

Technical Report on the Materials and Fabrication Issues of 1¹/₄Cr-1¹/₂Mo and 1Cr-1¹/₂Mo Steel Pressure Vessels

API TECHNICAL REPORT 934-D
FIRST EDITION, SEPTEMBER 2010



AMERICAN PETROLEUM INSTITUTE



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Downstream Segment

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Introduction

Numerous $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ and $1\text{Cr}-1\frac{1}{2}\text{Mo}$ vessels have been constructed and successfully used in various applications in petroleum industry and in other types of service applications. These vessels have been constructed to the requirements of the *ASME Boiler & Pressure Vessel Code*, Section VIII, Divisions 1 and 2, and to various international pressure vessel codes and standards. The $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ and $1\text{Cr}-1\frac{1}{2}\text{Mo}$ vessels are typically used in service conditions (e.g. high temperature and/or high pressure hydrogen), which require heavy walls and cause in service deterioration. As such, the steels are subject to special requirements, such as notch toughness, elevated temperature tensile properties, hardness, fabrication heat treatments, etc., which may limit the maximum thickness to be able to meet the desired properties. Corrosion protection by stainless steel weld overlay or cladding may also be required. It is important to know the limitations of these materials and precautions needed to avoid problems during fabrication and to eliminate or minimize in service deterioration. To better understand the current practices in fabricating $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ and $1\text{Cr}-1\frac{1}{2}\text{Mo}$ steels a questionnaire was distributed to steel fabricators as part of this study. Responses to this questionnaire have been used in this study and are summarized in Appendix 1.

Technical Report on the Materials and Fabrication Issues of $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ and $1\text{Cr}-1\frac{1}{2}\text{Mo}$ Steel Pressure Vessels

1 Scope

This API document provides background information and guidance on the implementation of API 934-C, *Materials and Fabrication of $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ Steel Heavy Wall Pressure Vessels for High Pressure Hydrogen Service Operating at Temperatures at or Below 825 °F (426 °C)* and API RP 934E, *Materials and Fabrication of $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ Steel Heavy Wall Pressure Vessels for High Temperature Service Operating Above 825 °F (426 °C)*, and should be used as a supplement to these recommended practices.

In recent years it has been recognized that there are important distinctions that need to be considered for $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ steels. Whereas API 934-A continues to provide materials and fabrication requirements for new $2\frac{1}{4}\text{Cr}-1\text{Mo}$ and $2\frac{1}{4}\text{Cr}-1\text{Mo}-\frac{1}{4}\text{V}$ steel heavy wall pressure vessels in high temperature, high pressure hydrogen service, different material, and fabrication requirements have been developed for $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ steel heavy wall pressure vessels. These requirements are covered in RP 934-C and 934-E.

This document contains a description of key damage mechanisms that relate specifically to $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ pressure vessels used in a variety of services. These damage mechanisms include elevated temperature damage mechanisms such as “reheat cracking” or “creep embrittlement” as well as other damage mechanisms that may occur at lower temperatures. Not all services are affected by the same damage mechanisms due to significant differences in service conditions. For example, Hydrofiner Reactors tend to operate at lower temperatures and higher pressures than Catalytic Reformer Reactors, and Coke Drums and FCC Reactors do not see hydrogen service. Also, as a result of the different services causing different damage mechanisms, the fabrication requirements also differ. To this end, API has developed two separate recommended practices to take this into account: API 934-C and 934-E. Accordingly, background information and guidance on the implementation of these two new documents are needed.

This document provides information and guidance on successful practices for fabrication of $1\frac{1}{4}\text{Cr}-1\frac{1}{2}\text{Mo}$ steel heavy wall pressure vessels for the intended services of both API 934-C and 934-E. The survey of steel producers and vessel fabricators (Annex 1) indicates that there is a need to evaluate the effect of heat treat cycles on materials properties (CVN toughness, tensile and yield strength). For this reason the connection of the Larson-Miller parameter is emphasized to better align the user needs with fabrication requirements. However, detailed attention is still needed to implement this approach for individual cases, as there are many secondary variables, such as heating and cooling rates that need to be considered and discussed between the user and the fabricator. The areas of fabrication that are covered in this document include steel making as related to chemical composition, heat treatment, forming, and welding.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Recommended Practice 934-A, *Materials and Fabrication of $2\frac{1}{4}\text{Cr}-1\text{Mo}/\frac{1}{4}\text{V}$, $3\text{Cr}-1\text{Mo}$ and $3\text{Cr}-1\text{Mo}/\frac{1}{4}\text{V}$ Steel Heavy Wall Pressure Vessels for High Temperature High Pressure Service*

