Technical Report on the Materials and Fabrication Issues of 1 $^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo 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 $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$Cr-$^{1}/_{2}$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 $1^{1}/_{4}$Cr-$^{1}/_{2}$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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo steels. Whereas API 934-A continues to provide materials and fabrication requirements for new $2^{1}/_{4}$/3Cr-1Mo and $2^{1}/_{4}$/3Cr-1Mo-$^{1}/_{4}$V steel heavy wall pressure vessels in high temperature, high pressure hydrogen service, different material, and fabrication requirements have been developed for $1^{1}/_{4}$/1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$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 $2^{1}/_{4}$Cr-1Mo/$^{1}/_{4}$ V, 3Cr-1Mo and 3Cr-1Mo/$^{1}/_{4}$V Steel Heavy Wall Pressure Vessels for High Temperature High Pressure Service*

API Recommended Practice 934-C, *Materials and Fabrication of $1^{1}/_{4}$Cr-1Mo 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 $1^{1}/_{4}$Cr-1Mo 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:

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

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 $1^1/_4$/1Cr-$^1/_2$Mo Refinery Equipment

Several refinery processes use $1^1/_4$/1Cr-$^1/_2$Mo 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 $1^1/_4$Cr-$^1/_2$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 $1^1/_4$Cr-$^1/_2$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 $1^1/_4$Cr-$^1/_2$Mo Steels

In-service cracking problems have been noted for $1^1/_4$Cr-$^1/_2$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 1$^1/_4$/1Cr-$^1/_2$Mo 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 1¼/1Cr-½Mo 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-$^1/_2$Mo	Catalytic Reformer reactor			Creep embrittlement
Singh/Bagdasarian (NACE 520) Corrosion 94	1Cr-$^1/_2$Mo	Catalytic Reformer reactor/ 37 years	900 (482) max	2.25 (57)	Loss of room temperature toughness
Bagnoli/Leedy (NACE 160) Corrosion 88	1Cr-$^1/_2$Mo/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 $1^1/_4$/1Cr-$^1/_2$Mo Product Specifications and Properties

The $1^1/_4$/1Cr-$^1/_2$Mo 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 $1^1/_4$/1Cr-$^1/_2$Mo 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 $1^1/_4$/1Cr-$^1/_2$Mo vessels, particularly those that operate in the creep range [at 950 °F (510 °C) for 1Cr-$^1/_2$Mo steels and 850 °F to 900 °F (454 °C to 482 °C) for $1^1/_4$Cr-$^1/_2$Mo 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 $1^1/_4$Cr-$^1/_2$Mo 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 1 1/4/1Cr-1/2Mo steels and concluded that the 1Cr-1/2Mo steel exhibited somewhat higher creep rupture strength than the 1 1/4Cr-1/2Mo steel. It was suggested that there may be a negative effect of the higher silicon content on creep strength in the 1 1/4Cr-1/2Mo 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	Specifi-cation	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	1 1/4Cr-1/2Mo	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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo plates is limited because of this alloy's hardenability properties, which leads to lower toughness than the $2^{1}/_{4}$Cr-1Mo 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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo steels than with the higher Cr-Mo steels such as $2^{1}/_{4}$Cr-1Mo 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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$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 $1^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo plates is limited to about 4 in. (100 mm) due to the above factors. However, thicker $1^{1}/_{4}$Cr-$^{1}/_{2}$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 $^{1}/_{4}$ *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 $^{1}/_{2}$ *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 $^{1}/_{2}$ *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 1Cr-$^{1}/_{2}$Mo and $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo Steels

The $1^{1}/_{4}$/1 Cr-$^{1}/_{2}$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 1¼/1Cr-½Mo steel vessels are generally stress relieved at 1250 °F (678 °C) minimum, typically 1275 °F ± 25 °F (690 °C ± 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).

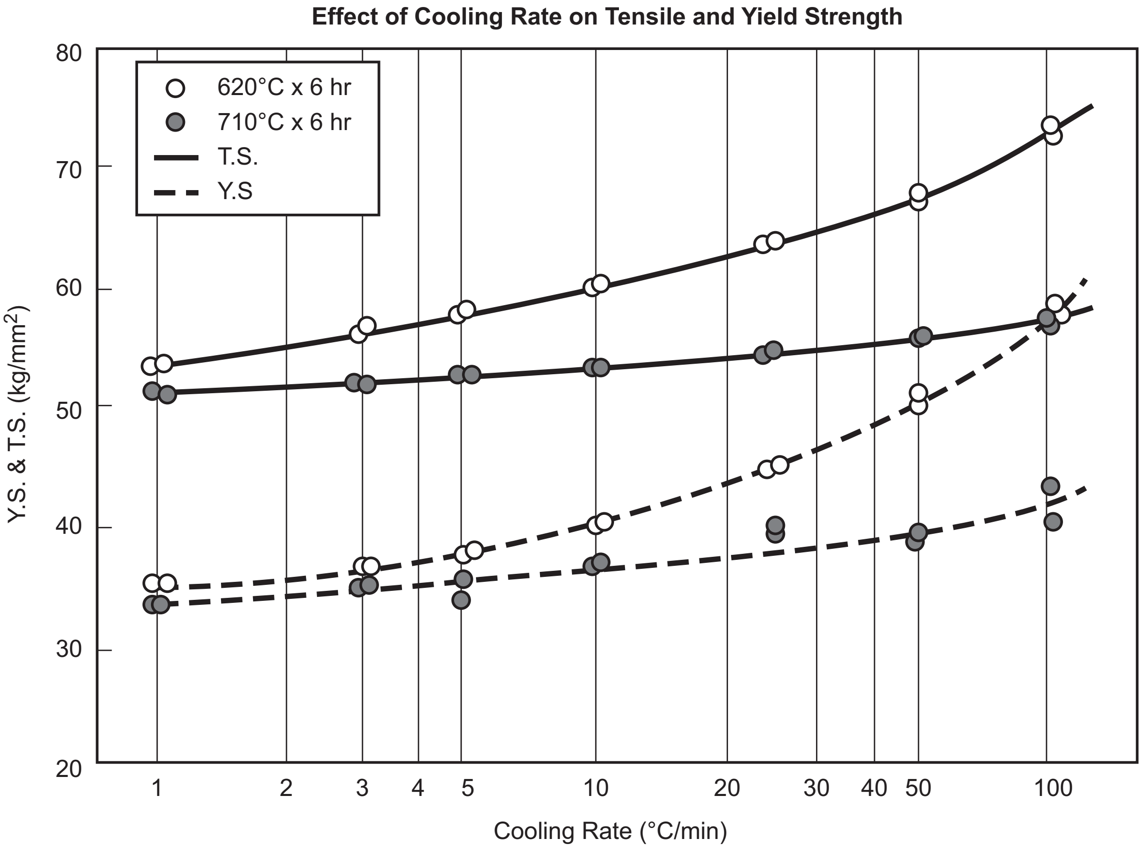


Figure 1—The Effect of Cooling Rate on Tensile Properties

The combination of high PWHT temperatures and long hold times results in loss of strength and notch toughness in the 1¹/₄/1Cr-¹/₂Mo materials. For example, Figure 2 [10] shows about 5 ksi (35 MPa) reduction in tensile strength in normalized and tempered (N&T) SA-387, Grade 11 steel when the LMP was increased from LMP = 34.86 [1 hr temper at 1250 °F (677 °C) + 6 hr PWHT at 1200 °F (649 °C)] to LMP of 36.94 [1 hr temper at 1350 °F (732 °C) + 6 hr PWHT at 1300 °F (704 °C)].

Shown in Figures 2, is the possible loss of tensile strength between the initial temper and the final PWHT when expressed in terms of the Larson-Miller parameter.

The above Larson-Miller parameters do not include the additional effect of the heating rate and cooling rate for each PWHT cycle during the PWHT. The following modification to the Larson-Miller formula which includes the combined effect of the time at the PWHT temperature plus the heating and cooling rates for each PWHT cycle to account for the heating and cooling effects on the tempering parameter (LMP):

$$\text{LMP} = T \times \left[20 + \log\left\{ \left[\frac{T}{2.3 \times Hr \times (20 - \log(Hr))} \right] + t + \left[\frac{T}{2.3 \times Cr \times (20 - \log(\text{C}r))} \right] \right\} \right]$$

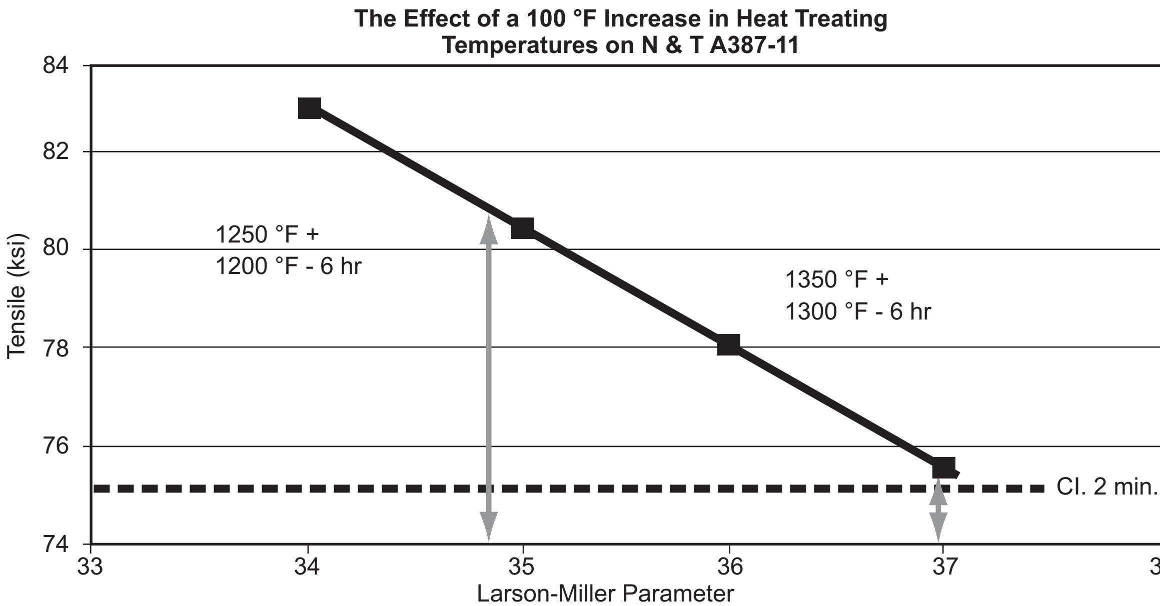


Figure 2—The Effect of Post-weld Heat Treating Temperature on Tensile Properties of N&T A387, Gr. 11 Steel as a Function of Tempering Parameter (LMP)

where

T is the PWHT temperature, as defined in 3.1 of this report;

t is the PWHT time, hr;

Hr is the heating rate, °F/hr (°C/hr);

Cr is the cooling rate, °F/hr (°C/hr).

For example, the LMP for 6 in. (150 mm) thick plate subject to three PWHT cycles (15.75 hr) at 1275 °F (690 °C) is 36.78×10^3 (20.41×10^3 based on °C). The LMP for the same plate is 36.82×10^3 (20.43×10^3 based on °C) when including heating and cooling rates for each PWHT cycle at 100 °F (55.6 °C) per hour.

6.2 The Effect of Thickness on Tensile Properties

Figure 3 [9] shows the effect of thickness on tensile properties for two thicknesses of A387 Gr 11 Cl. 2 steel, 3.2 in. and 5.6 in. (80 mm and 143 mm), respectively, with comparable chemical compositions. The simulated PWHT were made after quenching coupons made from rolled plate. This figure shows that the above grade can be obtained for tempering parameters up to about 37,800 (21,000 metric). There is no significant difference between both thicknesses with the same heat treat cycles (the same Larson-Miller parameter).

As specified in SA-20, the tension tests conforming to 0.500 in. (12.5 mm) diameter test specimens generally are taken from the $^1/_4$ *t* location in the plate. The impact test specimens should be taken from the $^1/_2$ *t* location of the plate, where the cooling rate is the lowest. Supplementary Requirement S53 in ASTM A387/A387M-06a permits the tensile test and impact test specimens to be taken from the $^1/_2$ *t* location of each plate tested, in lieu of the $^1/_4$ *t* location, which avoids the need for test specimens from both locations. This provision has been included in the SA-387 specification.

As discussed in paragraph 5(d) of this report, the cooling rate has a significant effect on the mechanical properties. Because of this and the multiple PWHT cycles at 1275 °F (690 °C) (or above) the 1Cr-$^1/_2$Mo and 1$^1/_4$Cr-$^1/_2$Mo

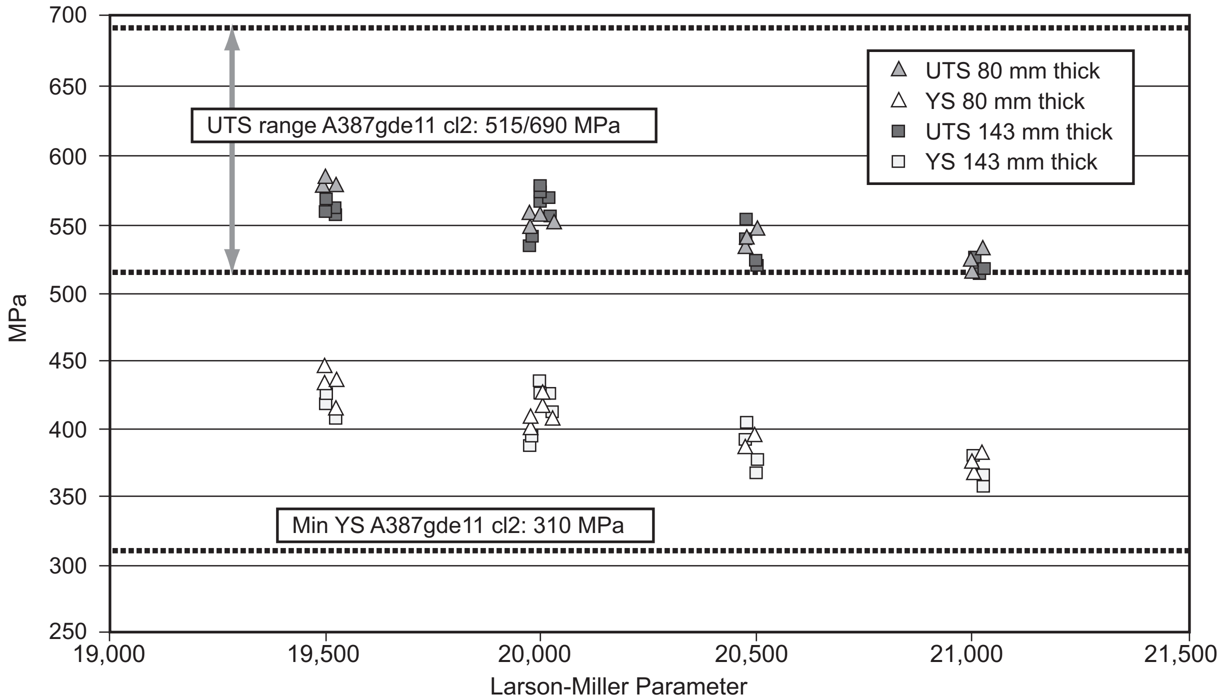


Figure 3—Tensile Properties of Two A387 Gr. 11, Class 2 Plates, 3.2 in. (80 mm) and 5.6 in. (143 mm) Thick as a Function of Tempering Parameter (LMP)

materials generally need to be quenched and tempered to achieve the specified tensile properties and meet the notch toughness requirements. Figure 4 [7] illustrates how a significant improvement in tensile strength can be realized by way of quenching and tempering for A387 Grades 12 and 22 steels.

6.3 The Effect of Chemical Composition on Tensile Properties

If the PWHT cycle is not too extensive, additional carbon or alloying elements may be added within specification limits to improve tensile properties. Proper use of and knowledge of carbon equivalents can be used to optimize tensile properties. The effect of carbon equivalent (CE) on tensile strength for normalized and tempered A387 Grade 11 steel is illustrated in Figure 5 [10] from Arcelor Mittal Steel. In this figure it can be seen that an increase of 0.1 in carbon equivalent can result in an increase of 10 ksi min tensile strength. It should be noted that the steel maker must carefully control these variables since these chemical elements affect other essential properties, such as weldability. The higher carbon equivalents (to achieve the higher tensile strength) increase the risk of cracking of welds and require additional precautions, such as higher preheat temperature, to avoid cracking. Figure 6 [7] shows the relative susceptibility of A387, Grade 11 and Grade 22 steels to HAZ cracking during welding.

