength at elevated temperatures, its application in hydroprocessing reactors has been discussed since 2000 [46]. Nowadays, internally clad/overlay Gr. 22V steel is widely used in hydroprocessing reactors. However, the design temperature of the steel is limited to 482 °C (900 °F) per ASME Code Section VIII, Division 2. An internal refractory lining is used when reactors are to be operated at temperatures above 482 °C (900 °F). However, this complicates the vessel fabrication scheme and increases the maintenance protocols.

For manufacturing hydroprocessing reactors that are operated at up to 500 °C (930 °F), technologies for heavy-wall Grade 91 steel production and pressure vessel fabrication projects were developed during 2010–2020. During this period, the two pressure vessel fabricators completed mockups to mimic a heavy-wall cylindrical shell course with nozzle welds.

10.2 Heavy-wall Plate

Grade 91 steel plates with thicknesses of 140 and 210 mm, conforming to ASME SA-387, were hot-rolled from an 82-metric-ton ingot [88, 89]. The chemical compositions examined at quarter- and half-thickness locations revealed no noticeable segregation. The plates were normalized at 1070 °C (1960 °F), followed by water quenching to obtain a fully martensitic microstructure throughout the thickness and tempering at 760 °C (1400 °F). **Figure 32** shows the microstructures of the 210 mm plate at sub-surface, quarter-thickness, and half-thickness locations, confirming the absence of δ -ferrite even at the half-thickness location. Vickers hardness profile throughout the wall thickness was between 188 and 205 HV. The mechanical properties of the 210 mm plate were examined at quarter-thickness after various simulated PWHTs (S-PWHTs), up to 22.5×10^3 in L.M.P (C=20). The yield strength and tensile strength at room temperature satisfied the limits specified in ASME SA-387 Gr. 91[17] and the CVN at -20 °C (-4 °F) was above 100 J (75 ft-lb). **Figure 33** presents the CVN transition curves obtained after a S-PWHT at 750 °C (1380 °F) for 12 hours. The fracture appearance transition temperature (FATT) was between -46 °C (-51 °F) and -25 °C (-13 °F).

A Grade 91 steel plate with thicknesses of 160 mm was also produced by another steel maker [90]; this plate was used to fabricate a mockup for pressure vessel shell course (refer to Section 10.5.1).

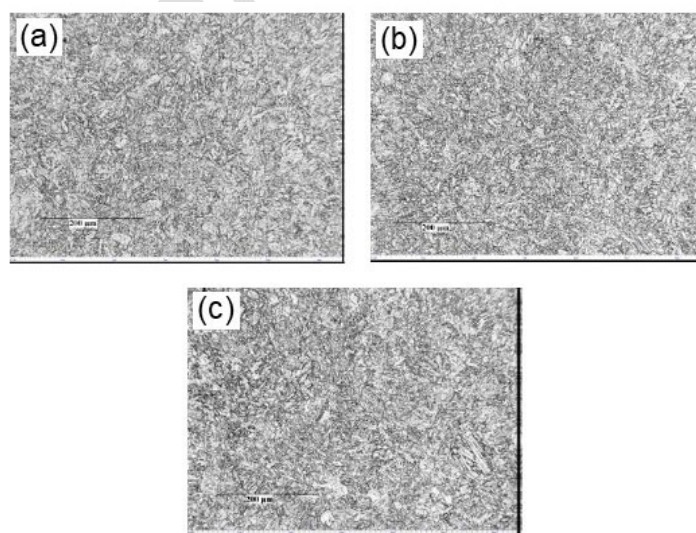


Figure 32—Micrographs obtained from Grade 91 steel plate with thicknesses of 210 mm:
(a) Sub-surface; (b) Quarter-thickness; (c) Half-thickness