API Recommended Practice 934-C, *Materials and Fabrication of $1\frac{1}{4}\text{Cr}-1\text{Mo}$ Steel Heavy Wall Pressure Vessels for High Pressure Hydrogen Service Operating at or Below 825 °F (440 °C)*

API Recommended Practice 934-E, *Recommended Practice for Materials and Fabrication of $1\frac{1}{4}\text{Cr}-1\text{Mo}$ Steel Pressure Vessels for Service Above 825 °F (440 °C)*

ASME *Boiler and Pressure Vessel Code*, ¹ Section VII, Division 1 and Division 2

ASME *Boiler and Pressure Vessel Code*, Section II, Part D

3 Terms, Definitions, and Acronyms

For the purposes of this document, the following definitions apply.

3.1 Definitions

3.1.1

ASME Code

ASME *Boiler and Pressure Vessel Code*, Section VIII, Division 1 and Division 2.

3.1.2

final PWHT

The last post-weld heat treatment after fabrication of the vessel and prior to placing the vessel in service.

3.1.3

hot forming

Mechanical forming of vessel components above the final PWHT temperature.

3.1.4

Larson-Miller Parameter (LMP)

Formula for evaluating heat treatments:

$$\text{LMP} = T \times (20 + \log t)$$

where

T is temperature in °R, where °R = °F + 460 or [(°K), where °K = °C + 273];

t is the time at temperature in hr;

C is the constant (typically 20 for low alloy steels).

The total LMP is a combination of the time during tempering of the material, as well as the PWHT cycles, including all intermediate heat treatments above 900 °F (482 °C).

3.1.5

minimum PWHT

Specified heat treatment of test specimens used to simulate the minimum heat treatments (austenitizing, tempering, and one PWHT cycle). To determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller Parameter may be used.

3.1.6

maximum PWHT

Specified heat treatment of test specimens used to simulate all fabrication heat treatments (austenitizing, tempering, the final PWHT, a PWHT cycle for possible shop repairs, and a minimum of one extra PWHT cycle for future use by the owner).

NOTE For minimum and maximum PWHT cycles: to determine the equivalent time at one temperature (within the PWHT range), the Larson-Miller Parameter may be used. *The results are to be agreed upon by the purchaser and the manufacturer.*

¹ ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.

3.1.7**J-factor**

Formula for evaluating susceptibility to temper embrittlement (typically used for base metal).

$$\text{J-factor} = (\text{Si} + \text{Mn})(\text{P} + \text{Sn}) \times 10^4$$

3.1.8**X-bar**

Formula for evaluating susceptibility to temper embrittlement (typically used for welding materials).

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

3.1.9**fine grain practice**

A steelmaking practice that is intended to produce a killed steel that is capable of meeting the requirements specified for fine austenitic grain size.

3.2 Acronyms

For the purposes of this document, the following acronyms apply.

CMTR	certified material test report
CVN	Charpy V-notch energy
FCC	fluid catalytic cracking
DHT	dehydrogenation heat treatment
FN	ferrite number
HAZ	heat-affected zone
HBW	Brinell hardness with tungsten carbide indenter
HV	Vickers hardness
Kv	alternative expression for Charpy V-notch energy
MDMT	minimum design metal temperature
MT	magnetic particle testing
NDE	nondestructive examination
PT	liquid penetrant testing
PWHT	post-weld heat treatment
RT	radiographic examination
UT	ultrasonic examination

4 Background**4.1 1¹/₄Cr-1¹/₂Mo Refinery Equipment**

Several refinery processes use 1¹/₄Cr-1¹/₂Mo steel pressure vessels and equipment. Some are listed in Table 1. Attention will be given to two major types of equipment: reformer reactors and hydrotreater reactors. Both operate with significant hydrogen partial pressures. However, there are significant distinctions between these two types of reactors in terms of operating temperatures, pressures, and wall thickness. Hydrotreater reactors typically operate in the temperature range of 750 °F to 850 °F (399 °C to 454 °C) and a pressure range of 1000 psi to 2000 psi (6.9 MPa to 13.8 MPa). Wall thickness ranges from 4 in. to 7 in. (100 mm to 175 mm). In contrast, catalytic reformer reactors typically operate in the temperature range of 900 °F to 1050 °F (482 °C to 566 °C) and a pressure range of 100 psi to 300 psi (0.69 MPa to 2.1 MPa). Wall thickness ranges from 2 in. to 4 in. (50 mm to 100 mm). Catalytic reformer

reactors can operate either in a cyclic mode (shut down every few days), semi-regenerative mode (shut down every few months), or continuous mode (at constant temperature without shutting down for regeneration).