6.4 Notch Toughness

6.4.1 Notch Toughness Requirements

The ASME Code Section VIII, Division 1 and the 2004 edition of Division 2 (with 2006 addenda) require a 15 ft-lb (20 J) minimum average energy level at the minimum design metal temperature (MDMT) with increasing energy levels with increasing thickness above about 1.5 in. (38 mm) thickness. The 2007 edition of Division 2 requires a minimum average Charpy V-notch energy value of 20 ft-lb (27 J) at the specified minimum MDMT with increasing energy values for SA-387, Grade 11, Class 2 material and welded joints in thicknesses above about 1 in. (25 mm) for non-stress relieved parts and above about 2.5 in. (64 mm) for stress relieved parts. However, the general practice in the petroleum industry is to specify higher energy values than those in the ASME Code, i.e. 40 ft-lb (54 J) min. average with 35 ft-lb (47 J) minimum single value at 0 °F (–18 °C) in the base metal, weld metal and in the HAZ for the

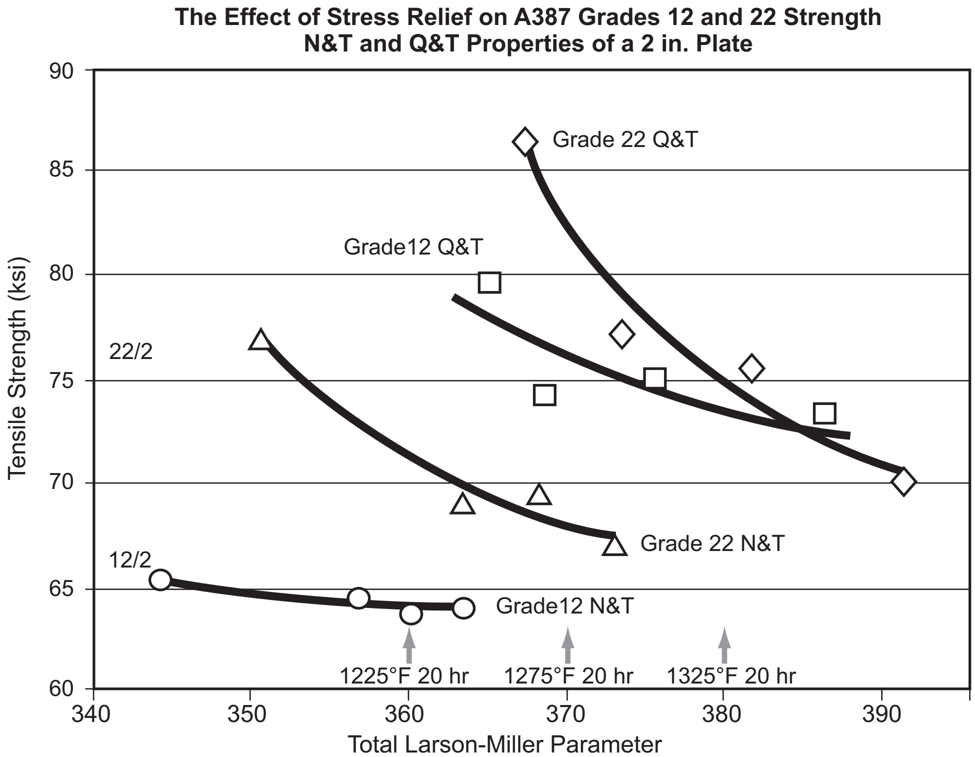


Figure 4—The Effect of Stress Relief on Tensile Strength of A387 Gr. 12 and Gr. 22 Plates as a Function of Tempering Parameter (LMP)

$1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo steels. API 934-C recommends 20 ft-lb (27 J) minimum single value because of the large scatter in the transition region of the Charpy impact test transition curve, instead of the 35 ft-lb (47 J) minimum single value in API 934-A for $2^1/_4$Cr-1Mo steels. The percent shear and lateral expansion opposite the notch in the Charpy V-notch test specimen should be added for information for all impact tested material as there have been previously reported cases of "high energy cleavage" [3].

API 934-E provides guidelines for vessels operating at temperatures above 825 °F (426 °C). As shown in Table 6, the allowable design stresses at temperatures in the creep range are the same the $1^1/_4$/1Cr-$^1/_2$Mo steels with Class 2 properties for plates (and Class 3 properties for forgings and fittings), therefore, there is no need to use the higher tensile strength grades in the creep range. The use of the Class 1 properties for these vessels also permits somewhat higher PWHT temperatures than the higher strength grades. Consequently, there is less risk of brittle fracture of the API 934-E vessels because of the lower strength of the Class 1 materials and the lower operating stresses and, therefore, less need for the higher energy values in API 934-C. However, all vessels must have adequate notch toughness for vessel fabrication and particularly for hydrostatic testing. In no case that should be less than ASME Code requirements, preferably not less than 20 ft-lb minimum average values in the direction transverse to the major direction of work of plates or forgings.

6.4.2 The Effect of Heat Treatment, Including Post-weld Heat Treatment (PWHT) on Toughness

High PWHT temperatures and long hold times degrade notch toughness of the material. (This is also generally known as irreversible embrittlement, which is described late in Section 7.) This is one of the main concerns with use of the 1Cr-$^1/_2$Mo and $1^1/_4$Cr-$^1/_2$Mo steels in heavy wall pressure vessel construction. Figure 7 [10] shows the shift in 40 ft-lb transition temperature in N&T and Q&T SA-387, Grade 11 steels vs. Larson-Miller parameter (LMP). It shows about 40 °F (22 °C) shift in the 40 ft-lb (54 J) transition temperature in the N&T SA-387, Grade 11 steel when the LMP is increased from LMP = 34.86×10^3 (19.37×10^3) (1 hr temper at 1250 °F + 6 hr PWHT at 1200 °F) to LMP of 36.94 ×

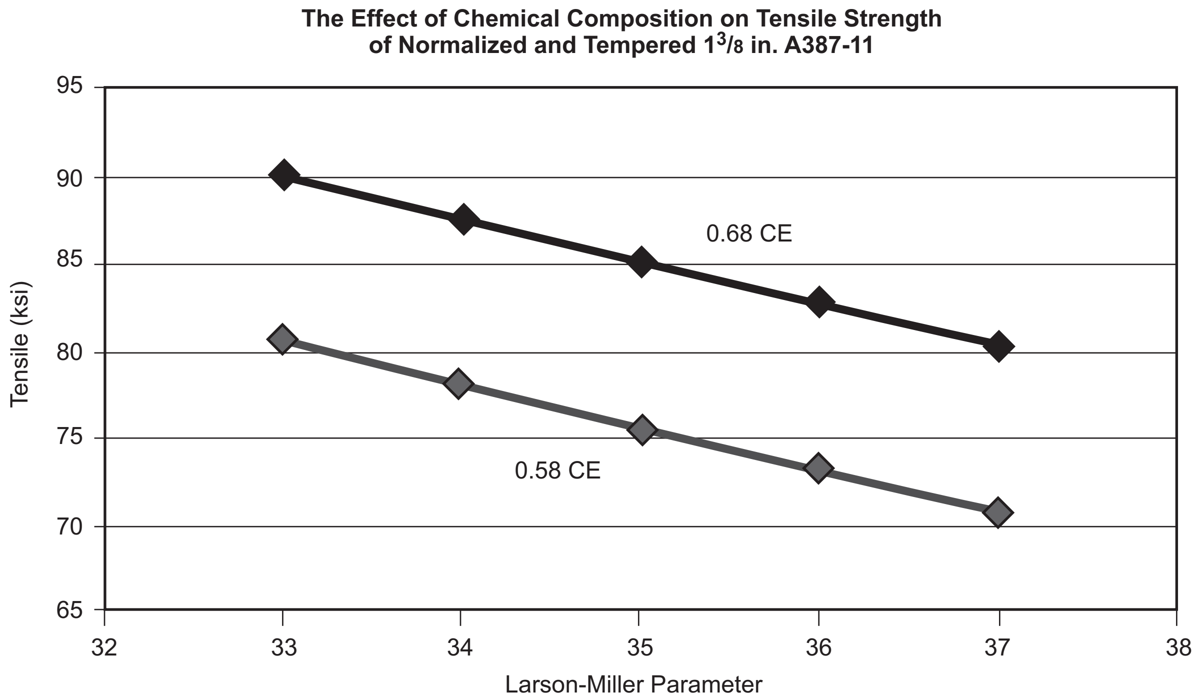


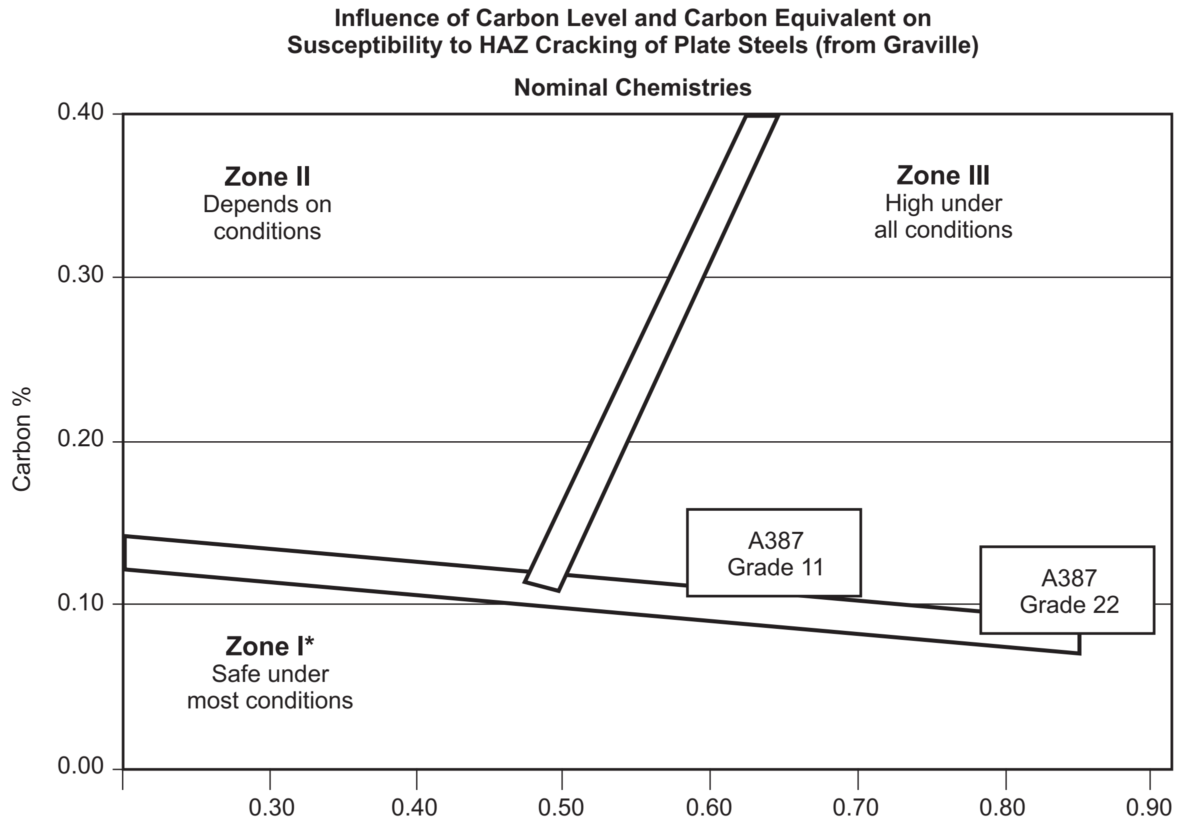
Figure 5—The Effect of Carbon Equivalent on Tensile Properties as a Function of Tempering Parameter (LMP)

10^3 (20.51×10^3) (1 hr temper at 1350 °F + 6 hr PWHT at 1300 °F). This figure also shows that quenching and tempering results in improved notch toughness and, therefore, permits higher LMP values while still achieving adequate toughness.

Figure 8, from another source, [9] shows the effect of thickness on CVN impact properties for two thicknesses of A387 Gr. 11 Class 2 steel. The figure shows that toughness properties at –29 °C (–20 °F) decline beyond a certain tempering parameter value. While for the 3.15 in. (80 mm) plate the drop in toughness occurs for tempering parameters between 36,000 (20,000 metric) and 36,900 (20,500 metric), for a 5.63 in. (143 mm) plate this drop in toughness appears approximately above 35,100 (19,500 metric). In this case and in most other cases where similar tests have been run there is a large scatter in toughness data in the transition area. This scatter in data for the transition region has led to somewhat lower minimum value requirements, i.e. 20 ft-lb (27 J) min. single value found in API 934-C.

6.4.3 Typically Available Larson-Miller Parameters to Meet 40 ft-lb (54 J) at –18 °C (0 °F)

Although not addressed in the ASME Code, the combined effects of all fabrication heat treatments and holding times at temperature generally are expressed in terms of the Larson-Miller parameter, or LMP. The heat treatment of the material (Q & T or N & T), thickness, and the related cooling rate, the fabrication heat treatments (in terms of LMP) all have a significant effect on notch toughness (impact test values). Data provided in Figure 7 [10] for 2 in. (50 mm) thick N&T and Q&T plates indicates a maximum LMP of about 36.5×10^3 (about 20.3×10^3) for N&T material and about 37.7 (about 20.9×10^3) for Q&T plates to be able to meet 40 ft-lb (54 J) at 0 °F (–18 °C). However, there are additional factors that need to be considered, such as composition, therefore, the ability for a steel producer to guarantee certain notch toughness is subject to agreement between purchaser and the supplier. This will be as illustrated later.



$$CE = C + \frac{MN + SI}{6} + \frac{Ni + Cu}{15} + \frac{Cr + Mo + V}{5}$$

*High strength welding consumables may require additional care.

Figure 6—Graville Diagram Showing Relative Susceptibility of A387 Steels to HAZ Cracking During Welding

6.5 Forgings for $1^1/_4$/1Cr-$^1/_2$Mo Reactors

Past experience with thick $1^1/_4$Cr-$^1/_2$Mo forgings has resulted in large scatter of the energy values and percent shear fracture appearance. For example, Charpy V-notch specimens had only 10 % shear appearance but high energy values (e.g. 60 ft-lb to 80 ft-lb, or 80 J to 110 J). As a result, the more hardenable 2½Cr-1Mo forgings sometimes are used for large and complex forgings in $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo vessels to achieve better toughness. Some manufacturing and testing considerations that improve quality, notch toughness, and other properties of $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo forgings are:

1) Fine grain practice.

2) Low sulfur and phosphorus contents, as well as other residual elements (Sb, and As ≤ 0.010 %, Sb ≤ 0.0025 %).

3) Vacuum degassing.

4) At least 3:1 reduction in all directions from billet to forging.

5) Quench and temper.

6) Examine the forging volumetrically by UT and perform surface examination by MT or PT methods, as applicable

7) Large and complex forgings should preferably be ordered to SA-336 forging specification instead of SA-182 (which is intended for forged pipe flanges, fittings and valves) as the testing requirements are better defined in SA-336 for large and complex forgings.

