

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

API TECHNICAL REPORT 938-B
FIRST EDITION, JUNE 2008



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

Downstream Segment

API TECHNICAL REPORT 938-B
FIRST EDITION, JUNE 2008



AVA Documents
Document Sharing Hub

Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

All rights reserved. No part of this work may be reproduced, stored in a retrieval system, or transmitted by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission from the publisher.
Contact the Publisher, API Publishing Services, 1220 L Street, N.W., Washington, D.C. 20005.

Copyright © 2008 American Petroleum Institute

Foreword

This recommended practice is under the jurisdiction of the API Subcommittee on Fiberglass and Plastic Tubulars.

For the purposes of this recommended practice the following definitions are applicable:

Shall: as used in a standard, “shall” denotes a minimum requirement in order to conform to the specification.

Should: as used in a standard, “should” denotes a recommendation or that which is advised but not required in order to conform to the specification.

May: as used in a standard, “may” denotes that a recommendation is optional.

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 1220 L Street, N.W., Washington, D.C. 20005. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually and updated quarterly by API, 1220 L Street, N.W., Washington, D.C. 20005.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, D.C. 20005, standards@api.org.

Contents

	Page
1 Scope	1
2 Terms, Definitions, Acronyms, and Symbols	1
2.1 Terms and Definitions	1
2.2 Acronyms	1
2.3 Symbols	3
3 Base Metal Chemical, Physical, Mechanical and Metallurgical Properties	3
3.1 General.	3
3.2 Chemical Composition	3
3.3 Physical Properties	3
3.4 Metallurgical Properties	7
3.5 Mechanical Properties	14
4 Metallurgy and Environmental Related Failure Mechanisms	21
4.1 Oxidation and Sulfidation Resistance	21
4.2 Wet Hydrogen Sulfide Cracking	21
4.3 Hydrogen Attack Resistance	22
4.4 Hydrogen Embrittlement, Hydrogen Diffusivity and Trapping	22
4.5 Temper Embrittlement	22
4.6 Type IV Cracking	22
5 Material Requirements	23
5.1 Base Metal	23
5.2 Welding Consumables	23
6 Fabrication and Welding Requirements	27
6.1 General Concerns	27
6.2 Cold Bending	27
6.3 Hot Bending	28
6.4 Welding	28
7 Examples of 9Cr-1Mo-V Applications and Refinery Experiences.	36
7.1 Experiences	36
7.2 Applications	36
Bibliography	40
Figures	
1 Thermal Conductivity	4
2 Mean Coefficient of Linear Expansion	6
3 Modulus of Elasticity vs. Temperature	7
4 Deep Hardening Behavior of Grade 91 Steel	8
5 Effect of Ni + Mn on AC ₁	9
6 CCT Diagram of Grade 91 Steel	9
7 Typical Microstructure of T/P91 After Normalizing and Tempering	10
8 Grain Coarsening Behavior	13
9 Typical Plot of Hardness vs. Tempering Temperature for Heat Rolled and Normalized Grade 91 Steel	14
10 Yield (0.2 %) and Ultimate Tensile Strengths vs. Temperature for Grade 91 Alloy Steel	15
11 Charpy Impact Energy vs. Temperature of Grade 91 Alloy Steel	17
12 Stress Rupture Strength of Commercial Heats of N + T Grade 91 Alloy Steel at 593 °C (1100 °F)	20
13 Comparison of Creep Rupture Strength of Grade 91 Steel Weldments to Base Metal	21

14	Hardness Profile of Grade 91 Weldment with Type IV Soft Zone	23
15	Effect of Oxygen Content on Toughness for Selected Grade 91 Weldments	26
16	Influence of PWHT Temperature on Toughness of Grade 91 Filler Metal	33
17	Influence of PWHT Temperature and Holding Time on Hardness of Grade 91 SMAW Weld Metal. . .	34