Because of the differences in operating conditions and damage mechanisms between catalytic reformer reactors and hydrotreater reactors, materials properties considerations are not completely the same. Whereas room temperature toughness considerations are important for both of the above applications, creep related damage mechanisms must be taken into account for catalytic reformer reactors and reactors in certain services other than hydrotreating.

Other typical uses of thick wall $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steel equipment include coke drums and FCC reactors. Typical characteristics for these vessels are also shown in Table 1.

Table 1—Typical Refinery Vessels Using $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ Steels

	Approximate Thickness Range in. (mm)	Approximate Temperature Range °F (°C)	Typical Pressure psi (MPa)	Damage Mechanisms (Mechanical)
Hydrofiner Reactors	4 to 7 (100 to 175)	750 to 850 (399 to 454)	1000 to 2000 (6.9 to 13.8)	Loss of toughness
Catalytic Reformer Reactors	2 to 4 (50 to 100)	900 to 1050 (482 to 566)	100 to 300 (0.69 to 2.1)	Loss of toughness, creep, creep embrittlement
Coke Drums	0.75 to 2 (19 to 50)	850 to 975 (454 to 524)	25 to 199 (0.17 to 1.4)	Thermal fatigue, high temperature tensile overstress, creep, loss of toughness
FCC Reactors	0.75 to 3.0 (19 to 76)	800 to 900 (427 to 482)	25 to 50 (0.17 to 0.34)	Creep, creep embrittlement, erosion

4.2 Past In-Service Cracking and Toughness Problems with $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ Steels

In-service cracking problems have been noted for $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steel equipment including pressure vessels and piping. [1] These problems were experienced in both the refining and electric power industries and were related to weld cracks. Nearly all cracking was in reactors and piping, listed in Table 2 and Table 3. Whereas most problems in the refining industry were related to pressure vessels, the electric power industry experienced cracking in longitudinal weld seams of high temperature steam lines, which operated primarily at or above approximately 850 °F (454 °C).

Most notable in the refining industry was creep related cracking of Catalytic Reformer reactors. This was reported in Japan, [2] and led to other studies in the United States. [3][4] It was categorized as creep embrittlement (a term that will be discussed later on). Several papers were published that described this cracking and other property changes. Table 4 lists the previous literature, experience, and data that describe these issues.

In December 1986 there was an MPC workshop on “Embrittlement of Low Alloy Steels During Exposure at Elevated Temperature Service”. Shortly afterwards API/MPC surveyed refineries worldwide on these cracking problems. [5] More than 70 incidents were reported from 25 companies. In all cases where deep cracks were found and major repairs required, the reactors were replaced within a few years. In the majority of cases, crack initiation was at major nozzle to reactor welds. Cracking was predominantly in heat affected zones (HAZ) and was intergranular. Creep fissuring was also found. Initially the term “creep embrittlement” was used to describe this phenomenon. In some cases where CVN toughness measurements could be made low toughness values were also reported.

Low toughness values in the range of 5 ft-lb to 10 ft-lb (at room temperature) were reported for both plate material and forgings. [3] It was difficult to improve the toughness with a postweld heat treatment (PWHT). In most cases normalizing was required to assure a return of toughness. [4] It was assumed at the time that the low toughness was related to long term exposure at operating temperatures above 1000 °F (538 °C), [3] but it is also possible that these steels had low toughness at the start. If so, the terms “irreversible embrittlement,” or “stress relief embrittlement” may

Table 2—Cracking Problems with 1¹/₄Cr-1¹/₂Mo Steel

Type of Equipment	Years in Operation	Temperature °F (°C)	Crack Location Note b, Note c	Crack Length	Crack Depth in. (mm)
Reactors ^[3] Note a	14	950 (510)	P	Several feet	thru wall
Reactors ^[3]	23	950 (510)	P,H/F,H	3 ft (0.9 m)	1/2 (13)
Reactors ^[3]	15	950 (510)	F,H	360°	thru wall
Reactors ^[3]	20	980 (527)	P,H/W	6 in. (15 cm)	1/2 (13)
Reactor	22	850 (454)	W	1 in. (25 mm)	1.25 (32)
Reactors ^[2]	23	950 to 1000 (510 to 538)	P,H/F,H	26 in. (66 cm)	1.5 to 1.75 (38 to 44)
Reactors ^[4]	14	900 to 980 (482 to 527)	W	1 in. (25 mm) to circ.	1/8 to 1.25 (3.2 to 32)
Reactors ^[3]	17	980 (527)	P,H/F,H	7 in. (18 cm)	1 (25)
Reactor	21	950 (510)	P,F	15.7 in. (40 cm) max.	0.71 (18) max.
Reactor	31	960 (516)	F,B,H	50 in. (127 cm)	1/2 to 1 (13 to 25)
Reactor	16 to 5	1010 (543)	W	6 in. to 26 in. (15 cm to 66 cm)	1 1/2 (38)
Pipe	5	not reported	B,W,H	4 in. (10 cm)	full wall
Pipe	11	950 (510)	WH	not reported	full wall
Pipe	10	950	W	6 in. (15 cm) rupture	thru wall

^a The numbers within the parenthesis designate number of reactors.