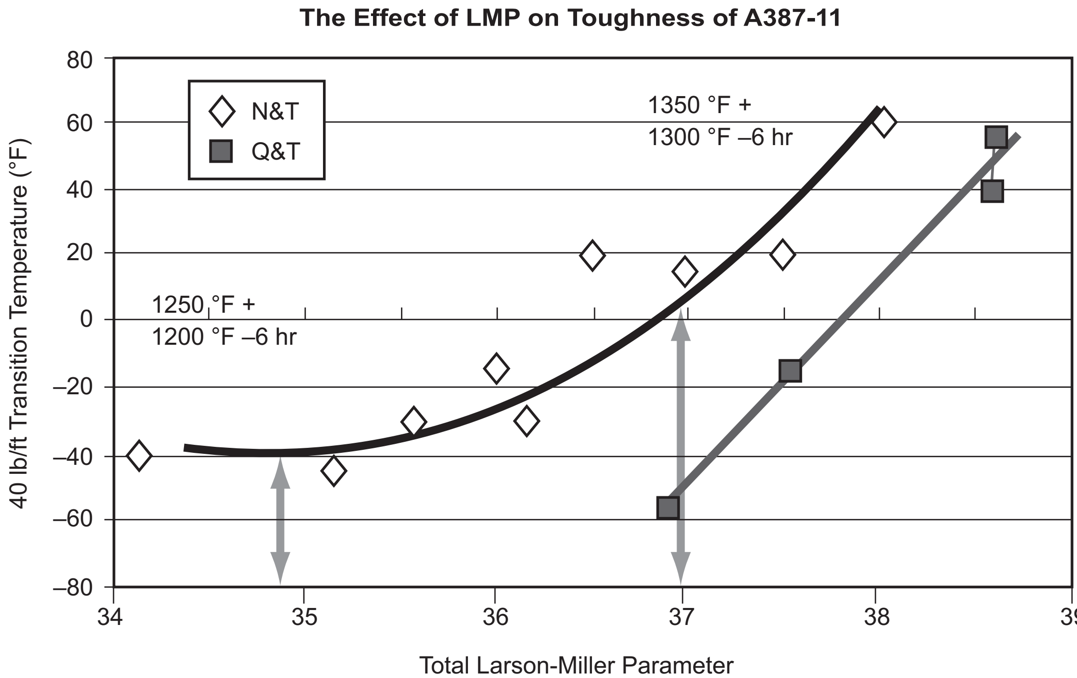


Figure 7—The Effect of Postweld Heat Treatment on 40 ft-lb (54 J) Transition Temperature in N&T and Q&T A387, Gr. 11 Plates as a Function of Tempering Parameter (LMP)

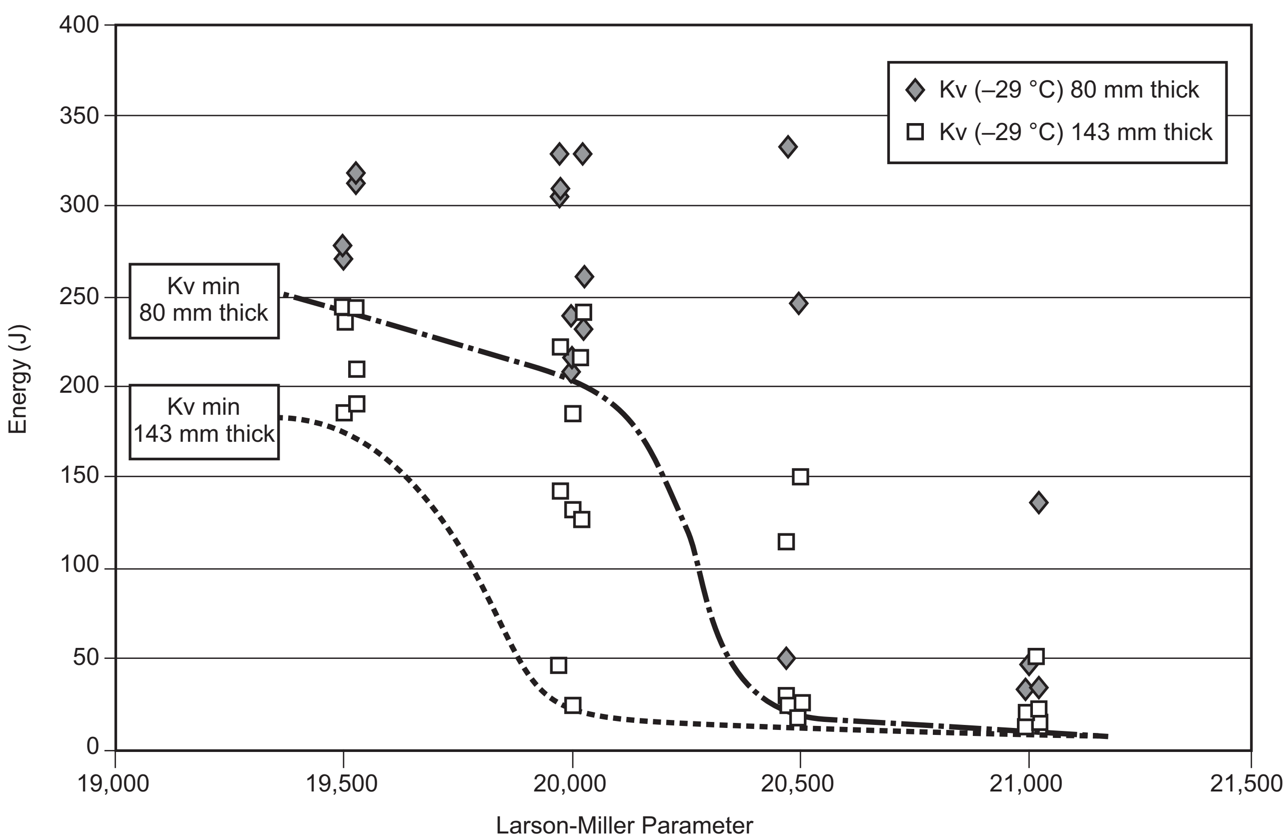


Figure 8—Toughness Properties (Kv) of Two Plates A387 Gr. 11, Cl. 2, 3.15 in. (80 mm) and 5.63 in. (143 mm) Thick as a Function of Tempering Parameter

8) Consideration should be given to testing large and complex forgings several directions (circumferential and longitudinal, or in special cases in all three directions).

API 934-C and API 934-E allow the use of $2^1/_4$Cr-1Mo thicker nozzle forgings to ensure that the toughness requirements are met. However, some users have expressed concerns about the mixed metallurgy. Some of the concerns with using $2^1/_4$Cr-1Mo forgings in $1^1/_4$/1Cr-$^1/_2$Mo vessel shells are:

1) different allowable design stresses for the $2^1/_4$Cr-1Mo and $1^1/_4$/1Cr-$^1/_2$Mo materials;

2) different PWHT temperatures;

3) different creep rates in the two base metals and welded joints in elevated temperature service, which may cause redistribution of residual stresses in the welds.

There may also be a different response to various forms of embrittlement in elevated temperature service. Consequently, each of these factors should be taken into account if $2^1/_4$Cr-1Mo forgings are to be used in combination with $1^1/_4$/1Cr-$^1/_2$Mo vessel shells.

7 Embrittlement and Cracking Issues In $1^1/_4$/1Cr-$^1/_2$Mo Base Metals and Welded Joints

7.1 General

There are two forms of embrittlement common with $1^1/_4$/1Cr-$^1/_2$Mo steels:

1) HAZ elevated temperature cracks caused by loss of creep ductility in that region which has been referred to as creep embrittlement [1][2] or reheat cracking, [6] and

2) loss of room temperature toughness which has been referred to as stress relief embrittlement [16] and "irreversible embrittlement." [13]

One should also take into consideration the potential for temper embrittlement, which is an important concern with $2^1/_4$Cr-1Mo alloy steels. Each of these materials degradation mechanisms is discussed below.

7.2 Temper Embrittlement

Previous studies have shown that $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo steels are susceptible to temper embrittlement. This effect is much less severe than that for $2^1/_4$Cr-1Mo but in a similar manner it occurs in the temperature range of 750 °F to 1000 °F (399 °C to 538 °C) and has been observed after exposure times of 1000 hours. Figure 9 [11] illustrates worst-case data for $1^1/_4$Cr and 1Cr-$^1/_2$Mo. Although the data show that temper embrittlement can be induced by step cooling the effect is probably too subtle to be observed for most typical heats of $1^1/_4$Cr and 1Cr-$^1/_2$Mo in most cases. Work by JSW also indicates that the temper embrittlement effect is much less severe for $1^1/_4$/1Cr-$^1/_2$Mo steels, than $2^1/_4$Cr-1Mo steels. [12]

At the present time there is some disagreement as to what method is best for control of the tendency for temper embrittlement for $1^1/_4$Cr and 1Cr -$^1/_2$Mo. Recent data reported by Industeel shows a strong influence of P on potential for temper embrittlement, Figure 10 [13] indicates that a maximum level of P of 0.007 % would be an effective limit for the control of temper embrittlement for $1^1/_4$Cr and 1Cr-$^1/_2$Mo steel. Based on their experience, some steel fabricators feel that the J factor, which is used to predict the propensity for temper embrittlement in $2^1/_4$Cr-1Mo steels, is not a useful method for prediction of the tendency for temper embrittlement for 1¼Cr and 1Cr-½Mo steels, particularly since the $1^1/_4$Cr-$^1/_2$Mo steel has a high silicon content. [14] The X-bar factor which was introduced by Bruscato [15] for $2^1/_4$Cr-1Mo weld material has been adapted by several Cr-Mo steel producers in an effort to minimize any tendency for temper embrittlement for $1^1/_4$Cr and 1Cr-$^1/_2$Mo Mo base metal and weld metal.

Based on the above literature the use of the J factor which is used for $2^1/_4$Cr-1Mo is not needed to control the tendency for temper embrittlement for $1^1/_4$Cr and 1Cr-$^1/_2$Mo. Similarly, step cooling should not be required to assess

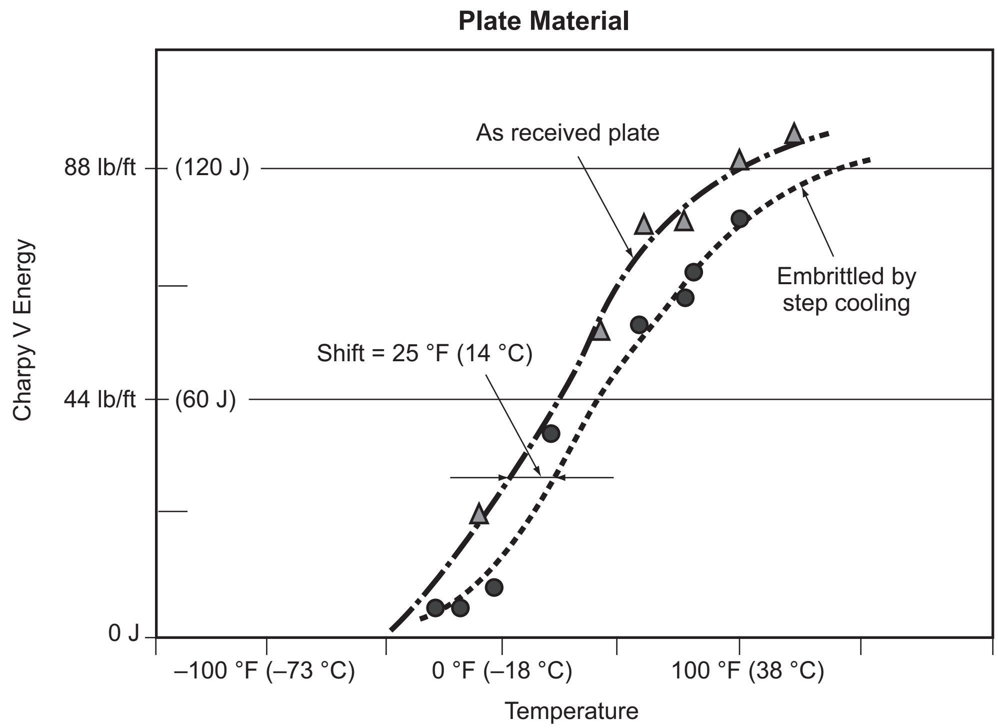


Figure 9—Transition Temperature Shift in 1$^1/_4$Cr-$^1/_2$Mo Plate Metal Due to Temper Embrittlement

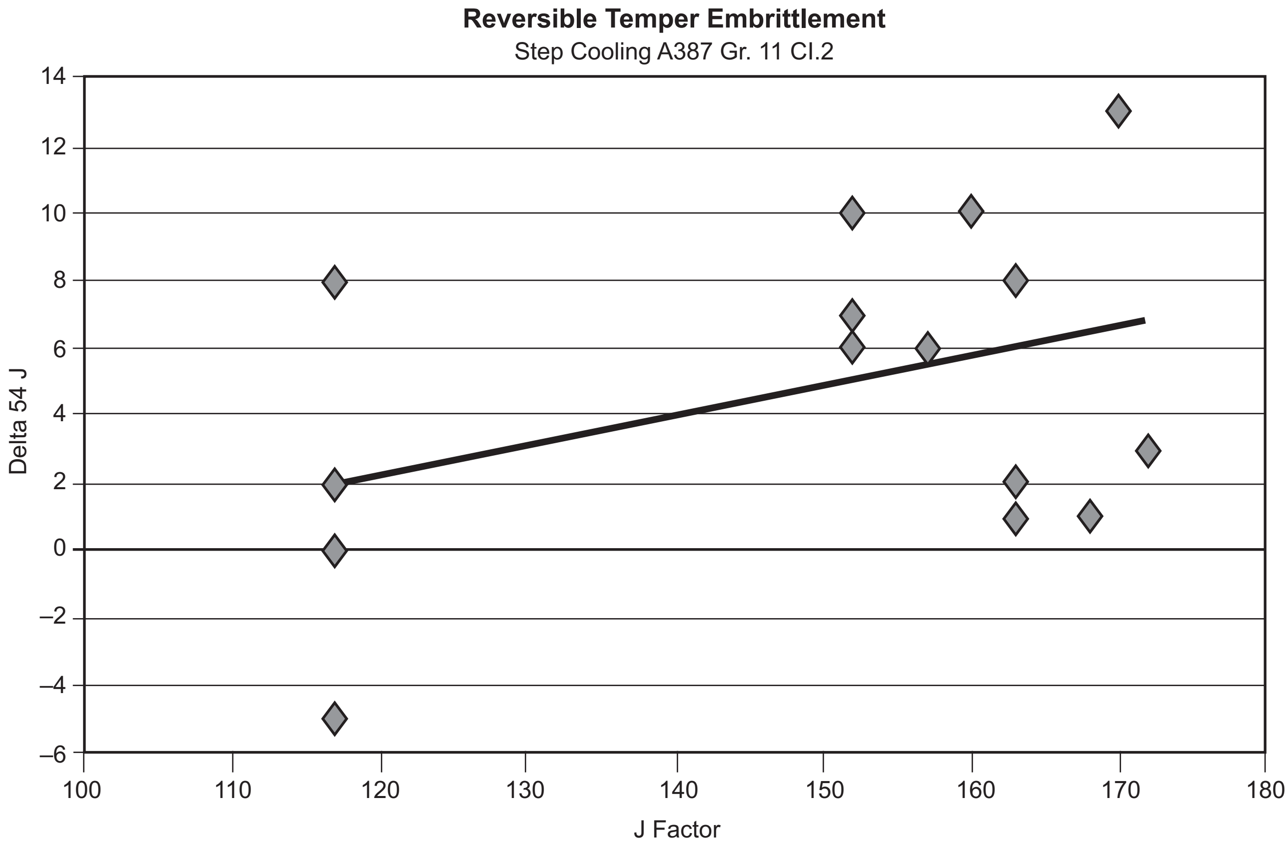
the propensity for temper embrittlement for 1$^1/_4$Cr and 1Cr-$^1/_2$Mo Mo steels since typical 40 ft-lb (54 J) transition temperatures are at much lower temperatures in modern Cr-Mo steels than in the older generation Cr-Mo steels.

7.3 Stress Relief Embrittlement

Some materials are susceptible to loss of strength and toughness due to excessive heat treatments, including thermal stress relief. This phenomenon affects certain types of pressure vessel steels including carbon steel and low alloy steels as reported by Pense et al. [16] This form of embrittlement is associated with carbide agglomeration at grain boundaries. It has been associated with loss of toughness observed with 1$^1/_4$Cr and 1Cr-$^1/_4$Mo steels and other carbon and low alloy steels after exposure to long term PWHT, as expressed in terms of Larson-Miller parameter [7][13] and also referred to as, “irreversible embrittlement.” The extent of PWHT of 1$^1/_4$Cr and 1Cr-$^1/_4$Mo steels, as expressed by the Larson Miller parameter, provides an indication of the degree of toughness degradation caused by irreversible embrittlement. As indicated previously, for a given refinery application such as a catalytic reformer reactor, this will require a tradeoff between the need to control creep embrittlement and the need to meet toughness requirements.

7.4 Creep Embrittlement

This elevated temperature damage mechanism has been manifested in the form of HAZ creep damage and cracking as well as intergranular fracture, Figure 11. Various terms have been used to describe this effect including creep embrittlement and reheat cracking. In some ways both terms are somewhat misleading. Creep embrittlement is meant to describe cracking that has usually occurred after long term service at the weld HAZ after the weld HAZ has lost ductility and creep strain tolerance. [3][17] The term is misleading in that it implies that loss of creep ductility or creep embrittlement occurs during service, which is probably not the case. The actual property change probably occurs during fabrication. On the other hand reheat cracking seems to suggest that all damage including cracking occurs at or near the time of fabrication. In actual fact what is probably occurring in the above cases is that property changes are taking place during fabrication and creep crack propagation is occurring during service.