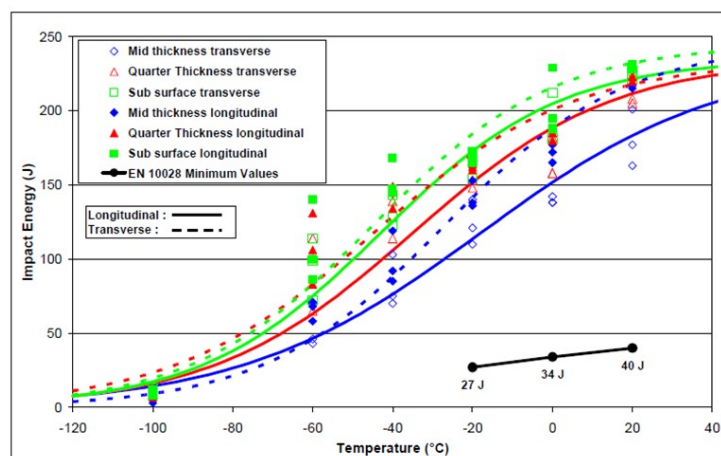


Figure 33—CVN toughness after PWHT (750 °C (1380 °F) for 12 hours) in longitudinal and transverse orientations (Grade 91 steel plate with thicknesses of 210 mm)

10.3 Heavy-wall Forged Ring

A Grade 91 steel forged ring with wall thickness of 225 mm (in the as-forged state, i.e., before machining, the thickness was 310 mm) conforming to ASME SA-336 F91 with an inner diameter of 4,000 mm and height of 2,580 mm was manufactured from an ingot weighing 190 metric tons [91]. The forged ring was normalized at 1060 °C (1940 °F) for 7 hours and water-quenched, followed by tempering at 740 °C (1365 °F) for 9 hours. The chemical compositions were measured at 225 mm from both ends of the ring at depths of quarter-thickness and half-thickness from the outer surface. Elemental segregation was not observed at any of the measured locations. **Figure 34** shows the tensile properties at room temperature and FATT at quarter- and half-thickness locations after a S-PWHT at 775 °C (1430 °F) for 32 hours. The yield strength satisfies the lower limit specified in ASME SA-336 F91 [17], whereas its tensile strength was slightly lower than the specified lower limit. The FATT was between -20 °C (-5 °F) and -10 °C (15 °F). This forged ring was used to fabricate another mockup for pressure vessel shell course (refer to Section 10.5.2).

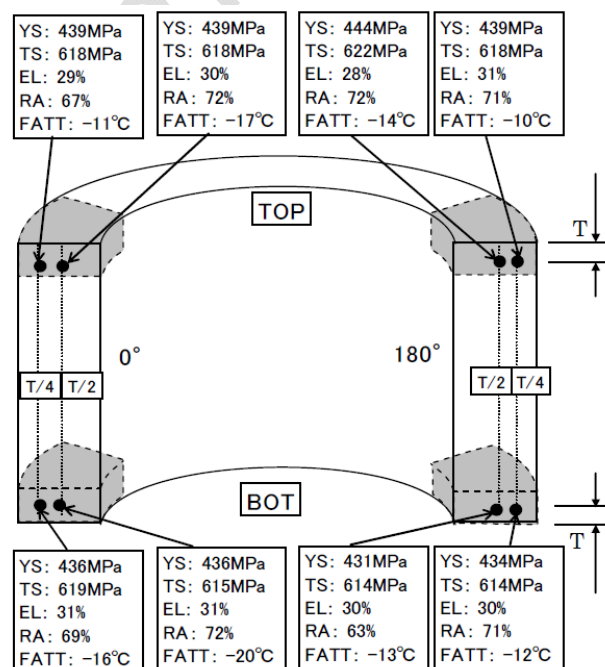


Figure 34—Tensile properties (RT) and FATT at quarter-thickness and half-thickness locations in forged ring

10.4 Welding Consumables

10.4.1 B91 welding consumables

Grade 91 steel welding consumables (B91) are widely used in power plant piping and boiler tube applications. They are primarily targeted for enhanced creep properties at high temperatures but not for toughness at low temperatures. Narrow-gap welding, which has typically been used in heavy-wall Grade 22V pressure vessel fabrication, is also not an originally considered for the usage of the consumables.