^b H = HAZ; W = Weld; P = Plate; F = Forging; B = Base metal.

^c When B and/or F are listed with H, cracking was observed in the HAZ of each these locations.

Table 3—Cracking Experience with 1¹/₄Cr-1¹/₂Mo Hot-Wall Reactors

Case	Operating Conditions	Design	Crack Location	Metallurgical
A	Pressure: 330 psi (2.3 MPa) Temperature: 980 °F (527 °C) Service Life: 16 years	4 Horizontal	Major nozzle to shell welds.	CVN tests showed poor properties. HAZ cracking.
B	Pressure: 400 psi (2.8 MPa) Temperature 980 °F (527 °C) Service Life: 20 years	3 Vertical	Outside surface of nozzle to shell welds and attached lugs.	Cracking intergranular and predominantly in HAZ.
C	Pressure: 300 psi (2.1 MPa) Temperature: 990 °F (532 °C) Service Life: About 15 years	Vertical (stacked)	Outside surface of nozzle.	CVN tests showed poor properties.
D	Pressure: 540 psi (3.7 MPa) Temperature: 970 °F (521 °C) Service Life: 14 years	3 Vertical	Longitudinal weld HAZ, some cracking in nozzle-to-shell welds.	Cracking intergranular in HAZ.

Table 4—Previous Literature/Data/Experience/Issues

	Material	Service	Temperature °F (°C)	Thickness in. (mm)	Major changes
Japanese Literature/1984 – 1990 [2][3] Site specific refs	1 ¹ / ₄ Cr-1/2Mo	Catalytic Reformer reactor			Creep embrittlement
Singh/Bagdasarian (NACE 520) Corrosion 94	1Cr-1/2Mo	Catalytic Reformer reactor/ 37 years	900 (482) max	2.25 (57)	Loss of room temperature toughness
Bagnoli/Leedy (NACE 160) Corrosion 88	1Cr-1/2Mo/plate/ forgings	Catalytic Reformer reactor/ 18 years	900 (482)	2.9 (74)	Creep embrittlement, loss of toughness. High energy cleavage

be applicable to this effect. Considering that the ASME toughness requirements (Figure UCS-66, Section VIII, Div. 1) were only established in 1987, well after these vessels were fabricated, these vessels may not have had Charpy V-notch (CVN) toughness testing requirements and, therefore, may have had low toughness values from the beginning. These steels may also have been produced to coarse grain practice. Another interesting observation related to CVN test results was that several test samples exhibited high impact energy values but failed in a cleavage mode. Appropriately, the term “high energy cleavage” was applied. [3] This result encouraged the use of percent shear and lateral expansion measurements in qualifying these steels in future construction.

5 General Considerations

5.1 1¹/₄Cr-1/2Mo Product Specifications and Properties

The 1¹/₄Cr-1/2Mo products are available to the specifications, grades, and classes shown in Table 5a. When using different product forms, (e.g. plates and forgings) in the same vessel or assembly, grades and classes of material with the same nominal chemical composition should be used so that the same PWHT temperatures and hold times can be used for the vessel or welded assembly. The same basic 1¹/₄Cr-1/2Mo steel compositions are also covered in a European specification EN 10028-2: 2003 as Grades 13CrMo4-5 and 13CrMoSi5-5. The European specification covers two categories, normalized and tempered, and quench and tempered, as shown in Table 5b. It also shows that the thicker plates need to be quenched and tempered.

5.2 Allowable Design Stresses

Many of the 1¹/₄Cr-1/2Mo vessels, particularly those that operate in the creep range [at 950 °F (510 °C) for 1Cr-1/2Mo steels and 850 °F to 900 °F (454 °C to 482 °C) for 1¹/₄Cr-1/2Mo steels] are designed and constructed to ASME Section VIII, Division 1 allowable design stresses. Table 6 lists the ASME Section VIII, Division 1 allowable stresses at temperatures up to 1050 °F (565 °C).