NOTE For phosphorus levels typical of Industeel production (< 0.010 %, target < 0.007%), there is no real influence of J-factor.

Figure 10—40 ft-lb (54 J) Transition Temperature Shift and J-Factor in Low Phosphorus Cr-Mo Steels

Figure 11—HAZ Cracks from Creep Damage

8 Guidelines On Chemical Composition, Heat Treatment and Mechanical Testing of 1$^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo Vessels

The two major refinery applications for 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo steels Hydrofiner reactors and Catalytic reformer reactors each see different service conditions. This is taken into account by way of two separate specifications API 934-C [18] and API 934-E. [19] Some of the requirements for chemical composition, heat treatment and testing for these two applications will be different and the others the same. A rationale is provided below for some of the major requirements.

8.1 Chemical Composition

Modern Cr-Mo steels for petrochemical industry typically are produced to fine grain practice, typically with Al content 0.020 %, improved chemical composition controls, and reduced amounts of residual elements, e.g. P = 0.010 %, and S = 0.005 %. These improvements in chemical composition control improve notch toughness, and improved resistance to temper embrittlement in the 700 °F to 1100 °F (371 °C to 593 °C) temperature range and creep embrittlement in the 850 °F to 1000 °F (454 °C to 538 °C) range.

8.1.1 Hydrofining Reactors and Other Equipment with Design Temperatures ≤ 850 °F (454 °C)

8.1.1.1 Temper Embrittlement

Temper embrittlement is not as great a concern with 1$^{1}/_{4}$Cr-$^{1}/_{4}$Mo and 1Cr-$^{1}/_{2}$Mo steels as it is with 2$^{1}/_{4}$Cr-1Mo steel as indicated in 7.2 of this report. Accordingly, specific chemical requirements such as J factor are not needed for 1$^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo steels. Similarly step cooling tests are not needed. Reducing the phosphorus content is an effective way to control temper embrittlement in Cr-Mo steels, however, it appears that a maximum phosphorus content of 0.010 % to 0.012 % is sufficient for 1$^{1}/_{4}$/1Cr-$^{1}/_{2}$Mo vessels which are not operating in the creep range (Annex A).

As indicated in Figure 9, there could be some loss of toughness in lower bound 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo base metal and weld metal. Therefore, additional steps should be taken to minimize the loss of toughness. Accordingly, X-bar ≤ 15 is advisable for base metal and weld metal [14]. Other chemical requirements include: Cu ≤ 0.20 % and Ni ≤ 0.30 %. The material should also be vacuum degassed. The J-factor generally is not considered to be important factors for use of the 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels since these steels are not as susceptible to temper embrittlement as the 2$^{1}/_{4}$Cr-1Mo steels

8.1.1.2 Creep Embrittlement

Creep embrittlement appears to be occurring above 850 °F (454 °C), which is somewhat above the service temperature range for Hydrofiner reactors. Therefore there is no need to address this concern for Hydrofiner reactors.

8.1.2 Catalytic Reforming Reactors and Other Equipment with Design Temperatures > 850 °F (455 °C)

8.1.2.1 Temper Embrittlement

Although temper embrittlement is not of real concern with 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels within the operating temperature range for Catalytic Reforming Reactors the same considerations as above should also be given for Catalytic Reforming Reactors.

8.1.2.2 Creep Embrittlement

Creep embrittlement occurs within the operating temperature range for Catalytic Reforming Reactors. Consequently, chemical controls will be required. Various approaches to chemical controls have been considered from a standpoint of effectiveness and applicability. MPC has studied past efforts for control of chemical composition as a preventive measure against creep embrittlement/reheat cracking and has assessed various existing parametric approaches (i.e. X-bar, J) and developed new parametric relationships, i.e. new MPC factors [6] that focus on control of elements such as Nb, V, and Ti. However, the limitations on certain alloying elements (e.g. Nb) are beyond accuracy of laboratory equipment at the steel producers laboratories and require special equipment, which interferes with “real time” melting operations.

It is recognized that the MPC factors represent a new approach for controlling reheat cracking that has yet to gain widespread acceptance by users and fabricators, However, this approach may need to be considered in the future as different scrap feed stocks that contain such elements as Nb, V, and Ti are used by the steel producers.

Various alternative proposals have been made to minimize the tendency for creep embrittlement. For example, one steel producer [13] has shown that limiting P to 0.007 % can maintain high level of creep ductility after long time exposure at 932 °F (500 °C), Figure 12. Based on these considerations, the use of X-bar ≤ 12 appears most reasonable. Other chemical requirements should include: Cu ≤ 0.20 %, Ni ≤ 0.30 % and C ≤ 0.14 %. The material should also be vacuum degassed. It appears that, based on the data in Figure 12, lower phosphorus contents than 0.010 % (e.g. 0.007 %) would be appropriate for $1^1/_4$1Cr-$^1/_2$Mo vessels operating in the creep range.

8.2 Heat Treatment for All Applications

8.2.1 PWHT of Hydrotreating Reactors and Other Vessels for Service Temperatures up to and Including 825 °F (440 °C)

ASME Code requires all vessels of P-No. 4, Group 1 materials (1Cr-$^1/_2$Mo and $1^1/_4$Cr-$^1/_2$Mo steels) to be stress relieved at 1200 °F (649 °C) for 1 hr/in. (1 hr/25 mm) for nominal thickness up to 5 in., plus additional 15 min/in. (15 min/25 mm) for thicknesses over 5 in. (127 mm). However, these vessels are often used in high-pressure high temperature hydrogen service or in other service conditions that require sufficient tempering of the heat affected zones to reduce hardness and minimize the risk of cracking. Therefore, these vessels should be stress relieved at 1225 °F (663 °C) minimum (1250 °F nominal ± 25 °F) (677 °C ± 18 °C) with the hold times specified in the ASME Code.

8.2.2 PWHT of Catalytic Reforming Reactors and Other Vessels for Service Temperatures Exceeding 850 °F (454 °C)

Vessels intended for catalytic reforming reactors and other vessels for service temperatures exceeding 850 °F (454 °C) are subjected to creep embrittlement [see 7.4], and generally need to be stress relieved at higher temperatures to minimize the risk of embrittlement and cracking. These vessels generally will be constructed of the lower strength Class 1 materials, which permit higher PWHT temperatures. These vessels typically are stress relieved at 1250 °F (677 °C) minimum (1275 °F nominal ± 25 °F) (690 °C nominal ± 14 °C), or 1300 °F (704 °C) minimum (1325 °F nominal ± 25 °F) (718 °C nominal ± 14 °C), for 1 hr/in. (1 hr/25 mm) for $t \leq 5$ in. (127 mm) with test coupons stress relieved at the nominal PWHT temperature for three PWHT cycles, plus any intermediate stress relief (ISR) cycles.

8.2.3 Minimum PWHT Temperature to Achieve the Desired Hardness Values in Welded Joints

Experience has shown the HAZ and weld metal to be the problem areas for meeting maximum hardness values of 235 Hv10 on the cross section of the welded joint in procedure qualifications and 225 HBW surface hardness in production tests. It has been helpful to reduce weld metal carbon content when trying to meet these values. A PWHT temperature of 1250 °F (677 °C) minimum for at least 2 hours has been necessary to meet these values in the HAZ. A PWHT range of 1275 °F nominal ±25 °F (690 °C ±28 °C) is a good compromise between strength, hardness, and notch toughness.

8.2.4 Use of the Final PWHT as the Final Temper at a Higher Temperature than the Mill Temper of the Material

The final PWHT may be used as the final temper; however, this establishes the final properties of the material and therefore proper heat treatment controls by the vessel manufacturer and should be done only with prior agreement by the material manufacturer. The heat treatment procedures must also be agreed to and approved by the vessel

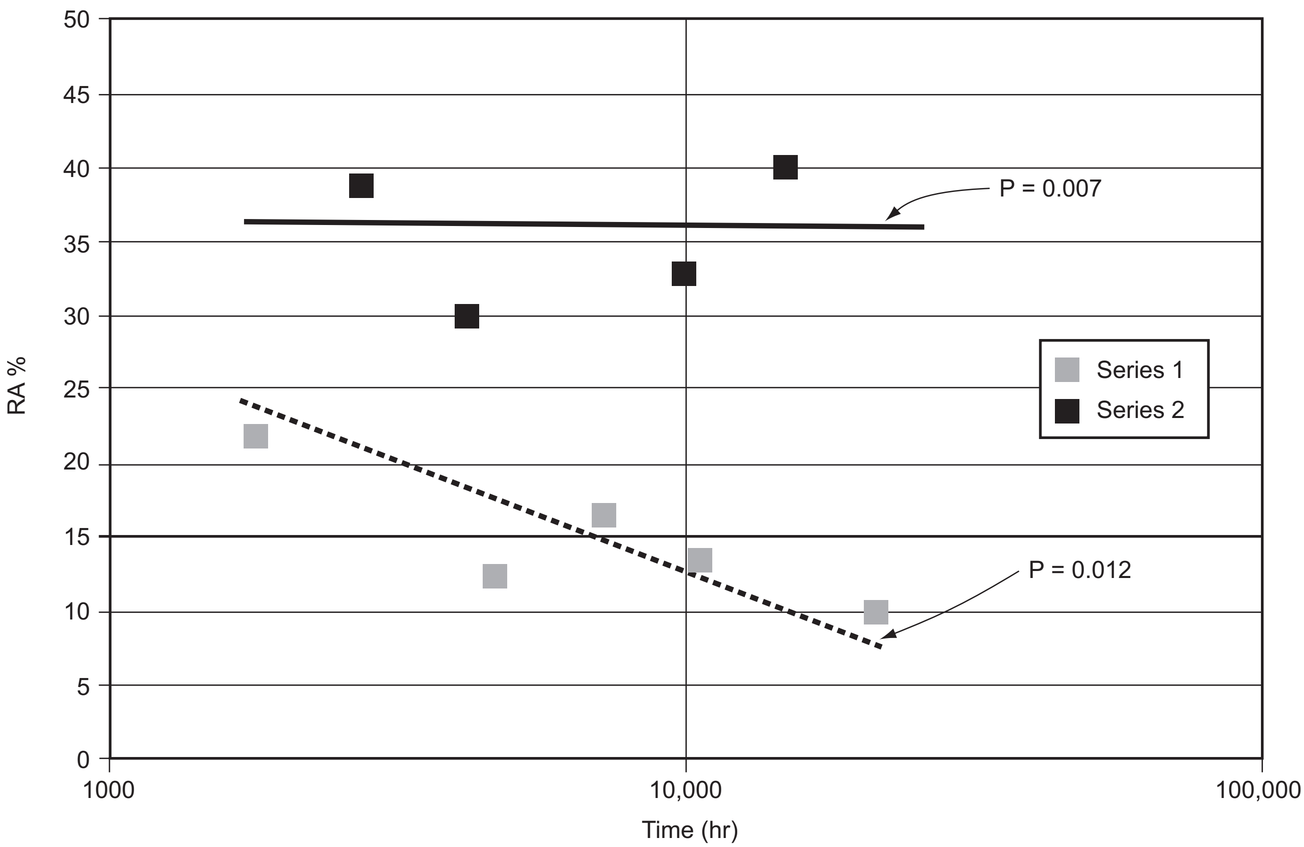


Figure 12—The Role of Phosphorus in Creep Embrittlement and Cracking
Creep Rupture Elongation of A387 Gr. 11 at 500 °C

purchaser before the final PWHT. It should be noted that in most cases, and more particularly for thicker vessels, the final properties are established by the PWHT (even if the tempering temperature is higher than the PWHT).

The test specimens should be obtained from sample test coupons that have been heat treated in the same manner as the vessel materials during the vessel fabrication, including the heating rates, hold times and cooling rates. When the final PWHT is used as the final temper, the test coupons should be stress relieved with the nominal temperature at or near the upper limit of the PWHT temperature, e.g. 1290 °F ± 10 °F (699 °C ± 6 °C) for vessels stress relieved at 1275 °F (690 °C) nominal ± 25 °F (14 °C) and simulate the cooling rates that will occur in the vessel. Such test coupons should be heat treated together with the vessel.

8.2.5 Other Heat Treatments

Heat treatment must be considered from a standpoint of accumulated heat treat cycles using the allowable Larson-Miller time-temperature parameter (LMP). The steel fabricator must then develop a heat treat schedule that will comply with the user's requirements for tensile properties and CVN toughness requirements for the design temperature. This will require discussions between the user and the supplier to establish the available options.

Sample Case for Available Options Between User and Fabricator:

G. Masson et al [9] provided an example of the options available to purchasers for thick wall vessels. Suppliers have often had difficulty in complying with user specifications for thick plate based on PWHT requirements. Table 9 indicates three supplier proposals based on LMP. Figure 3 and Figure 8 indicate that both tensile and CVN properties decrease significantly at a LMP value of approximately 36,180 (20,100 in terms of °C).

Table 9—Example of Requirements for SA-387 Gr. 11 Cl.2 and Possible Proposals. Plate Thickness: 6 in. (125 mm)

	Tempering °F (°C)	PWHT °F (°C)	LMP	Kv	Max LMP Acceptable
Requirement	≥ 1274 (≥ 690)	1238 (670) – 17h	36,316 (20,176 metric)	> 54 J avg. (–18 °C)	36,180 (20,100 metric)
Proposal 1	1202 (650)	1238 (670) – 17h	39,099 (20,055 metric)	> 54 J avg. (–18 °C)	36,180 (20,100 metric)
Proposal 2	≥ 1274 (≥ 690)	1220 (660) – 17h	36,059 (20,033 metric)	> 54 J avg. (–18 °C)	36,180 (20,100 metric)
Proposal 3	≥ 1274 (≥ 690)	1238 (670) – 17h	36,317 (20,176 metric)	> 54 J avg. (–12 °C)	36,540 (20,300 metric)

Several alternative proposals can be made from Table 9:

— **Proposal 1**: it is possible to meet the requirements of the specification in term of impact properties and PWHT, although the tempering temperature is below the PWHT temperature.

— **Proposal 2**: if one wants to keep the tempering temperature at 690 °C, maintaining impact properties, then it is necessary to reduce the PWHT temperature. It can be a difficulty for the vessel manufacturer.

— **Proposal 3**: it is also possible to follow heat treatment requirements (tempering and PWHT) but then to reduce impact test requirements.

This example illustrates there is not a single answer and that there is a need of discussion between the different concerned parties to define the best adapted solution.

8.2.6 Test Coupons to Simulate Vessel Heat Treatment

The material used in the vessel shall be represented by test specimens which have been subjected to same postweld heat treatments as the vessel. The test specimens shall be obtained from test coupons that have been heat treated in the same manner as the vessel material, including any heat treatments by the material producer before shipment. The heat treatments shall include all thermal treatments of the material during fabrication exceeding 900 °F (480 °C). In addition, the test coupons shall be subjected to at least three cycles of PWHT at 1275 °F (649 °C) to allow for one PWHT cycle for any repairs after the vessel has been placed in service. The ASME Code permits combining the individual PWHT cycles for test coupons in a single PWHT cycle. The total time at temperature for the test coupons shall be at least 80 % of the total time at temperature during the actual heat treatment of the vessel or part.

9 Testing of Plates and Forgings

9.1 Test Specimen Location to Simulate the Cooling Rates in Plates and Forgings

Test specimens shall be taken from locations that are representative of the actual cooling rates in the part during the heat treatment. The slowest cooling rate usually is at the mid thickness of the plate or the thickest part of the forging. In case of plates, the test specimens shall be taken from the $^1/_2\ t$ location of the plate and at least one T from the edge of the plate. Test specimens should be orientated transverse to the maximum amount of working in the plate or forging.

Several alternative locations are given in most forging specifications for obtaining the test specimens. That includes the following:

1) The $^1/_4\ t \times t$ location of the actual production forging or a separately forged test blank.

2) The $t \times 2\ t$ location, as defined in the ASME Section VIII, Division 2 or in the forging specification.

3) The use of metal buffers as permitted by the forging specification.