Solidification cracking tends to occur when tandem SAW is performed with B91 wires (**Figure 35**) [72]; trials using single SAW process with up a heat input of 2.8 kJ/mm (70 kJ/inch) were successful [92, 93]

Weld test coupons with thickness of 50 mm were prepared using single SAW, SMAW and GTAW with B91 welding consumables [94]. These coupons were subjected to S-PWHTs, up to 22.3×10^3 in L.M.P. (C=20). The mechanical properties were then evaluated (**Figure 36** [94]). The yield strength and tensile strength at room temperature satisfied the requirements specified in the ASME SA-387 Gr. 91 [17], and those of 540 °C (1000 °F) satisfied 90% of the values listed in ASME Section II, Part D, Table U [4] for ASME SA-387. The maximum Vickers hardness of the welds was 260 HV. The CVN values were within 50–150 J (35–110 ft-lb) for the SMAW and SAW weld metals, although higher values were observed for the GTAW weld metal.

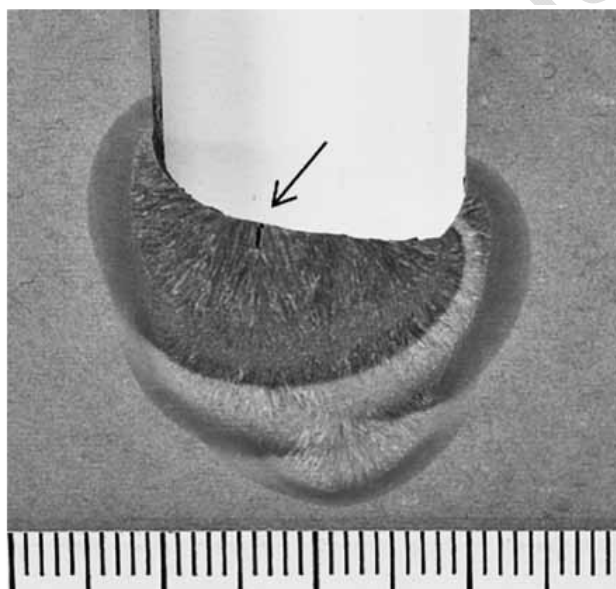


Figure 35—Hot cracking in narrow-gap B91 SAW welds.