Tables

1	Specifications and Code Cases for 9Cr-1Mo-V Steels	4
2	Chemical Composition (Heat Analysis) of 9Cr-1Mo-V and 9Cr-1Mo Steels.	5
3	Physical Properties of T/P91 Alloy vs. Temperature	6
4	Heat Treatment and Mechanical Properties of 9Cr-1Mo-V Steel and 9Cr-1Mo Steel	11
5	Temperature Limits for 9Cr-1Mo-V Steel per ASME Section VIII, Division 1 (Section II, Part D)	16
6	Temperature Limits of 9Cr-1Mo-V Steel per Section VIII, Division 2 (Section II, Part D)	16
7	Maximum Allowable Stress Values “S” in ASME Section VIII, Division 1, for 9Cr-1Mo-V Steel in Comparison with 2 1/4 Cr-1Mo-V, 2 1/4 Cr-1Mo 9Cr-1Mo Alloy Steels and 316H Stainless Steel	18
8	Design Stress Intensity Values “S _m ” in ASME Section III, Division 2, for 9Cr-1Mo-V Steel in Comparison with 2 1/4 Cr-1Mo, 2 1/4 Cr-1Mo-V, 9Cr-1Mo Steels and 316 H Stainless Steel	19
9	Creep Rupture of ASTM A213 Grade T91 Steel.	20
10	Compositional Specifications of 9Cr-1Mo-V Steels Weld Consumables	24
11	Dissimilar Welding Filler Metal Selection for 9Cr-1Mo-V Steels	35
12	Guideline for PWHT Temperature for Dissimilar Metal Welds.	35
13	Case Histories of Grade 91 Refinery Uses Reported in NACE REFIN-COR	37
14	Additional Case History for Using Grade P91/T91 Steel	38

Introduction

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

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

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

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

1 Scope

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

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

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

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

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

2 Terms, Definitions, Acronyms, and Symbols

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

2.1 Terms and Definitions

2.1.1

weld

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

2.1.2

weldment

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

2.2 Acronyms

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

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

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

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

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

2.3 Symbols

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

3 Base Metal Chemical, Physical, Mechanical and Metallurgical Properties

3.1 General

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

3.2 Chemical Composition

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

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

3.3 Physical Properties

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

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

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

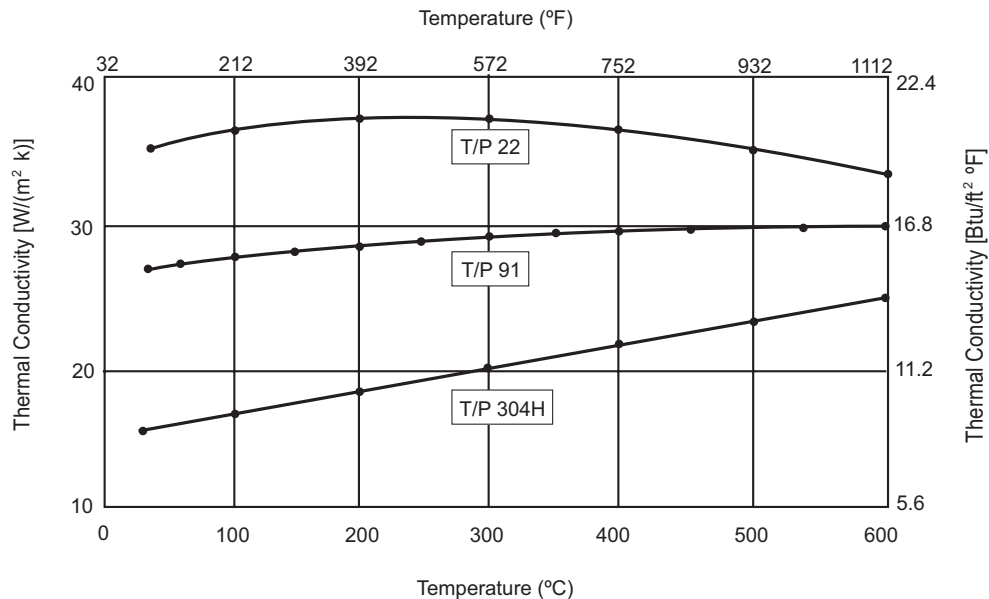
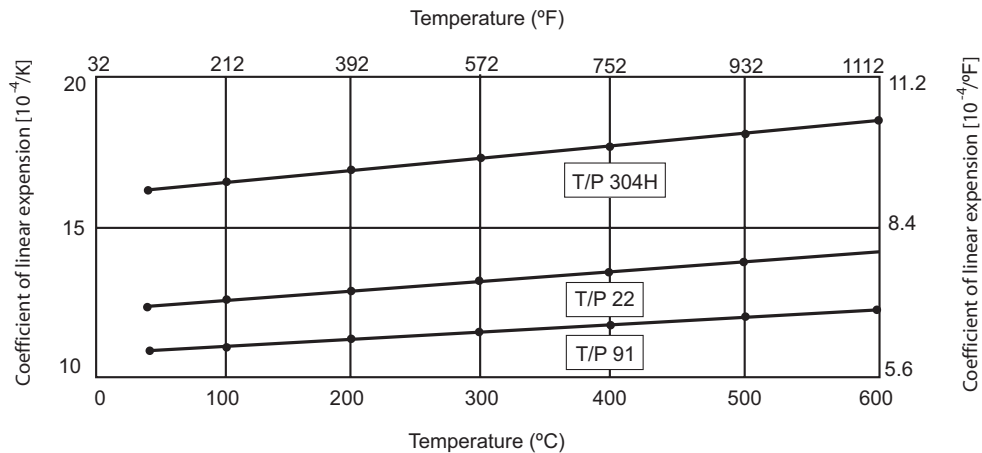
**Figure 1—Thermal Conductivity**