Thicker pressure vessels, such as hydrofiner reactors, are often designed and constructed to ASME Section VIII, Division 2 allowable design stresses. Table 7 and Table 8 give a comparison between the allowable design stresses for vessels designed to the 2004 and earlier editions of Division 2 and the 2010 edition of Division 2, respectively. Although the 2004 and earlier editions of Division 2 did not have provisions for design of vessels in the creep range, designs in the creep range were permitted by ASME code case 1489-2 using the allowable stresses permitted for Division 1 vessels, provided the vessel or part was exempt from fatigue analysis by the provisions of AD-160.1 of Division 2.

The 2010 edition of Division 2 permits design of 1¹/₄Cr-1/2Mo vessels in the creep range using the allowable design stresses in Tables 5A and 5B of Section II, Part D. However, the vessel shall be exempted from fatigue analysis in

Table 5a—ASME SA Specifications

Product Form	Specification	Grade	Class	Melting Practice	Heat Treatment	Tensile Strength ksi (MPa)	Yield Strength, min. ksi (MPa)
Plate	SA-387	Gr. 11	Cl. 1		Ann., N&T, Q&T	60 to 85 (415 to 585)	35 (240)
			Cl. 2		N&T, Q&T	75 to 100 (515 to 690)	45 (310)
		Gr. 12	Cl. 1		Ann., N&T, Q&T	55 to 80 (380 to 550)	33 (230)
			Cl. 2		N&T, Q&T	65 to 85 (450 to 585)	40 (275)
Forged Fittings	SA-182	Gr. F11	Cl. 1		Anneal, N&T	60 (415) min.	30 (205)
			Cl. 2		Anneal, N&T	70 (485) min.	40 (275)
			Cl. 3		Anneal, N&T	75 (515) min.	45 (310)
		Gr. F12	Cl. 1		Anneal, N&T	60 (415) min.	32 (220)
			Cl. 2		Anneal, N&T	70 (485) min.	40 (275)
Forgings	SA-336	Gr. F11	Cl. 1		Ann., N&T, Q&T	60 to 85 (415 to 585)	30 (205)
			Cl. 2		Ann., N&T, Q&T	70 to 95 (485 to 655)	40 (275)
			Cl. 3		Ann., N&T, Q&T	75 to 95 (515 to 655)	45 (310)
		Gr. F12			Ann., N&T, Q&T	70 to 95 (485 to 655)	40 (275)
Piping Fittings	SA-234	WP11	CL1	CGP or FGP	Anneal, N&T, Q&T	60 to 85 (415 to 585)	30 (205)
			CL2	CGP or FGP	Anneal, N&T, Q&T	70 to 95 (485 to 655)	40 (275)
			CL3	CGP or FGP	Anneal, N&T, Q&T	75 to 100 (515 to 690)	45 (310)
		WP12	CL2	CGP or FGP	Anneal, N&T, Q&T	70 to 95 (485 to 655)	40 (275)
Pipe	SA-335	P11		CGP		60 (415) min.	30 (205)
		P12				60 (415) min.	32 (220)
Tubes	SA-213	T11			Anneal, N&T	60 (415) min.	30 (215)
		T12			Anneal, N&T	60 (415) min.	32 (220)

accordance with the fatigue design rules in the 2010 edition of Division 2 for design temperatures above 700 °F (371 °C).

The use of the higher allowable design stresses in the 2007 edition of Division 2 results in thinner and lighter vessels at design temperatures up to the creep range. The allowable design stresses in the creep range are the same for Class 1 and Class 2 materials. However, the allowable stresses at temperatures in the creep range are somewhat higher for Grade 12 materials than those for the Grade 11 materials for Division 1 and for Division 2 construction. In the 1980's the ASME Code committee analyzed all the available data at that time from the 1¹/₄Cr-1¹/₂Mo steels and concluded that the 1Cr-1¹/₂Mo steel exhibited somewhat higher creep rupture strength than the 1¹/₄Cr-1¹/₂Mo steel. It was suggested that there may be a negative effect of the higher silicon content on creep strength in the 1¹/₄Cr-1¹/₂Mo steel; however, it is not known to what extent other factors, such as the existing data base, may have contributed to the difference in the creep strength.

There is an economical advantage in using Class 2 or Class 3 properties vs. Class 1 properties at temperatures below the creep range. However, there is no economic advantage in using the Class 2 or Class 3 properties for vessels intended for use at temperatures in the creep range. The use of the lower strength materials to Class 1 properties for vessels in the creep range generally results in lower carbon contents and permits higher PWHT temperatures, which reduces the risk of creep embrittlement and cracking. However, the steel should be normalized and tempered since the annealed material generally has poor notch toughness.