All of these locations are acceptable; however, past experience indicates that the use of separately forged test blocks does not result in representative test results from the actual forging. That is because (and regardless of the specification requirements for separately forged test blocks) the amount of working of the separately forged test block is not representative of the actual forging. Therefore, where possible, tests of specimens obtained from the actual forging are recommended.

Consideration should be given to multiple test specimens from forgings since the direction of the maximum amount of working (or elongation) may not be known. Consideration should also be given to the direction of the maximum stresses in the forging. For large or complex forgings, test specimens should be taken from the transverse and longitudinal directions. In case of forgings subjected to significant transverse (through thickness) stresses, consideration should also be given to taking test specimens in the through thickness direction.

9.2 Test Coupons to Simulate Vessel Fabrication Heat Treatments

The material used in the vessel shall be represented by test specimens which have been subjected to the same postweld heat treatments as the vessel. The heat treatments shall include all thermal treatments of the material during fabrication exceeding 900 ° (482 °C). The test coupons should be subjected to at least three cycles of PWHT at the nominal PWHT temperature [e.g. at 1275 °F (690 °C), for a vessel or part that is stress relieved at 1275 °F ± 25 °F (690 ± 14 °C)], to allow for one extra PWHT cycle for any repairs after the vessel has been placed in service, plus any intermediate stress relief (ISR) cycles exceeding 900 °F (482 °C).

9.3 Test Specimen Location to Simulate the Cooling Rates in Plates and Forgings

ASME Section VIII, Division 2, Part 3 includes specific requirements for obtaining test specimens and coupons from plates and forgings for materials to be used in Division 2 construction. Test specimens shall be taken from locations that are representative of the actual cooling rates in the part during the heat treatment. The slowest cooling rate usually is at the mid thickness of the plate or the thickest part of the forging. In case of plates, the test specimens shall be taken from the $^1/_2\ t$ location of the plate and at least one t from the edge of the plate. Unless a procedure is used that produces the same cooling rate in the test specimen as the cooling rate at the specified location in the main body of the product, the dimensions of the test coupon for plates shall not be less than $3t \times 3t \times t$, where t is the nominal thickness of the plate.

In the case of forgings, the test specimens should be taken from at $^1/_2\ t$ location of the prolongation or from a separate test block which represents the midwall of the heaviest section of the production forging. A separate test block, if agreed to by the purchaser, shall be obtained from an ingot, slab, or billet from the same heat used to make the forging it represents, which should have received substantially the same reduction and type of hot working as the production forging, and should be of the same nominal thickness as the production forging. The separately forged test block shall be heat treated together with the forging it represents. However, separately forged test blocks may not always be representative of the actual forging, therefore test specimens taken from the forging or forging prolongation are recommended when fracture toughness is a consideration.

9.4 Hot Tension Tests

Figure 13 shows the upper and lower statistical limits of typical hot tensile test results. The upper curve plots the tensile strength values for the $1^1/_4$Cr-$^1/_2$Mo steels in ASME Section II, Part D, Table U, and the lower curve the yield strength values in Table Y-1. The test data in Figure 13 shows that it is not possible to meet the tensile strength values in Table U with high PWHT temperatures and long PWHT hours (e.g. LMP = 20,400 based on °C, or LMP = 36,700, based on °F). The purchaser and the steel producer should agree upon hot tension test values if the hot tension test is deemed necessary. Hot tensile strength values equal to 90 % of those in Section II, Part D, Table U generally have been acceptable. [13]

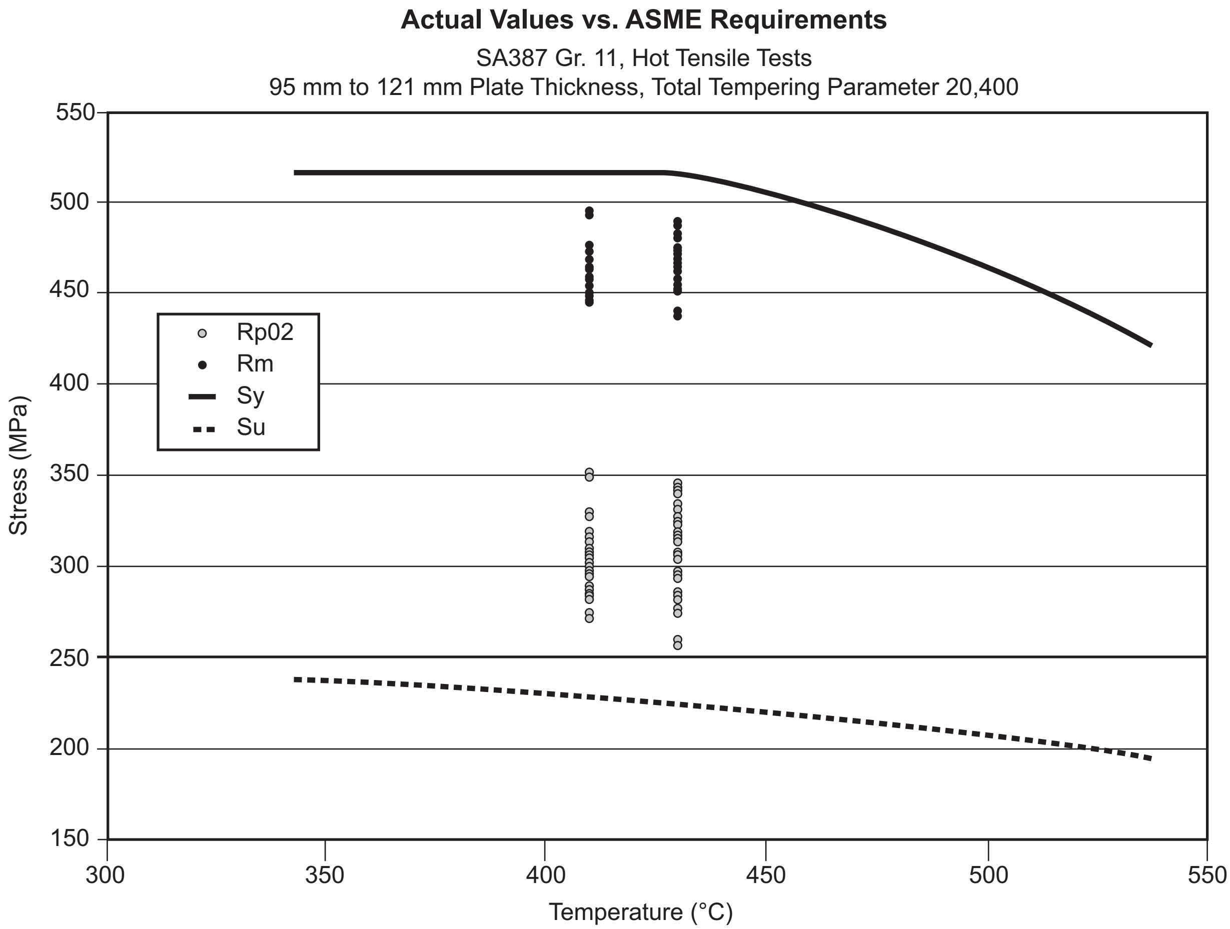


Figure 13—Results of Hot Tensile Tests from SA-387 Gr. 11 Plates After Heat Treatment to Tempering Parameter (LMP) of 20,400 in Terms of °C (36,700 in Terms of °F)

10 Fabrication/Metal Forming

10.1 Forged Shell Rings vs. Shell Rings Made of Plate

Vessel shell may be made of forged rings or plate. Typical maximum vessel shell thicknesses for forged shell rings and for plates produced to SA336, Grade 11, Class 1 and Grade 12, Class 1 properties and for plates produced to SA-387, Gr. 11, Class 1 and Grade 12, Class 1 properties is about 8 in. (203 mm). Forged shells of SA336, Grade 11, Class 2 and 3 material, and plates produced to SA-387, Grade 11, Class 2 and Grade 12, Class 2 properties are generally limited to about 4 in. (102 mm) maximum thickness because hardenability problems at mid-thickness of thicker sections. Therefore, most of the 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo vessels are made of SA-387, Grade 11, Class 2 plates and are up to about 4 in. (102 mm) thick.

Cylindrical shells of forged rings have certain advantages over the plate construction. Forged rings do not have a longitudinal shell seam and are machined on both surfaces. They can be made to close tolerances and do not need an intermediate PWHT (ISR) or a DHT of the longitudinal shell seams. However, shell rings less than 4 in. (102 mm) thick generally are not available because of the costs; therefore vessel shells up to and including 4 in. (100 mm) thick generally are made of plates.

10.2 Forming

Shell plates for a pressure vessel must be formed to the correct shape to create the vessel. Head plates are generally dished to the correct shape by pressing into a die and are curved in both directions. The proper die is loaded into a hydraulic press and a skilled operator forms the plates. Forming to the correct shape may involve progressive steps and use more than one die. The shape (curvature) is checked using a sweep board cut to the vessel radius. Plates are formed to a cylindrical shell by pressing or rolling. A satisfactory result may be achieved using either a press or plate rolls.

Cracking of shell plates can occur, but should not be a problem when proper precautions are applied. Generally forming is done in one of three temperature ranges. The three temperature ranges are summarized in Table 10.

Table 10—Forming Temperature Ranges

Forming Method	Temperature Range °F (°C)	Comments
Cold	70 to 400 (20 to 204)	Care is required to avoid brittle failure while forming.
Warm	800 to 1100 (427 to 593)	Warm forming generally is used to reduce the strength of material to overcome low press/roll capacity. Warm forming is done at temperatures below the PWHT temperature.
Hot	1600 to 1750	Hot forming is done above the PWHT temperature and within the normalizing temperature range for the material. Care is required to avoid die marks in surface of the plate. Plates may require heat treatment after forming.

Plates ordered without the specified heat treatment (“green” plates) must be handled with care. There is no knowledge about the properties of the “green” plates. Some fabricators have these plates stress relieved before forming. This reduces the risk of cracking or breaking the plate when handling in the shop. When temporary attachments are welded to such plates for handling, etc., the preheat requirements should be more stringent than for heat treated plates. Plates have been damaged by attempting to weld temporary attachments to the plate without preheat.

10.3 Cold Forming

Cold forming is the most commonly used method. Plates being cold formed generally are at their highest strength level. Plates to be cold formed are stress relieved or annealed at the mill if shipped “green” (not heat treated), or have not been heat treated for properties (N&T, Q&T, etc.) but have not received any of the fabrication heat treatments (PWHT) recorded on the mill test reports. The mill heat treats test coupons to simulate all expected fabrication heat treatments and lists the test results from the test coupons used to simulate all fabrication heat treatments. Depending on PWHT requirements plate material received at the steel mill, it may be 10,000 psi to 15,000 psi stronger than the tensile strength recorded on the mill test reports. To avoid brittle fracture during forming, stress raisers (notches) must be removed from the tension side of the plate. It is recommended that a radius of ¼ *t*, or a maximum ⅜ in. (9.5 mm) radius be ground on the tension edge of the plate being formed. Plate temperature during forming preferably should be at or near the upper shelf of the transition temperature, and not be less than room temperature (70 °F). Notch toughness of the plates received without PWHT may not be the same as those reported on the mill test reports. Therefore, extra care is required when cold forming these plates.

The temperature range between 400 °F (204 °C) and 800 °F (427 °C) should be avoided for any forming. This temperature range includes the blue brittle range where the risk of cracking a plate is increased.

Plates supplied to the vessel fabricator generally have the minimum amount of temper to allow for additional tempers (PWHT) during the vessel fabrication and may have a tensile strength on the high end of the range and lower toughness than in the PWHT condition, therefore, forming (rolling, dishing) of Cr-Mo plates need certain precautions to avoid cracking during forming. That includes the following:

a) prior to forming, visually inspect all plate surfaces for any defects;

b) the plate edges and welding bevels should be in accordance with paragraph 6.6.5.3 of Section VIII, Division 2, 2007 ed., and inspected prior to forming;

c) form plates over 2 in. (50 mm) thick at temperature of 200 °F (93 °C) minimum;

d) avoid welding attachments to tension surfaces and having hard heat affected zones from any prior attachments on any surfaces;

e) after forming, visually inspect the plate surfaces and edge bevels for any defects cause by forming.

The maximum forming strains should be calculated by the formulas given in Table 6.1 of ASME Code Section VIII, Division 2, 2007 ed. For one piece double curved shells (e.g. one piece heads) the forming strains are calculated by the following formula:

$$\varepsilon_f = 100 \ln\left(\frac{D_b}{D_f - 2t}\right)$$

where

D_b is the diameter of the blank plate, or the diameter of the intermediate product;

D_f is the outside diameter of the finished product;

t is the nominal thickness if the of the plate before forming.

The formula above is different than the bending strain formula in Section VIII, Division 1 and in the 2004 edition of Division 2. The above formula calculates circumferential (compressive) membrane strains due to the reduction of the outside diameter of the (flat) blank to the final outside diameter of the head (the finished product), whereas, the ASME formula only calculates bending strains. The use of the above formula generally results in higher forming strains than the ASME bending strain formula.

Table 11 is provided for guidance when cold formed plates should be stress relieved during forming or after forming.

Table 11—Maximum Forming Strains without Heat Treatment

Stain, %	Recommended Stress Relief (SR)
< 3	SR is not required.
≥ 3 ≤ 4.5	Final SR or PWHT of the part. [Form at 200 °F (93 °C) minimum unless intermediate SR is performed at 3 % strain.]
≥ 4.5 ≤ 7.0	Intermediate SR when the strain reaches 3 % and final SR or PWHT after the forming is completed.
≥ 7.0 ≤ 9.0	SR when strain reaches 3 % and again at 6 %. Final SR, or PWHT, or heat treat in accordance with the material specification requirements.
> 9.0	Hot form the plate and heat treat in accordance with the material specification requirements.

10.4 Warm Forming

Warm forming is used when the pressing/rolling capacity is marginal. By heating plates to the 800 °F (427 °C) to 1100 °F (593 °C) temperature range the tensile strength is reduced and plates can be formed as required. The material is softer in this temperature range and care is required to avoid die marks on the surface. Deep die marks can compromise plate thickness if they are deep enough. Precautions must be taken to protect press/roll operators from heat when forming in this temperature range. When the material is subjected to heat treatments above 900 °F (482 °C), the test specimens shall be obtained from test coupons which have been heat treated in the same manner as the material, including the heat treatments that were applied by the material producer.

10.5 Hot Forming

Hot forming requires an experienced fabricator with appropriate equipment (furnaces, quench tank) and experienced personnel to design and implement the program. Care must be used during forming to prevent gouges of the plate surface. Precautions must be taken to protect press/roll operators from the heat when forming in this temperature range. Plates require heat treatment for properties after the forming is complete. By heat treating after forming is complete the time at temperature does not count against the total PWHT time available.

Generally hot-formed plates are welded into complete assemblies before final heat treatment is performed. Vessel subassemblies (shell rings, head plate assemblies) are dimensionally more stable during heat treatment than individual plates. For example when plates are water quenched, the size of the plate will grow by about 1 %. Various explanations have been offered to explain this phenomenon, but there is no rigorous explanation. Properly buffered test coupons must accompany the hot-formed plates, as they are heat treated for properties. The test specimens shall be obtained from test coupons which have been heat treated in the same manner as the material, including the heat treatments that were applied by the material producer.

11 Fabrication/Welding

11.1 Welding Processes for 1¹/4Cr-¹/2Mo and 1Cr-¹/2Mo Welding

Section VIII of the ASME Code allows the use of a wide range of welding processes. This allows the fabricator to plan vessel welding with welding processes best suited for the application. Fabricators will select welding processes based on experience, equipment available, and availability of high quality weld materials that meet physical requirements of the project. Weld processes most likely to be considered include Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW) and Flux Cored Arc Welding (FCAW).

1¹/4Cr-¹/2Mo welding consumables are used for welding both 1Cr-¹/2Mo and 1¹/4Cr-¹/2Mo steels. Only weld consumables that produce a low hydrogen deposit are acceptable.

Table 12 is a summary of weld processes and weld consumables for 1Cr-¹/2Mo and 1¹/4Cr-¹/2Mo steels. A detailed description of these processes may be found in the AWS Welding Handbook Volume 2, Eighth Edition.

11.2 Preheat and DHT to Avoid Cracking

Preheat has long been known as an effective method to prevent cracking in weld metal and base metals. It lowers the cooling rate in the weld metal and heat affected zone (HAZ) in the base metal that produces a softer (more ductile) structure to resist cracking. Preheat also provides time for hydrogen present in the weld metal to diffuse out of the weld metal and HAZ without causing cracking. It also reduces shrinkage caused by welding. Reducing or eliminating the risk of hydrogen cracking (also called cold cracking) is by far the most important benefit of preheat.