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

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

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

Temperature °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 2—Mean Coefficient of Linear Expansion**

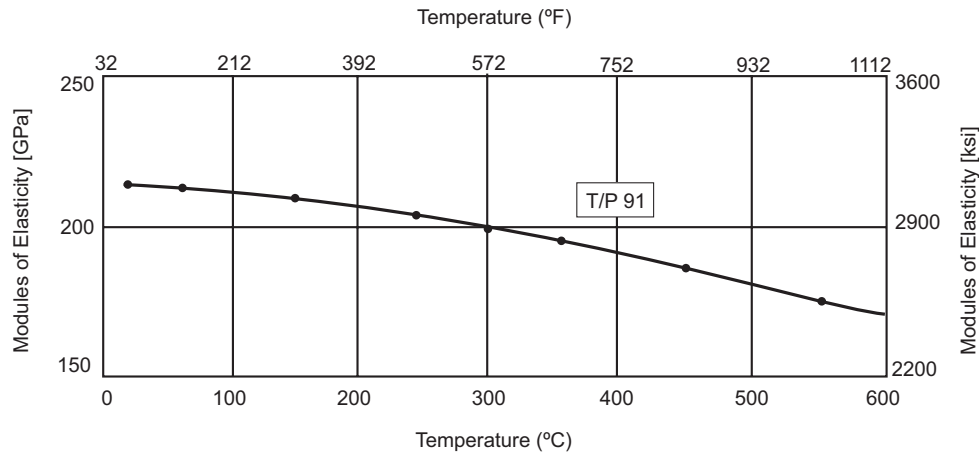


Figure 3—Modulus of Elasticity vs. Temperature

3.4 Metallurgical Properties

3.4.1 Transformation Data

Alloy 9Cr-1Mo-V is a deep hardening steel. Figure 4 shows the Jominy end quench HRC hardness test results for 101.6 mm (4 in.) long bars of Grade 91 and 2 1/4 Cr-1Mo steels of approximately the same carbon content [39, 40]. A metallurgical investigation showed that the critical cooling rate to obtain 100 % Martensite is about 0.2 °C/s (0.36 °F/s) [39]. Depending on the chemical composition, the A_{c1} temperature was found to be as low as 785 °C (1445 °F) with most values between 800 °C (1472 °F) and 830 °C (1526 °F). The A_{c3} temperature was found to be in the range of 891 °C (1635 °F) and 941 °C (1725 °F) [38]. Figure 5, shows A_{c1} values obtained for Grade 91 products listed in Table 2 as a function of their minimum and maximum Ni + Mn contents [37]. As indicated in 6.4.6, it is important that the A_{c1} is not exceeded during PWHT.