Table 5b—European Specification EN-10028-2:2003

Product Form	Specification	Grade	Type	Melting Practice	Heat Treatment	Thickness mm (in.)	Tensile Strength MPa (ksi)	Yield Strength, min. (MPa) ksi
Plate	EN 10028-2: 2003	13CrMo4-5	1Cr-½Mo	NS	N&T	$t \leq 16$ ($t \leq 5/8$)	450 to 600 (65 to 87)	300 (44)
				NS	N&T	$16 < t \leq 60$ ($5/8 < t \leq 2.4$)	450 to 600 (65 to 87)	290 (42)
				NS	N&T	$60 < t \leq 100$ ($2.4 < t \leq 4$)	440 to 590 (64 to 86)	270 (39)
				NS	N&T or Q&T	$100 < t \leq 150$ ($4 < t \leq 6$)	430 to 580 (62 to 84)	255 (37)
				NS	Q&T	$100 < t \leq 150$ ($4 < t \leq 6$)	420 to 570 (61 to 83)	245 (36)
Plate	EN 10028-2: 2003	13CrMoSi5-5	1¼Cr-½Mo	NS	N&T	$t \leq 60$ ($t \leq 2.4$)	510 to 690 (74 to 100)	310 (45)
				NS	N&T	$60 < t \leq 100$ ($2.4 < t \leq 4$)	480 to 660 (70 to 96)	300 (44)
				NS	Q&T	$t \leq 60$ ($t \leq 2.4$)	510 to 690 (74 to 100)	400 (58)
				NS	Q&T	$60 < t \leq 100$ ($2.4 < t \leq 4$)	500 to 680 (73 to 99)	390 (57)
				NS	Q&T	$100 < t \leq 250$ ($4 < t \leq 10$)	490 to 670 (71 to 97)	380 (55)

NOTE NS = not specified

Table 6—Allowable Design Stresses, for ASME Section VIII, Division 1 Vessels

Dimensions in ksi (MPa)

Name/Grade & Class	-20 to 100 °F (-18 to 38 °C)	200 °F (93 °C)	700 °F (371 °C)	750 °F (399 °C)	800 °F (427 °C)	850 °F (454 °C)	900 °F (482 °C)	950 °F (510 °C)	1000 °F (538 °C)	1050 °F (566 °C)
SA-387 Gr. 11, Cl. 1	17.1 (118)	17.1 (118)	17.1 (118)	17.1 (118)	16.8 (116)	16.4 (113)	13.7 (94)	9.3 (64)	6.3 (43)	4.2 (29)
SA-387 Gr. 11, Cl. 2	21.4 (148)	21.4 (148)	21.4 (148)	21.4 (148)	21.4 (148)	20.2 (139)	13.7 (94)	9.3 (64)	6.3 (43)	4.2 (29)
SA-387 Gr. 12, Cl. 1	15.7 (108)	15.4 (106)	15.1 (104)	15.1 (104)	15.1 (104)	15.1 (104)	14.7 (101)	11.3 (78)	7.2 (50)	4.5 (31)
SA-387 Gr. 12, Cl. 2	18.6 (128)	18.2 (126)	17.9 (123)	17.9 (123)	17.9 (123)	17.9 (123)	17.4 (120)	11.3 (78)	7.2 (50)	4.5 (31)

NOTE The allowable stresses shown in italics are based on time dependent properties (in the creep range).

Table 7—Allowable Design Stresses, for ASME Section VIII, Division 2 Vessels (2004 Edition)

Dimensions in ksi (MPa)

Name/Grade & Class	-20 to 100 °F (-18 to 38 °C)	200 °F (93 °C)	300 °F (149 °C)	400 °F (204 °C)	500 °F (260 °C)	600 °F (316 °C)	650 °F (343 °C)	700 °F (371 °C)
SA-387 Gr. 11, Cl. 1	20.0 (138)	20.0 (138)	20.0 (138)	19.6 (135)	18.9 (130)	18.3 (126)	18.0 (124)	17.6 (121)
SA-387 Gr. 11, Cl. 2	25.0 (172)	25.0 (172)	25.0 (172)	25.0 (172)	24.4 (168)	23.5 (162)	23.1 (159)	22.6 (159)
SA-387 Gr. 12, Cl. 1	18.0 (124)	18.3 (126)	17.6 (121)	17.6 (121)	17.2 (119)	16.8 (116)	16.5 (114)	16.3 (112)
SA-387 Gr. 12, Cl. 2	21.7 (150)	21.3 (147)	20.8 (143)	20.8 (143)	20.8 (143)	20.3 (140)	20.0 (138)	19.7 (136)

Table 8—Allowable Design Stresses, for ASME Section VIII, Division 2 Vessels (2010 Edition)

Dimensions in ksi (MPa)