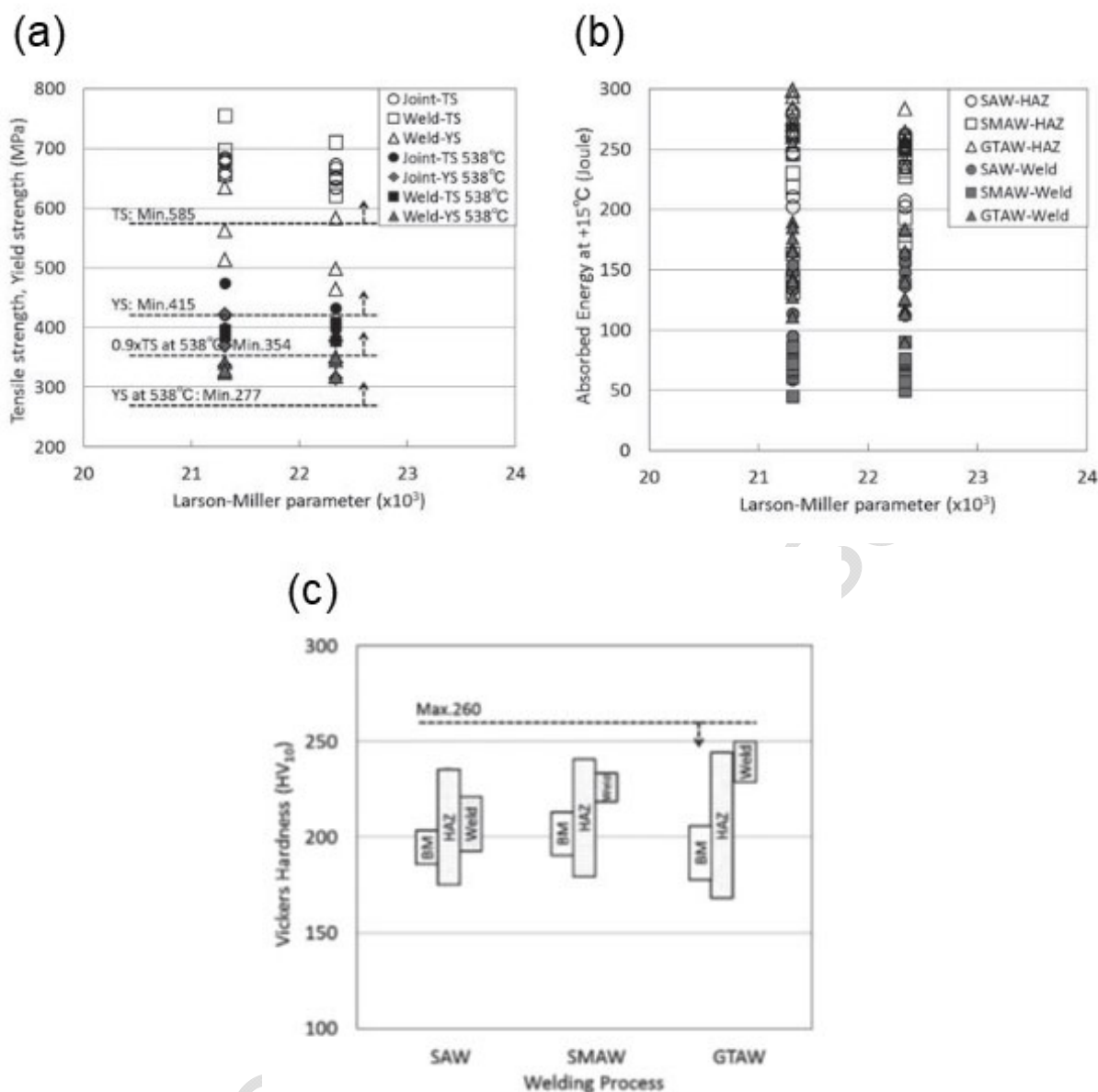


Figure 36—(a) Tensile properties (at room temperature and 540 °C (1000 °F)), (b) CVN toughness (at 15 °C (50 °F)), and (c) Vickers hardness of B91 weld metals.

10.4.2 Modified Welding Consumables

SAW Welding consumables intended for Grade 91 steel heavy-wall pressure vessel fabrication were newly developed by a welding consumables supplier [72, 95]. Compared with B91 consumables (i.e., for steam applications), the susceptibility to solidification cracking was reduced by reducing the C concentration, whereas the tensile strength and impact toughness increased with increasing Ni + Mn concentration. A weld test coupon was prepared using this modified welding consumables.

The chemical composition and mechanical properties of the SAW weld metal after S-PWHTs (760 °C (1400 °F) for 32 hours and 745 °C (1370 °F) for 8 hours) are shown in **Table 14**. The tensile properties were similar to those obtained in the aforementioned heavy-wall plate (Section 10.2) or forged ring (Section 10.3). However, the impact toughness was lower than that of the plate or forged ring. The use of the modified welding consumables to fabricate a mockup made of forgings is discussed in Section 10.5.2.