3.4.2 Martensite Formation

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

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

3.4.3 Heat Treatment

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

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

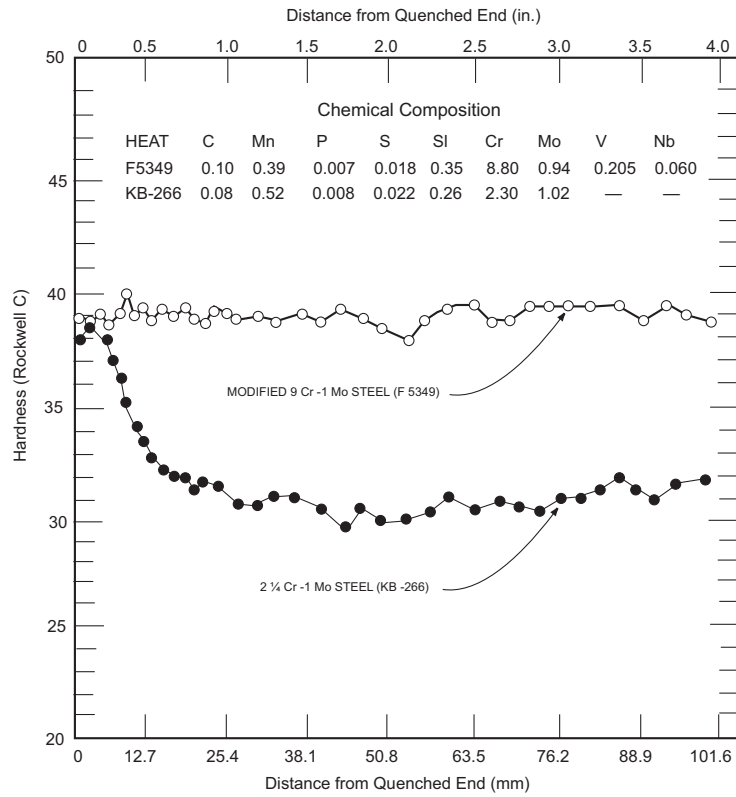


Figure 4—Deep Hardening Behavior of Grade 91 Steel

to permit PWHT at a higher temperature to achieve acceptable weld metal hardness as indicated in 6.4.6.1 [43]. Higher tempering temperature improves toughness but slightly reduces Grade 91 mechanical properties (tensile and yield strengths and elongation percent). It is important to be sure that the tempering temperature does not exceed 788 °C (1450 °F) to avoid getting into the two-phase region, i.e. exceeding 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 [42].

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

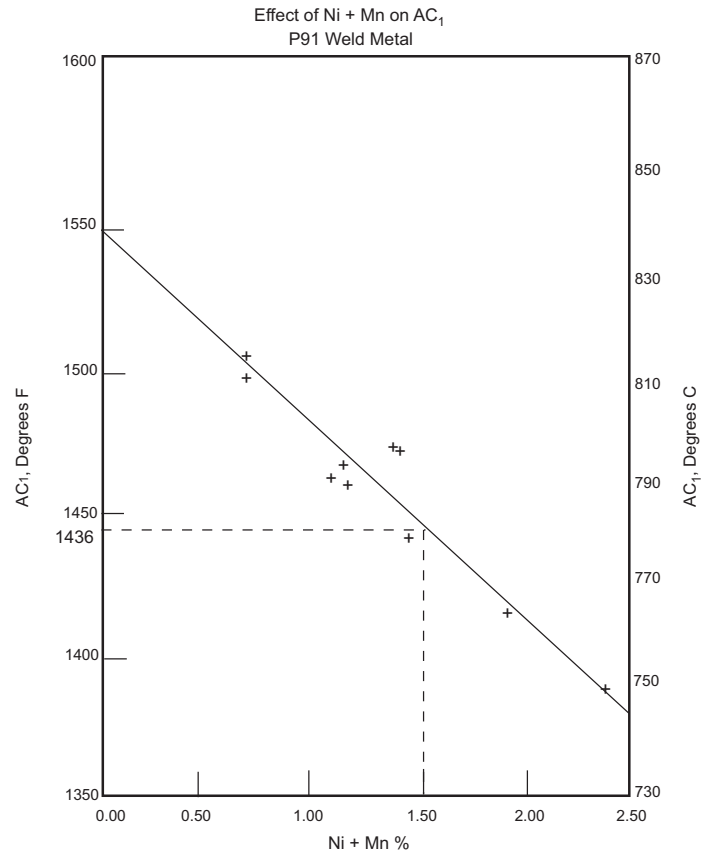


Figure 5—Effect of Ni + Mn on AC₁

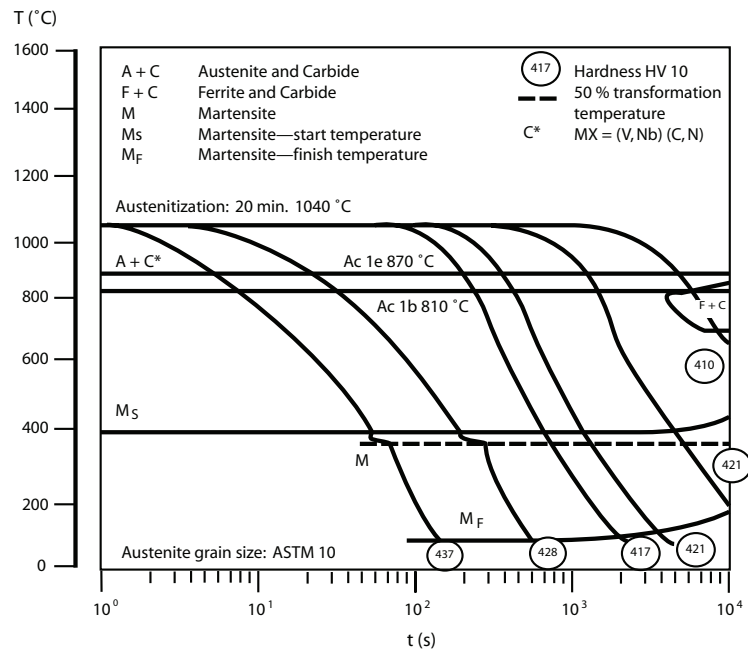


Figure 6—CCT Diagram of Grade 91 Steel