1Cr-¹/2Mo and 1¹/4Cr-¹/2Mo are deep hardening alloys and require preheat during welding. Both are ASME P4 Group 1 materials. Suggested preheat and DHT requirements are listed in Table 13.

Table 12—Welding Processes for $1^1/_4$/1Cr-$^1/_2$Mo Vessels

Welding Processes	SFA Specification	Weld Consumables	Shielding Gas	Comments
SMAW[a]	SFA 5.5	E7015 B2L, E7016 B2L, E7018 B2L, E8016 B2, E8018 B2.	None	Widely used by many fabricators. Experienced welders are available. High quality weld consumables are available.
SAW[a]	SFA-5.23	EB2R, B2R	None	1. Wire and flux from one manufacturer, tested, with properties guaranteed, by the manufacturer is preferred 2. Typical wire flux combination is F8P0-EB2-B2
GTAW[a]	SFA-5. 28	ER70S-B2L, ER80S-B2	100 % Argon	Non consumable tungsten electrode used. Commonly used for pipe welding.
GMAW[a]	SFA-5. 28	ER70S-B2L, ER80S-B2	Argon-CO_2 mixtures	
FCAW[a]	SFA-5.29	E80T5-B2L, E80T1-B2, E80T1-B2L, E81T1-B2, E80T5-B2.	Argon-CO_2 mixtures as recommended by manufacturer.	Use depends of availability of consumables that meet physical properties required.

[a] Use only weld consumables that produce a low hydrogen deposit. H8 or lower is desirable.

The most important role of preheat and DHT is to allow time for hydrogen in the weld to diffuse out. Three things are required for hydrogen cracking to occur: susceptible microstructure, tensile stress, and hydrogen. The Cr-Mo materials generally have a susceptible microstructure in the heat affected zone. A tensile stress occurs as a result of making the weld. The only part of the equation that can be controlled is the amount of hydrogen present. Welding consumable formulation and the care and handling of welding materials can control the hydrogen that may be present in the weld by preheat/DHT. Both are very important and contribute to successful welding of Cr-Mo steels. Care and handling of weld material was discussed earlier.

The recommended minimum preheat practice is summarized in Table 13. Preheat may be applied by using either gas or electric heaters as a heat source. Either is equally acceptable if applied properly. Electric preheat is best suited for a stationary work piece. In a typical shop setting where the vessel is placed with axis horizontal in turning rolls gas is the easiest to use, in which case heaters may be placed under the seam being welded and adjusted to reach the required temperature range. For safety reasons it is best to place gas preheat on the side opposite the side where the welder is working. It is important to reach the required preheat before welding starts. Once welding has started the preheat needs to be adjusted (turn the gas down) to account for the heat added by the welding arc. Preheat temperature must be maintained between the minimum preheat temperature required and the maximum weld interpass temperature. A good practice is to aim for is 25 °F to 50 °F (14 °C to 28 °C) above the minimum preheat temperature.

The welder should monitor the preheat temperature with temperature indicating crayons or other means. Crayons are relatively inexpensive and easy to use. Three crayon temperatures are recommended: one for the minimum preheat temperature; one for 50 °F (28 °C) above the minimum preheat temperature and one 50 °F (28 °C) below the minimum preheat temperature. Other temperature monitoring instruments are also available, but are more expensive and may not be as accessible to the welder as the crayons.

Preheat generally is not required when studs are welded to Cr-Mo material using automatically timed stud welding equipment. If studs are welded manually with SMAW or any other arc welding process, preheat of the area where the stud is attached is required.

Table 13—Preheat and Postheat Requirements

Material P No.	Preheat			DHT		
	Thickness at Weld in. (mm)	**Permanent Welds – Butt & Fillet** °F (°C)	**Tacking while fitting (temporary)** °F (°C)	**Thickness at Weld** in. (mm)	**Permanent Welds – Butt & Fillet** °F (°C)	**Tacking while fitting (temporary)** °F (°C)
ASME P-No. 4, Group 1	2 (50) and less	300 (149) Notes 2, 3, 5	300 (149) Notes 2, 3, 5	2 (50) and less	600 (316) for 1 hour. Notes 3, 4	300 (149) for 1 hour. Notes 3, 4
ASME P-No. 4, Group 1	Greater than 2 (50)	300 (149) Notes 1, 2, 5	300 (149) Notes 1, 2, 3, 5	Greater than 2 (50)	600 (316) For 2 hours Notes 4	300 (149) For 2 hours Note 4

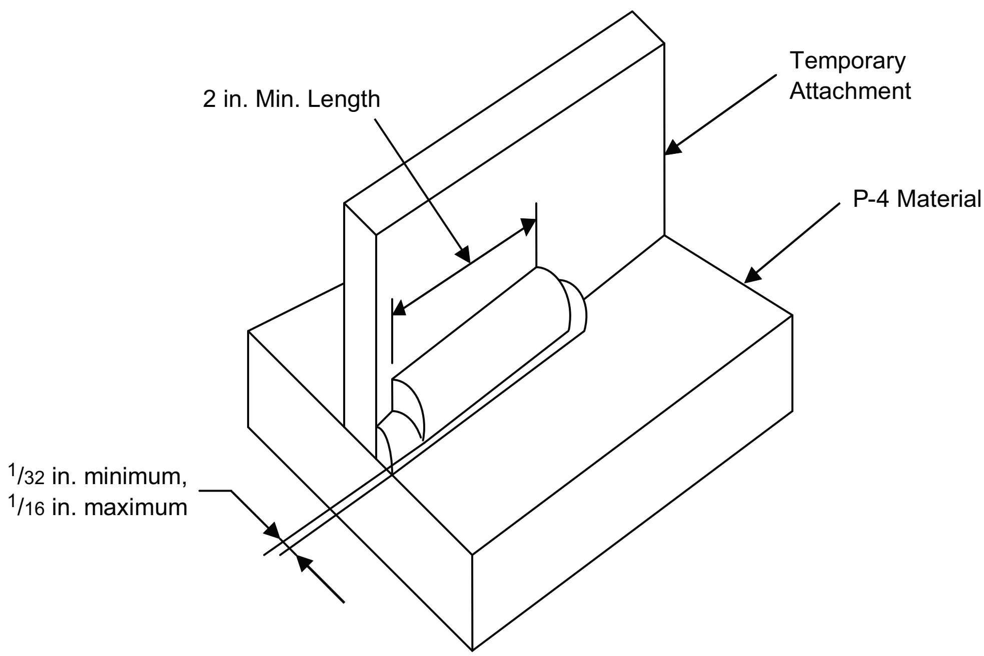
NOTE 1 Material greater than 2 in. (50 mm) in thickness the entire joint should be continuously preheated from start to finish of welding.

NOTE 2 For corrosion resistant weld metal overlay, preheat of 200 °F (93 °C) may be used.

NOTE 3 For temporary attachment welds (fit-up gadgets, etc.) a temper bead technique (see Figure 14) may be used. This technique should not be used for attaching lifting lugs. The plate (P-No. 4 material) surface should be examined with MT or PT methods after temporary attachment is removed. (See Figure 14.)

NOTE 4 DHT is not required for welds (including overlay) made with austenitic stainless steel or Nickel based electrodes.

NOTE 5 Preheat of 200 °F (93 °C) may be used for welds (including overlay) made with austenitic stainless steel or Nickel based electrodes.



NOTE 1 The temper bead is placed on the weld metal next to the last weld bead that ties into the base material.

NOTE 2 Maintain 400 °F (204 °C) minimum preheat within 3 in. (76 mm) of the attachment weld.

NOTE 3 Minimum fillet weld size is ¼ in. (6.4 mm) with a 2 in. (50 mm) minimum length.

Figure 14—Temporary Attachment Welds Using Temper Bead Technique

ASME Code Section VIII Division 1, Non mandatory Appendix R, and Division 2 (2007 edition), Table 6.7 include guidelines for preheat temperatures. Preheat of 250 °F (120 °C) is recommended for P-No. 4 material which has either a minimum tensile strength in excess of 60,000 psi (410 MPa) or a thickness at the joint over 0.5 in. (13 mm). Experience has shown minimum preheat temperatures of 300 °F (149 °C) to be very safe. The cost of preheating is mainly in obtaining and setting up the equipment. The incremental cost of 300 °F (149 °C) preheat over 250 °F (121 °C) is minimal, therefore, the 300 °F (149 °C) preheat should be used during welding, rolling, thermal cutting, and gouging operations. The minimum preheat temperature should be 200 °F (93 °C) for depositing of the first layer of weld overlay. Lower preheat temperatures have been used to weld thin tubular structures with low restraint and low hydrogen weld processes (GTAW and GMAW).

DHT is a very important step in welding 1Cr-$^1/_2$Mo and 1$^1/_4$Cr-$^1/_2$Mo steels. DHT provides time for hydrogen to diffuse out of the last portion of the seam welded. It is a good practice to cover the weld with insulation to allow slow cooling after the DHT is finished. This provides additional time for hydrogen to diffuse from the weld.

Continuous preheat should be used after the welding has started to prevent leaving embedded defects in the weld seam. See Figure 15 for a potential location of embedded defect if preheat is interrupted while welding seam. Defects in this location are not likely to be detected by normal NDE techniques. The defect is small and not oriented to be detected by a radiograph. Magnetic particle (MT) or liquid penetrant (PT) of the seam before the weld is completed most likely will show an indication that will be judged as non-relevant. This defect will show as a tear on a side bend test. Embedded defects may be avoided by applying recommended preheat and DHT practices and by proper handling of weld materials.

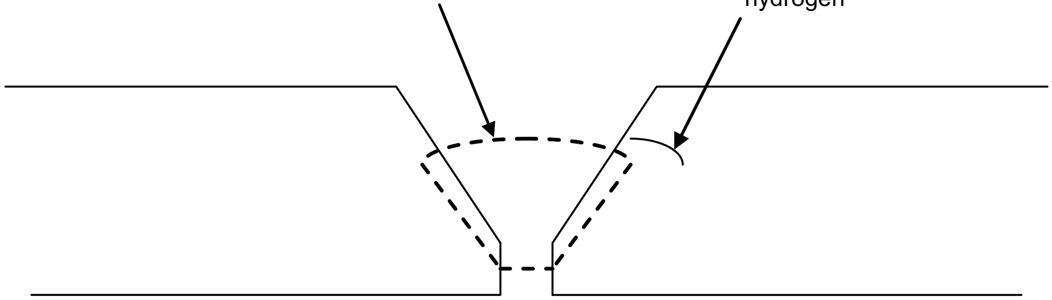


Figure 15—Possible Embedded Hydrogen Crack Caused by Interrupting Preheat on Partially Welded Seam without Postheat

Another form of hydrogen cracking is chevron cracking. It occurs in weld metal and is transverse to the direction of welding. It frequently occurs in one weld bead or one layer of weld metal. The cracks lay at approximately 45° to the plate surface. Chevron cracks occur in clusters and repeat about every $^3/_8$ in. (9.5 mm). Chevron cracking generally occurs in weld metal with a tensile strength of 90,000 psi (620 MPa) or greater. Cr-Mo weld metals generally have a tensile strength above 90,000 psi (620 MPa) in the as-welded condition. Chevron cracking is prevented by applying good preheat/DHT practice and proper handling and storage of weld materials. The orientation of chevron cracks makes them difficult to detect with nondestructive examination (NDE) techniques required by the Section VIII Division 1 and 2. The best NDE method to detect the presence of chevron cracks is with shear wave UT at 45° scanned along the direction of welding. Many vessels (carbon steel and chrome-moly steels) are shipped with chevron cracks present because the NDE techniques used did not detect their presence. Additional NDE to detect chevron cracking is recommended for 1$^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo vessels.

11.3 ISR vs. DHT for 1$^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo Materials

When welding is complete on a weld seam hydrogen is still in the weld. To protect the weld seam from hydrogen cracking preheat must be continued or apply a procedure to remove the hydrogen applied. It is impractical to maintain preheat on completed assemblies. This is very important on a hardenable alloy such as the 1¼Cr-½Mo or 1Cr-½Mo. Two options are available to the fabricator. They are Intermediate Stress Relief (ISR) and Dehydrogenization Treatment (DHT). Both are equally acceptable when properly executed.

11.3.1 Intermediate Stress Relief (ISR)

Intermediate stress relief can be used when a fabricator has ample furnace capacity that is easily accessible. ISR is conducted at a temperature lower than the planned final PWHT. Typically the final PWHT for Cr-Mo steel is conducted at 1250 °F (677 °C) to 1300 °F (704 °C). The amount of time available at these temperatures is limited, as it will reduce the tensile strength of material. ISR is typically conducted at 1100 °F (593 °C) for 15 min/in. (15 min/25 mm) of thickness, but not less than 2 hr. This is a very effective hydrogen removal procedure. Time applied to the material is above 900 °F (482 °C) must be accounted for as required by the ASME Code for heat treatment of test coupons. The 1100 °F (593 °C) heat treatment makes only a small contribution to the total Larson-Miller Parameter. Preheat should be maintained until the piece is loaded into the furnace and ready to start the ISR.

11.3.2 Dehydrogenization Treatment (DHT).

Fabricators without furnace capacity can use dehydrogenization Treatment. This procedure involves heating the completed weld seam to an elevated temperature (typically 600 °F, or 316 °C) and holding the temperature for a period of time, as stated in API RP 934-C. [18] After the heating is complete the seam is covered with insulation to allow slow cooling. Since heating is below 900 °F (482 °C), it does not affect the Larson Miller parameter and need not be recorded per the ASME Code.

Either of the ISR or the DHT procedure is acceptable to allow a completed weld seam to cool to ambient temperature when properly executed. It is not practical to maintain preheat on completed assemblies after welding is complete. One of the procedures above should be applied to protect welds on subassemblies.

12 Austenitic Stainless Steel Cladding and Weld Overlay

12.1 Weld Overlay

Refinery vessels frequently need austenitic stainless steel corrosion resistant linings for protection. The two basic methods of providing the lining are the use of clad plate and weld overlay. There are two methods of cladding, roll bonded and explosion bonded. The manufacturing process for these two products is very different, but the product delivered to the fabricator is handled the same. The clad is striped back along vessel weld seams to avoid contamination of the vessel welds. After vessel welding is complete, a clad restoration weld is made over the vessel weld seams. This restoration weld is made with one of the wire processes (SMAW, SAW, GTAW, GMAW, FCAW) using an alloy that provides corrosion protection equal to the clad. Clad is usually used on thinner vessels [2 in. (50 mm) and under]. Past evaluations of cost between clad and weld overlay have shown clad to be cost competitive up to about 3 in. (76 mm) thickness. At this point cost is a break even between clad and weld overlay. Often the deciding factor between clad and weld overlay is schedule.

Weld overlay is used to provide a corrosion resistant lining using weld metal. Weld overlay is generally used on vessels 2 in. (50 mm) thick and greater in thickness. Thinner vessels are more likely to suffer distortion from the welding heat input than thicker vessels. Weld processes used for overlay include all wire processes (SMAW, SAW, GTAW, GMAW, FCAW) plus strip procedures. Strip procedures include SAW and ESW (Electro Slag Welding) and are suited for covering large areas with corrosion resistant material. The goal is to produce a weld deposit matching the chemistry of the selected alloy with ferrite number (FN) between 3 and 10. The welding engineer is faced with two concerns when selecting the weld process to produce this deposit. These are achieving the correct chemistry in the weld deposit and using cost effective procedures.

The dilution in the weld deposit when welding Cr-Mo steel can cause problems. Dilution from the Cr-Mo steel adds chromium (increases ferrite) and carbon (increases austenite) to the weld deposit. Dilution is process dependent and weld operator dependent and further complicated by oxidation of some elements while crossing the arc (chromium and carbon fall into this category). The wire processes are more weld operator dependent than strip processes. This is because the weld operator controls the weld bead spacing and heat input on the wire processes. Because of the wide shallow (thin) weld bead deposited with the strip processes they are more robust and less weld operator dependent. For both the wire processes and strip processes controls must be in place to monitor the result. Two methods of ferrite measurement are available, chemistry checks of the deposit and ferrite measurement instruments. Both are recommended. Ferrite measurement for real time checks in the work place and planned chemistry checks of samples taken from the work. Ferrite checks can be made on a planned frequency as the work proceeds using a Severn Gauge or Ferrite Scope. Regular ferrite checks are a good quality control tool. Chemistry checks should be on a planned schedule and performed using a process accurate enough to measure the carbon content. When taking real time readings, the actual temperature of the cladding must be taken into consideration. A room temperature reading of 5 FN or 10 FN becomes 6 FN and almost 15 FN at 400 °F (204 °C).