Table 14—Chemical composition and mechanical properties of SAW weld metal produced using modified welding consumables developed for heavy-wall pressure vessel fabrication

C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	N	Mn + Ni
0.05	0.13	0.85	0.006	0.004	0.77	8.26	0.93	0.23	0.05	0.04	1.62
			0.2% YS	TS	EL						
PWHT: 760 °C, 32 h			423 MPa	600 MPa	33%						
			CVN at 0 °C				CVN at 20 °C				
PWHT: 745 °C, 8 h			Each: 124 J, 103 J, 53 J, Average: 93 J				Each: 147 J, 166 J, 159 J, Average: 157 J				

10.5 Fabrication of Heavy-wall Mockups

10.5.1 Mock-up Made from Plate

A 160-mm-thick cylindrical shell course (inner diameter = 2,500 mm; height = 1,900 mm) comprising three nozzle welds was fabricated by a Japanese fabricator [92, 94]. ASME SA-387 Grade 91 plate with thickness of 160 mm (refer to Section 10.2) and normal B91 welding consumables (refer to Section 10.4.1) were used.

Cold forming was used to form the shell course from the plate without preheating. During welding fabrication, preheating was performed at a minimum temperature of 200 °C (390 °F), and DHT was performed at a minimum temperature of 300 °C (570 °F) for 1 hour minimum. After completion of four longitudinal weld seams, located at every 90° around the shell course, and three nozzle welds, one cycle of PWHT was performed at 750 °C (1380 °F) for 10 hours. A photograph of the completed mockup is shown in **Figure 37**.



Figure 37—Completed mock-up with a wall thickness of 160 mm, comprising four longitudinal weld seams and three nozzle welds

10.5.2 Mock-up made of Forged Ring

A 225-mm-thick cylindrical shell course (inner diameter = 4,000 mm; height = 2,580 mm) comprising one nozzle weld was fabricated by another Japanese fabricator [91, 95]. Two pieces of ASME SA-336 F91 forged rings were circumferentially welded using conventional B91 SMAW electrodes and the modified SAW wires and fluxes (Section 10.4.2). For the circumferential joint, SMAW (25 mm), single-SAW (50 mm), and tandem-SAW (150 mm) were employed.

The welding parameters used for fabrication are summarized in **Table 15** [96]. Preheating was performed at a minimum temperature of 200 °C (390 °F), and the interpass temperature was limited to 300 °C (570 °F). DHT was

carried out at a minimum temperature of 350–400 °C (660–750 °F) for 2 hours. A photograph of the mockup during fabrication is shown in **Figure 38** [72].

Table 15—Welding conditions used for mock-up fabrication

	Welding Process	Welding Current	Arc Voltage	Travel Speed	Heat Input
Shell	tandem-SAW	500–550 A	Lead: 30 V Trail: 30 V	450–500 mm/min	2.7–3.1 kJ/mm
Nozzle	singe-SAW	500–550 A	30 V	400 mm/min	2.3–3.5 kJ/mm
Preheating: 250 °C (480 °F) Interpass temperature: 300 °C (570 °F) DHT: 350–400 °C (660–750 °F) for 2 hours					



Figure 38—Mock-up with a wall thickness of 225 mm (forged ring), comprising one circumferential seam and one nozzle weld

11. Example of Grade 91 Heat Exchanger Shell Fabrication

A study was conducted to specify a replacement heat exchanger for one constructed of C-0.5Mo and Grade 11 steel that had reached its end of life. It suffers from degraded material properties owing to creep and graphitization of the internal components. A new heat exchanger with higher operating temperatures was proposed to debottleneck the unit. The mechanical design was complicated owing to space and weight limitations. Grade 22 steel and Type 347 SS alternatives were too heavy for existing civil structures. Therefore, a new heat exchanger with a Grade 91 steel shell, an O.D. of 5 m, and a wall thickness of 25 mm met the design requirements and was fabricated, as shown in **Figure 39**.



Figure 39—Regenerator heat exchanger with Grade 91 steel shell

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