Name/Grade & Class	−20 to 100 °F (−18 to 38 °C)	150 °F (66 °C)	200 °F (93 °C)	250 °F (121 °C)	300 °F (149 °C)	350 °F (177 °C)	400 °F (204 °C)	450 °F (232 °C)	500 °F (260 °C)	550 °F (288 °C)
SA-387 Gr. 11, Cl. 1	23.3 (161)	22.2 (153)	21.5 (148)	21.0 (145)	20.5 (142)	20.0 (138)	19.6 (135)	19.3 (133)	18.9 (130)	18.6 (128)
SA-387 Gr. 11, Cl. 2	30.0 (207)	28.5 (197)	27.7 (191)	27.0 (186)	26.3 (181)	25.8 (178)	25.3 (175)	24.8 (171)	24.4 (168)	23.9 (165)
SA-387 Gr. 12, Cl. 1	22.0 (152)	20.6 (142)	19.9 (137)	19.2 (132)	18.7 (129)	18.2 (126)	17.9 (123)	17.5 (121)	17.2 (119)	17.0 (117)
SA-387 Gr. 12, Cl. 2	26.7 (184)	25.0 (172)	24.1 (166)	23.3 (161)	22.7 (157)	22.1 (152)	21.7 (150)	21.3 (147)	20.9 (144)	20.6 (142)
Name/Grade & Class	600 °F (316 °C)	650 °F (343 °C)	700 °F (371 °C)	750 °F (399 °C)	800 °F (427 °C)	850 °F (454 °C)	900 °F (482 °C)	950 °F (510 °C)	1000 °F (538 °C)	1050 °F (583 °C)
SA-387 Gr. 11, Cl. 1	18.3 (126)	18.0 (124)	17.6 (121)	17.2 (119)	16.8 (116)	16.4 (113)	13.7 (94)	9.3 (64)	6.3 (43)	4.2 (29)
SA-387 Gr. 11, Cl. 2	23.5 (162)	23.1 (159)	22.6 (156)	22.2 (153)	21.6 (149)	20.2 (139)	13.7 (94)	9.3 (64)	6.3 (43)	4.2 (29)
SA-387 Gr. 12, Cl. 1	16.8 (116)	16.5 (114)	16.3 (112)	16.0 (110)	15.7 (108)	15.4 (106)	15.0 (103)	11.3 (78)	7.2 (50)	4.5 (31)
SA-387 Gr. 12, Cl. 2	20.3 (140)	20.0 (138)	19.7 (136)	19.4 (134)	19.1 (132)	18.6 (128)	18.0 (124)	11.3 (78)	7.2 (50)	4.5 (31)

NOTE The allowable stresses shown in *italics* are based on time dependent properties (in the creep range).

5.3 Steel Making Practices and Processing

The older generation Cr-Mo steels were typically produced to coarse grain practice to provide higher creep strength at the elevated temperatures. The increased notch toughness requirements [e.g. 40 ft-lb average at 0 °F (−18 °C)] and concerns about the various forms of embrittlement (temper embrittlement, creep embrittlement) have led to several improvements to produce cleaner steels and improved notch toughness. As a result of this, most Cr-Mo steels which are subjected to the increased toughness requirements are now produced to fine grain practice (as defined in ASTM A941), vacuum degassed, with lower phosphorus and sulfur contents, and with particular emphasis on the reduction of the residual elements, as monitored by the X-bar factor. Whereas the older generation steels may have had typical aim composition values such as Al = 0.003 %, P = 0.02 – 0.03 %, and S = 0.020 %, the modern Cr-Mo steels may typically have Al = 0.020 %, P = 0.010 %, and S = 0.005 %. The P and S values in modern Cr-Mo steels are substantially lower than those listed in the material specifications. These changes in chemical composition control have improved notch toughness and provided better resistance to temper and creep embrittlement problems, while maintaining the same elevated temperature properties. [7]

Class 2 and Class 3 materials are generally produced in the quenched and tempered condition, particularly in thicknesses over about 2 in. (50 mm) to be able to meet the notch toughness and tensile strength requirements with PWHT temperatures at 1275 °F ± 25 °F (690 °C ± 14 °C) and multiple PWHT cycles, particularly in thicknesses over 2 in. (50 mm).

Class 1 plates produced in the normalized and tempered (N&T) condition can be stress relieved at higher PWHT temperatures than Class 2 plates or Class 2 or Class 3 forgings. However, the higher PWHT temperatures for Class 1 materials (which typically have lower carbon contents) may reduce their toughness. The steel producers cannot use the low carbon steel (which is desirable for improved toughness in Cr-Mo steels) for high PWHT temperatures. Such Class 1 plates may need to be quenched and tempered to meet the toughness requirements.