There is always a discussion about whether overlay should be one or two layer It is possible to provide a single layer deposit which will meet the chemistry and ferrite requirements when low carbon is not required or specially tailored wires/strips/fluxes are used. A single layer type 304/308 weld deposit can be achieved in one layer. If good dilution control is used with a type 309 wire the chemistry will be acceptable. Type 309 wire has a nominal composition of 25 % Cr and 12% Ni. This allows the chemistry to meet the deposit chemistry for type 304/308 which is 18 % Cr and 8 % Ni after dilution. The same is true when strip cladding is used, especially where nickel base deposits are specified.

Carbon is the most difficult element to control in single layer overlays. The carbon content will depend on the amount of carbon in the base metal and the amount of dilution resulting from the welding process. Typical carbon content for a single layer overlay deposit on a Cr-Mo backing material will be in the range of 0.05 % to 0.08 %.

Recommended Procedures:

1) Monitor the weld deposit with either the Severn Gauge or the Ferrite Scope while the welding is in progress. In process monitoring of the ferrite content during welding will prevent the welding process from getting out of control.

2) Use alloyed weld wire for weld overlay. Do not allow alloying through the flux. Some alloying addition through the flux to compensate for chemistry loss across arc is acceptable.

3) Maintain a ferrite content in the overlay between 3 FN and 10 FN. Require ferrite control for stainless steel weld overlay during overlay deposition by use of either Ferrite Scope or a Severn Gauge. Other controls will be needed for nickel base alloys.

4) Examine weld overlay surfaces with the liquid penetrant NDE process. Due to the large surfaces to be examined water washable, biodegradable type penetrant is desirable. High-pressure water washes should not be used to remove water washable penetrant.

12.2 Weld Overlay Procedure Qualifications

Weld overlay procedure qualifications shall be in accordance with 7.5.3 of API 934-C.

12.3 Preheat and Heat Treatments During Weld Overlay

12.3.1 Base metal should be preheated in accordance with Table 13 for the first layer of weld overlay.

12.3.2 Preheating is required for the second layer if the deposited thickness for the first layer is equal to or thinner than 0.12 in. (3 mm) or if a new heat affected zone occurs in the base metal

12.4 Production Testing of Weld Overlay

Production testing of weld overlay shall be in accordance with 7.3.5 of API 934.

12.5 Weld Overlay Disbonding

12.5.1 Causes and Concerns

Weld overlay disbonding has been a problem in vessels operating in high temperature, high-pressure hydrogen service. Vessels that have experienced disbonding have been subjected to a rapid shut down. The rapid shut down does not allow hydrogen diffusion before reaching ambient temperature.

Weld overlay surfaces made with wide beads are more susceptible to clad disbonding than those made with narrow beads. For example a surface made with a SAW wire process will be less likely to suffer gross disbonding than one created with SAW strip. The first layer of weld overlay on a backing material has a grain boundary parallel to the backing material HAZ. During PWHT there is a carbon migration from the backing material into the overlay deposit. This carbon migration weakens the grain boundary and makes it more susceptible to disbonding. A 304/308/309 type deposit is more susceptible than a 347/309Cb deposit. Tests have shown the columbium (niobium) has a higher affinity for carbon than Cr and will tie the carbon up before it can deplete the chromium content.

12.5.2 Weld Disbonding Tests

Figure 16 includes weld overlay disbonding tests on $1^1/_4$Cr-$^1/_2$Mo, $2^1/_4$Cr-1Mo steels, and 3Cr-1Mo base metals under the same conditions. [13] There were fewer tests on $1^1/_4$Cr-$^1/_2$Mo than on $2^1/_4$Cr-1Mo and 3Cr-1Mo steels. This data shows that weld overlay on the $1^1/_4$Cr-$^1/_2$Mo steel was susceptible to disbonding at about 300 ppm hydrogen at the base metal/weld overlay interface.

12.5.3 When Are Weld Overlay Disbonding Tests Necessary?

Clad disbonding tests should be performed on any $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo vessel that is in high-pressure hydrogen service that may be subjected to rapid cool down conditions from service.

12.5.4 Test Procedures

Weld overlay disbonding test should be conducted as outlined in API 934-A. [20] The disbonding test shall be carried out for information only. As a minimum, the test shall represent the actual operating conditions (hydrogen pressure, temperature and cooling rates) to which the equipment will be subjected to during service. Test results should meet the area ranking A and distribution ranking 1 of ASTM G146, paragraph 12.16.

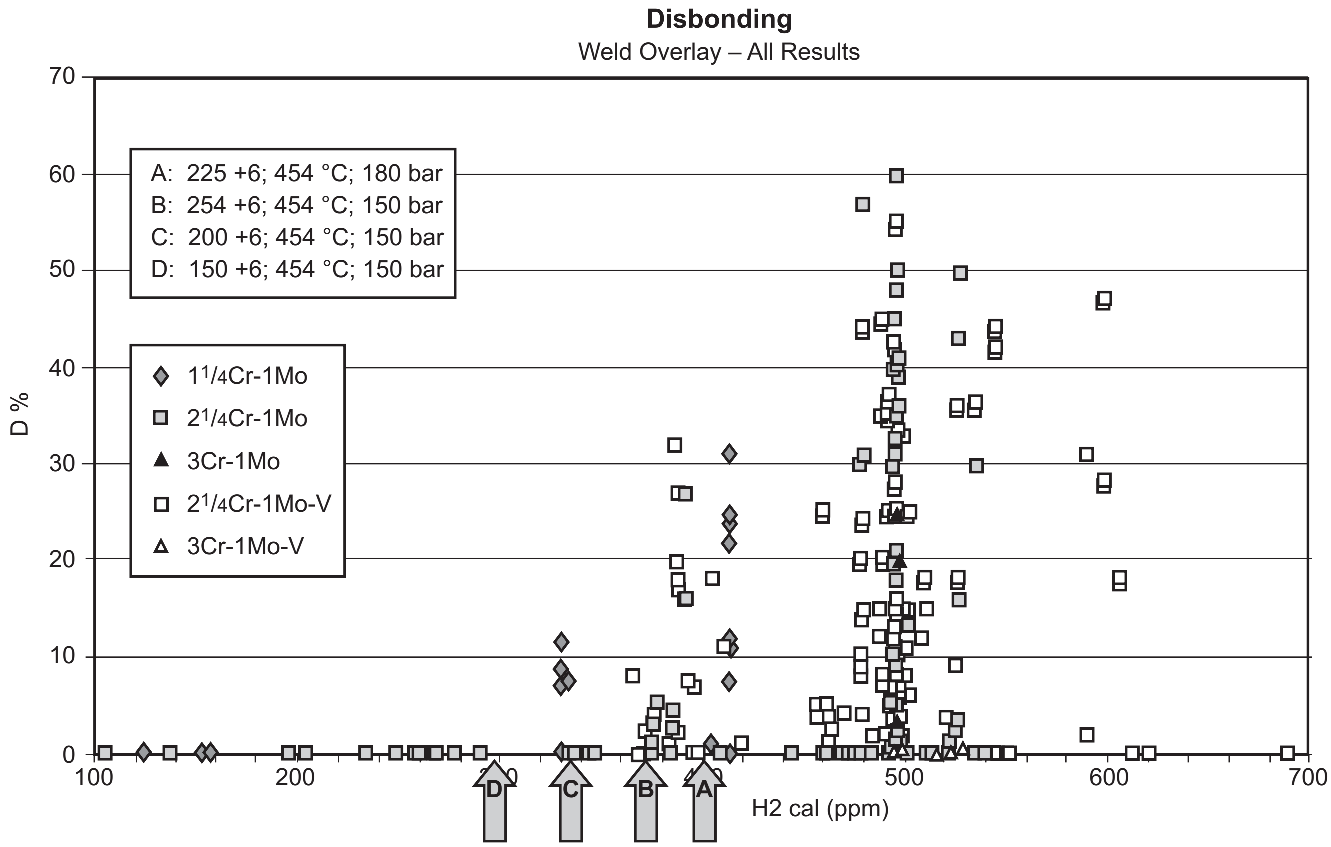


Figure 16—Weld Overlay Disbonding Tests on Cr-Mo Steels

Annex A
(informative)

API 934-D Questionnaire on 1Cr-$^{1}/_{2}$Mo and 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo Issues

#	Topic	Background	Questions
1	**Melting practices and chemical composition**	*It is understood the mills need to use clean steel technology (vacuum degassing, low P and S contents) to achieve the best notch toughness (e.g. 40/35 ft-lb at 0 °F, or lower)*	*(1) What would be the best mill practices and chemical composition ranges to achieve the optimum notch toughness?* *(2) Should specific steel making practices such as: basic electric furnace, fine grain practice, or aluminum killed be included to specification requirements?*

Summary of Comments on Topic 1, Question (1):

1. There is a general consensus that the material should be vacuum degassed and should have low phosphorus content (P ≤ 0.015, or lower) and low sulfur content (S ≤ 0.005 %, or lower). One respondent recommends P ≤ 0.007 % and S ≤ 0.003 % for best practices to achieve optimum notch toughness.

2. One respondent also recommends shape control and Q & T (vs. N & T).

3. Another respondent requires the following for design metal temperatures over 850 °F (455 °C): P ≤ 0.012 % (preferably P ≤ 0.07%) and Sn ≤ 0.015.

Summary of Comments on Topic 1, Question (2):

1. Specify vacuum degassing.

2. Fine grain practice is needed for notch toughness and should be specified. FGP implies killed steel, whether Al or Si killed; however, several respondents stated that Al killed steel should also be specified.

3. Q & T is needed to meet notch toughness requirements and should be specified.

#	Topic	Background	Questions
2	**Other mill practices**	*Most steel is now produced by continuous casting.*	*(1) Does this limit the maximum plate thickness?* *(2) What is the minimum reduction ratio for plates from continuous cast slabs? What properties does this ratio affect?*

Summary of Comments on Topic 2, Questions (1) and (2):

Not all steel mills produce plates from continuous cast slabs. Several plate producers recommend a minimum reduction ratio of 3:1 as stated in ASTM A 20. However, ASTM A 20 does permit a reduction ratio of 2:1 for certain carbon steel plates 3 in. (75 mm) thick and thicker produced from continuous cast slabs, providing such plates meet the additional requirements in paragraph 5.3 of A 20. This permits thicker plates from continuous cast slabs than a 3:1 maximum reduction ratio. Some respondents felt that a reduction ratio down to 2:1 would be possible also for the Cr-Mo steels with proper procedures but not less than 2:1, which may result in poor internal quality and poor notch toughness at the $^{1}/_{2}t$ location. Another respondent stated that a reduction ratio of 2.5 seems to be acceptable.

<table>
<tr><th>#</th><th>Topic</th><th>Background</th><th>Questions</th></tr>
<tr><td rowspan="2">3</td><td>Silicon and phosphorous content</td><td>Recently some steel producers have been considering low silicon (0.05 % min. Si instead of 0.50 % minimum Si) for Gr 11. Similar considerations have been made for P.</td><td>(1) What are the advantages of low Si and low P in 1¹/4Cr-¹/2Mo and 1Cr-¹/2Mo steels?

(2) Are there data available that show current Si and P level may cause problems in achieving optimum toughness.</td></tr>
<tr><td colspan="3"><u>Summary of Comments on Topic 3, Question (1):</u>

1. There was a general agreement that low phosphorus content improves notch toughness.

2. There were different opinions about Silicon content. Some felt that low Si content also improves toughness; but it is not an important consideration for temper embrittlement of 1Cr-$^1/_2$Mo and 1$^1/_4$Cr -$^1/_2$Mo steel since temper embrittlement generally is not of concern in these steels. Some also questioned the basis for the minimum Si content of 0.50 % in the 1$^1/_4$Cr-$^1/_2$Mo steel (e.g. SA-387, Gr. 11).

<u>Summary of Comments on Topic 3, Question (1):</u>

Most respondents stated that there is no specific data that shows that the current levels of Si and P cause problems in achieving optimum toughness. However, low P and low Si contents generally improve toughness. One respondent stated that the current version of Grade 11, being FGP, is designed for low temperature toughness, which may not be consistent with the original design of Grade 11, where Si was added to improve high temperature properties.</td></tr>
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#	Topic	Background	Questions
4	**Forming limits**	*Cracking problems have been reported with forming and rolling of most Cr-Mo steels. The extent of this problem with $1\frac{1}{4}$Cr-$\frac{1}{2}$Mo and 1Cr-$\frac{1}{2}$Mo steels has not been clearly established in the literature.*	*(1) What type of cracking problems can be experienced during forming or rolling of $1\frac{1}{4}$Cr-$\frac{1}{2}$Mo and 1Cr-$\frac{1}{2}$Mo steels? Can you provide some example of where this problem has occurred?* *(2) Recommended practices to avoid cracking problems or to impair properties (notch toughness).* *(3) Limitations on cold forming strains [below 900 °F (480 °C)] without subsequent heat treatment?*

Summary of Comments on Topic 4, Question (1):

Several respondents stated that they do not have experience with cracking problems.

One respondent stated that there are examples mostly dealing with improper edge treatments, trying to form hard gas cut edges with lots of notches, and trying to weld attachments and leaving hard HAZ on tension surfaces.

Another respondent stated that cracking has occurred in several occasions during forming of plates for cylindrical shells. In one case this was attributed to flame cut edges that were not ground before rolling of the plate. This respondent also has concern about induction bent $1\frac{1}{4}$Cr-$\frac{1}{2}$Mo and 1Cr-$\frac{1}{2}$Mo pipe.

Summary of Comments on Topic 4, Question (2):

The respondents provided several recommendations:

1. Use low P and Q&T plates for improvement of notch toughness, and eliminate irregular sharp corner edges before forming. These method can avoid cracking and improper properties even without preheating for forming.

2. Grind edges and corners. Don't weld on surfaces without SR; stress relieve hardened gas cut edges. Form on the upper shelf and don't trust someone who forms without knowing what they are forming and without established procedures.

3. Grind and inspect flame cut edges, or machine and inspect the bevels. Preheat during cold forming. Use hot or warm forming depending on thickness. Use materials with improved toughness (including of low P, Q&T).

Summary of Comments on Topic 4, Question (3):

Two respondents provided the following recommendations:

1. Limited the cold forming strains below 3 % without stress relieving.

2. Limit the cold forming strain to 5 %, maximum without subsequent heat treatment.

#	Topic	Background	Questions
5	**Maximum thickness and hardenability**	*It is generally understood that the maximum thickness of 1$^1/_4$Cr-$^1/_2$Mo plates and 1Cr-$^1/_2$Mo plates is limited to about 4 inches because of lesser hardenability and poor toughness of these materials than the 2$^1/_4$Cr-1Mo plates. However thicker 1$^1/_4$Cr-$^1/_2$Mo plates have been used in pressure vessels.*	*(1) What is the maximum practical thickness of 1$^1/_4$Cr-$^1/_2$Mo plates and 1Cr-$^1/_2$Mo plates to Class 1 properties and to Class 2 properties?* *(2) What limits the maximum thickness?* *(3) What causes non-uniform structure in thick plates and forgings, e.g. in thicknesses exceeding about 4 in.? Is there a way to improve it?* *(4) Have alloying additions such as Ni been used to improve notch toughness? If so, what additions are considered necessary and what improvements can be expected in toughness? Also, what negatives can result from such alloying additions?*

Summary of Comments on Topic 5, Question (1):

The respondents provided the following responses to Question (1):

1. In case of Q&T and 2-PWHT cycles, the practical thickness is 8 in. for SA-387-11 and 6 in. for 387-12 with meeting the requirement of 40/35 ft-lb at –18 °C (at $^1/_4$ T sample location).

2. About 10 in. (250 mm) to be able to meet tensile properties for Class 2 properties.

3. Based on this producer's experience, the following materials will meet 40 ft-lb at 0 °F:

1$^1/_4$Cr-$^1/_2$Mo, Class 1: 80 mm by N & T.