5.4 Hardenability Limitations that Affect Mid-Wall Tensile Properties and Notch Toughness

The maximum thickness of $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ plates is limited because of this alloy's hardenability properties, which leads to lower toughness than the $2\frac{1}{4}\text{Cr}-1\text{Mo}$ plates. The addition of Cr and Mo aids in increasing the hardenability of the material by forming carbides. These carbides reduce the growth rate of the austenite/ferrite interface by allowing for slower cooling rates to produce a completely homogeneous bainitic microstructure through the thickness of the plate up to a critical cooling rate. Cr has a strong influence on this effect. As a general rule, the steel's hardenability increases as the Cr content increases. Therefore, there is a lesser potential for retaining a completely homogeneous bainitic microstructure with $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steels than with the higher Cr-Mo steels such as $2\frac{1}{4}\text{Cr}-1\text{Mo}$ steel at higher thickness levels. Some steel producers indicate that this is indirectly affected by rolling reduction ratio. This non-uniform microstructure can be directly correlated to variations in mechanical properties, especially tensile strength and toughness, through the thickness of the plate. Figure 1, [8] provides an indication of the influence of cooling rate on through thickness tensile properties.

The API survey of steel producers (Attachment 1) indicates that producers are willing to provide $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steels to a wide range of thicknesses despite the above metallurgical limitations, depending on the heat treatment and PWHT condition. Many steel producers and fabricators believe that the maximum thickness of $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ plates is limited to about 4 in. (100 mm) due to the above factors. However, thicker $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ plates have been used in pressure vessels. For example, one steel producer indicated the following: for Q&T and 2-PWHT cycles, the practical thickness would be 8 in. (200 mm) for SA-387 Gr. 11 and 6 in. (150 mm) for 387 Gr. 12 meeting the requirement of 40/35 ft-lb (54/47 J) at 0 °F (−18 °C) at $\frac{1}{4} t$ sample location. Another steel producer gives a maximum thickness of 6 in. (150 mm) for Q&T (quenched and tempered) SA-387, Gr. 11 and a maximum thickness of 4 in. (100 mm) for Q&T SA-387, Gr. 12 for meeting 40/35 ft-lb (54/47 J) at 0 °F (−18 °C) at $\frac{1}{2} t$ location. Appendix 1 summarizes responses from several steel producers regarding their capabilities in producing plate thickness limitations for achieving CVN toughness requirements per the API survey. Actual experience with thicknesses greater than 4 in. (100 mm) is limited, and special care should be taken when attempting to use these greater thicknesses.

It is important to note that toughness measurements are to be taken at $\frac{1}{2} t$ for heavier walled vessels because it represents the area with the lowest toughness properties. For heavier thicknesses it is likely that the material will need to be quenched and tempered since normalizing and tempering may not be able to achieve the appropriate cooling rates to generate the desired bainitic microstructure for heavier sections of plate. Special care should be taken to make sure that suppliers can meet the desired toughness requirements for heavier sections. Figure 1 [8], provides an indication of the influence of cooling rate from the austenitizing temperature on tensile properties. The cooling rate would be expected to have a similar effect on toughness.

6 Mechanical Properties

Both tensile properties and CVN properties are discussed with special attention to the effect of PWHT temperature/time as expressed in the form of the Larson-Miller Parameter (LMP). This is a convenient way to evaluate the effect of all heat treatments (temperatures and hold times at temperature) on tensile strength and on notch toughness properties.

6.1 The Effect of Heat Treatment, Including Post-weld Heat Treatment (PWHT) on Tensile Strength and Yield Strength of $1\text{Cr}-\frac{1}{2}\text{Mo}$ and $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ Steels

The $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steels are ASME P-No. 4, Group 1 materials. ASME requires PWHT at 1200 °F (649 °C) of these materials with 1 hr/in. hold time for thicknesses up to and including 5 in. (127 mm), and 15 min/in. (15 min/25 mm) for thicknesses exceeding 5 in. (127 mm). However, there has been a trend to higher PWHT temperatures to soften hard zones, stabilize the microstructure, and ensure full tempering of the heat affected zones. That reduces the risk of cracks initiating in the hard zones in presence of hydrogen or due to embrittlement. The $1\frac{1}{4}\text{Cr}-\frac{1}{2}\text{Mo}$ steel vessels are generally stress relieved at 1250 °F (678 °C) minimum, typically 1275 °F $\pm$ 25 °F (690 °C $\pm$ 14 °C) for at least two or three PWHT cycles (two for vessel fabrication and one for repairs). The ASME Code requires that heat treatments to be considered shall include all thermal treatments of the material during fabrication exceeding 900 °F (480 °C).