1$^1/_4$Cr-$^1/_2$Mo, Class 2: 100 mm by Q & T.

4. About 9 in., if there are no other considerations such as impacts at –20 °F, etc.

5. About 4 in. to avoid ferrite islands at the core. Ni addition and Si reduction could have positive effect.

6. Limit the use of 1$^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo steel with Class 1 properties to maximum thickness to 3.5 in. (89 mm) when the design temperature is higher than 850 °F (454 °C). Limit the use of 1$^1/_4$Cr-Mo and 1Cr-$^1/_2$Mo steel with Class 2 properties to maximum thickness to 3.5 in. (89 mm) for any use temperature.

Summary of Comments on Topic 5, Question (2):

The respondents provided the following comments:

1. The thickness is limited by the following: 1) lower toughness due to lower hardenability than 2$^1/_4$Cr-1Mo during quenching, and, 2) the rolling reduction ratio of 3.

2. Notch toughness requirements. The CVN properties depend on thickness and the total LMP (including tempering and PWHT time and temperature). Thicker plates have a large scatter in impact test values and poor notch toughness.

3. Chemistry, PWHT, and the limitations on the tempering temperature.

4. Toughness requirement caused by maintaining hardenability and limit of rolling reduction ratio.

Summary of Comments on Topic 5, Question (3):

1. Mainly due to lack of hardenability. Quenching and tempering and the use of Cr and Mo contents near the upper limit will be an effective method.

2. The non-uniform structure is linked to low hardenability of the grade. A mixed ferrite/bainite microstructure can be found in thicknesses above 3 in. to 4 in. after quenching.

3. There is no way to prevent the precipitation of ferrite and non-uniform structure by water cooling for wall thickness over 100 mm.

4. Cooling rate, primarily, and inability to deform centerline thickness sufficiently to achieve grain refinement in the absence of sufficient hardenability. The slower cooling rate in thicker plates leads to ferrite/pearlite microstructure.

Summary of Comments on Topic 5, Question (4):

1. In general, Ni improves notch toughness and to some extent, hardenability. The negative factors are higher cost and decreasing the creep strength. (Nickel content is limited to 0.40 % by SA-20, Table 1.)

2. Ni addition is not recommended due to reduced resistance to temper embrittlement.

3. Cr, Mo, Cu, and Ni elements improve the hardenability and toughness because hardenability improvements affect the toughness improvement.

But, high Cu cause the temper embrittlement or SR cracking.

4. Nickel improves toughness due to increases in hardenability but it also creates higher strength that may have to be dealt with higher tempering temperatures. High residual nickel in Cr-Mo isn't necessarily a good thing. It, along with additions of more molybdenum or tungsten can create HAZ issues. This does not address the hazards of intentional vanadium additions to resist tempering response.

5. Ni improves deep hardenability and results in better microstructure.

#	Topic	Background	Questions
6	**Notch toughness requirement**	*The Users typically require 40 ft-lb (54 J) minimum average [with no single values less than 35 ft-lb (48 J)] at 0 °F, or lower (e.g. –20 °F), which may not be practical in thick plates and forgings.*	*(1) Do you have data or information that shows the effect of thickness on toughness of 1¼Cr-½Mo and 1Cr-½Mo plates and forgings?* *(2) What is the effect of PWHT temperatures and hold times (in terms of LMP) on toughness?* *(3) What is an acceptable minimum impact test temperature for the 40 ft-lb energy level?* *(4) Should also the Cr-Mo steels with Class I properties meet 40/35 ft-lb CVN, or are lower energy values acceptable for the lower strength steels (with Class 1 properties)?*

Summary of Comments on Topic 6, Question (1):

1. In general, the toughness will decrease in thicker plates due to lowering of cooling rate.
2. One respondent stated that, basically, 40 ft-lb average and 35 ft-lb minimum of impact value is impractical regardless product thickness.
3. Another respondent stated that the required values (40 ft-lb average and 35 ft-lb minimum) could be achieved at 0 ° F for thicknesses < 4 in. with the following heat treatment: PWHT for 6 hr to 8 hr at 1238 ° F (670 °C) ± 18 °F (10 °C).

Summary of Comments on Topic 6, Question (2):

1. All respondents agreed that high PWHT temperatures and long hold times (in terms of LMP) generally reduce notch toughness.
2. Impact energy will be decreased by stress relief embrittlement because slow cooling from austenite temperature cause the precipitation of carbide.
3. High PWHT temperature will also affect creep rupture strength.
4. Lukens/IGS Plate/Mittal have presented several papers on the problems related to too much PWHT on toughness

Summary of Comments on Topic 6, Question (3):

The responses varied significantly. The following is a summary of the responses:

1. Our acceptable temperature is –20 °F for Q&T Plates and forgings, and 0 °F for weld metals.
2. The minimum temperature is –18 °C (0 °F) or –29 °C (–20 °F), depending on thickness and LMP.
3. The 40 ft-lb energy value is acceptable at 0 °F for 1¼Cr-½Mo plates under the following conditions:
   Class 1: $t < 80$ mm.
   Class 2: $t < 100$ mm.
4. The general test temperature will be 50 °F (10 °C) for 40 ft-lb energy level.
5. It is not unusual to have results like 4-4-80 ft-lb at a given temperature in the transition range. The current API trend to 40/20 ft-lb is reasonable approach.
6. The material and welded joints should meet the ASME Code required impact test values at temperatures no higher than 0 °F (–18 °C). [This generally results in the material also meeting 40 ft-lb average at 32 °F (0 °C)].

Summary of Comments on Topic 6, Question (4):

The consensus of the comments was that in general, lower energy values acceptable for the lower strength steels because of lower design stresses for the lower strength steels; however, the lower energy values may require some fracture mechanics evaluation.

#	Topic	Background	Questions
7	**Minimum tempering conditions**	*Insufficient tempering of Cr-Mo steels results in high hardnesses and poor notch toughness.*	*What minimum tempering temperature and hold time is required for adequate notch toughness (e.g. 40/35 ft-lb transverse at 0 °F) for the PWHT temperatures and hours for the plate thicknesses listed below for vessel fabrication and repairs?*

Summary of Comments on Topic 7:

The respondents provided several comments:

The general consensus was that 1150 °F (620 °C), as stated in SA-387, seems to be sufficient. High tempering temperature will reduce the mechanical properties.

1. The holding time of tempering is subject to agreement by mill suppliers since they also have to guarantee the mechanical properties after PWHT.

The recommended tempering temperature has to be stated by steel maker as a compromise between toughness and tensile properties.

2. One respondent stated: 1 h/2 in. at 1200 °F (650 °C).

3. Another respondent stated: 1256 °F to 1310 °F (680 °C to 710 °C).

4. Adequate toughness is achieved with a minimum amount of tempering (e.g., LMP 34.5 or so). Beyond that, it goes down. Above about 36 LMP the toughness reduces rapidly.

5. One respondent stated that the PWHT temperature should be below the tempering temperature of material manufacturing stage.

6. Another respondent stated that the tempering temperature should be at least 50 °F (28 °C) above the PWHT temperature. The test coupons should be stress relieved at or near the upper PWHT temperature, e.g., 1295 °F ± 5 °F, or 1295 °F ± 10 °F for vessels stress relieved at 1275 °F nominal ± 25 °F.

The general consensus was that 1150 °F (620 °C), as stated in SA-387, is sufficient. High tempering temperature will reduce the mechanical properties.

#	Topic	Background	Questions
8	**N&T vs. Q&T**	*It is generally understood that plates produced to Class 1 properties may need to be Q&T when the thickness exceeds about 3 in., and plates with Class 2 properties may need to be Q&T in all thicknesses (or at least exceeding 1 in. to 2 in.). It is also generally understood that there is no cost difference between the N&T and the Q&T plates.*	*(1) Do you agree with the guidelines shown in the adjacent column?* *If not, please state your reasons.* *(2) How does the LMP (the required hours at the specified PWHT temperature) affect the heat treatment?*
	<u>Summary of Comments on Topic 8, Question (1):</u> 1. The heat treatment also depends on CVN toughness requirements. 2. One respondent stated that from that mill the N&T generally is same price as Q&T but that the heat treatment can affect forming capabilities. Also, Class 1 properties are easily achievable through much thicker sections than Class 2 properties but not necessarily with 40 ft lbs at –20 °F. Q&T of Class 1 in thinner sections actually requires a substantial modification (within the allowable range) to normal melting aims. If not, substantially higher tempering is required to maintain 85 ksi maximum tensile strength. This reduces toughness. The consensus was that there is a cost difference between N&T and Q&T because of different manufacturing requirements. Q&T incurs additional cost due to a larger number of test specimens and inspection and the extra process to ensure the required flatness. <u>Summary of Comments on Topic 8, Question (2):</u> 1. If the LMP will be increased as the result of increased cycles of PWHT, the tempering temperature needs to be sufficiently lower to maintain the total LMP. 2. High LMP will affect impact energy and mechanical properties. LMP needs to be controlled within about 20×10^3 in terms of °C (about 36×10^3 in terms of °F). 3. It is difficult to give general rule since it is a combination of total LMP (tempering plus PWHT), the thickness, and the CVN requirements that need to be considered. In general, Q&T should be considered whenever the CVN requirements need to be met at a low temperature (lower than 0 °C), whatever the class. 4. LMP affects final properties and it doesn't matter how you get there, i.e. less time at higher temperatures or higher temperatures for shorter times. The data shows that properties decrease with increase in LMP regardless of the path. Typically a 40 °F shift in T40 (40 ft-lb transition temperature) occurs for every 1.0 point increase in LMP (e.g. 36.4 to 37.4).		

<table>
<tr><th>#</th><th>Topic</th><th>Background</th><th>Questions</th></tr>
<tr><td>9</td><td>Required PWHT temperatures and PWHT hours for vessel fabrication and repairs (total required LMP)</td><td>The common practice from Users has been to require 3 PWHT cycles on test coupons (two for vessel fabrication and any repairs during fabrication) and one for any repairs by the User. The ASME Code requires 1 hr/in. up to 5 in. of thickness and 15 min. for any additional inch above 5 in. This results in the following LMP from PWHT:
T = 2 in.: 6 hr at 1275 °F, or LMP = 36.05×10^3
T = 4 in.: 12 hr at 1275 °F, or LMP = 36.57×10^3
T = 5 in.: 15 hr at 1275 °F, or LMP = 36.74×10^3
T = 6 in.: 15.75 hr at 1275 °F, or LMP = 36.78×10^3
The total PWHT time at temperature has a significant effect on the available tensile properties and notch toughness. High PWHT temperatures and long hold times result in loss of strength and notch toughness. Q&T generally permits higher total LMP.</td><td>What maximum Larson-Miller parameters are the steel producers willing to guarantee for the various plate thicknesses and still be able to meet the specified tensile properties (UTS and YS) and 40/35 ft-lb, transverse impact test values at 0 °F (or lower) with test specimens at ½ T location? Can they provide this information for Gr. 11 Class 1 and Gr. 11, Class 2 properties and for Gr. 12 properties?</td></tr>
<tr><td></td><td colspan="3"><u>Summary of Comments on Topic 9:</u>
This question generated a variety of comments:
1. The LMP values listed in the background information in the questionnaire do not take into account the tempering treatment. If a maximum LMP parameter is considered, it should take into account the initial tempering. The following are examples of some typical values:
3 in. $< T <$ 4 in.: 20,400 (in terms of °C), where LMP = (°C + 273)(20 + Log t)
3 in. $< T <$ 4 in.: 20,100
3 in. $< T <$ 4 in.: 19,850
2. Two respondents stated that in their opinion it is possible to guarantee 6 in. (max) for SA-387 Gr.11 and 4-in. (max) for SA-387 Gr. 12 in the QT condition with 3 PWHT cycles
3. This respondent also suggested not to use 690 °C (1275 °F) PWHT temperature, since no data was available to him in the 1275 °F PWHT condition.
4. Some of the requested information is proprietary or viewed as a competitive advantage by the steel manufacturer.
5. Another respondent stated that they do not specify the minimum or maximum PWHT cycles, but they do require that the test coupon heat treatment shall include all PWHT cycles required for vessel fabrication, including intermediate PWHT + one repair cycle. This could be a total of 3 or 4 PWHT cycles.</td></tr>
</table>

#	Topic	Background	Questions
10	**Final PWHT as the final temper**	*It is sometimes necessary to use the final PWHT as the final temper (particularly for thicker plates and those subjected to high PWHT temperatures and/or long hold times at the PWHT temperature). This can be done but requires the test specimens to be stress relieved at or near the maximum PWHT temperature.*	*(1) What are the considerations and concerns with PWHT exceeding the mill's tempering temperature and using the PWHT as the final temper? (e.g. temperature controls, uniformity of properties, cooling rates, etc.)* *(2) What should be the temperature for the test coupons if the vessel is stress relieved at 1275 °F ± 25 °F (1300 °F, 1275 °F)?*

Summary of Comments on Topic 10, Question (1):

1. The majority of the respondents felt that the final PWHT may exceed the mill's tempering temperature and may be used as the final temper; however, this requires a very stringent quality procedure and system that can guarantee close control during fabrication and PWHT (e.g., ± 25 °F). If this becomes necessary, it would be essential for the test coupons to properly simulate all heat treatments during the vessel fabrication and any repairs. Consideration should also be given to a requirement for test coupons to be heat treated together with the vessel or vessel parts during all heat treatments.

2. Several respondents felt that for 1¼Cr-½Mo and 1Cr-½Mo steels, the PWHT temperature should not exceed the mill's tempering temperature in order to control the LMP.

Summary of Comments on Topic 10, Question (2):

1. Most respondents stated that the test coupons should be stress relieved at 1275 °F (690 °) (with a tight temperature control) when the vessel is stress relieved at 1275 °F ± 25 °F (690 °C ± 14 °C).

2. One respondent stated that the test coupons should be stress relieved at or near the maximum PWHT temperature.

3. Another respondent stated that it should be 1300 °F (704 °C), since that is the more detrimental condition. This is the maximum value that should be considered for calculating LMP.

#	Topic	Background	Questions
11	**½T vs. ¼T test specimen location**	*Most Users require Cr-Mo plates tested at the ½T location with the tension tests and impact tests to be taken in the transverse direction.*	*What are the differences in the guaranteed properties for 1¼Cr-½Mo plates and 1Cr-½Mo plates tested at the ½ T location and the ¼ T location (notch toughness, tensile strength)?*

Summary of Comments on Topic 11:

1. The hardenability and structure are not uniform through the thickness. Because of insufficient hardenability due to chemical composition of 1¼Cr-½Mo and 1Cr-½Mo, the mechanical properties at ½ T location are somewhat lower than ¼ T location. That is why the test coupons should be taken from the ½ T location. As to actual difference, it depends on the thickness and the heat treatment conditions during vessel fabrication. Q&T generally results in higher impact test values than N&T because of the faster cooling rate.

2. For thicknesses below 6 in. (150 mm), there is no big difference between ½ T and ¼ T.

3. There is no need to take test specimens from both the ¼ T and ½ T locations. In some cases the ¼ T and ½ T test specimens may actually overlap. ASTM has added a supplementary requirement S53 to specification A387 which has been adopted by the ASME. This removes redundant testing.

<table>
<tr><th>#</th><th>Topic</th><th>Background</th><th>Questions</th></tr>
<tr><td rowspan="2">12</td><td>Forgings</td><td>Forgings have some additional considerations. The quality and mechanical properties (notch toughness) often depend on melting practices used and on the amount of working of the billet during the forging process. The use of separately forged test blocks for mechanical testing often is not representative of the actual properties of the forging resulting in higher impact test values than in the actual forging. Knowledgeable vessel fabricators often require at least 3:1 reduction from the billet in all directions during forging, and/or test specimens to be taken from the $^1/_4$ T × T location in the actual forging or from the forging prolongations (or the use of buffering), instead of separately forged test blocks.</td><td>(1)What is the maximum practical thickness limit for SA-336 Gr. F11, Class 2 and Class 3, and Gr. F12 (as well as SA-182, Gr. F11, Class 2 and Class 3, and Gr. F12, Class Cl. 2) forgings?

(2) What are recommended good manufacturing practices for improving the quality and notch toughness of Gr. 11 and Gr. 12 forgings (chemical composition, amount of working during forging, etc.)?

(3) Are there any technical reasons why the test specimens should be taken from the $^1/_2$ T instead of the $^1/_4$ T location in the forging?

(4) Should impact testing of these Cr-Mo forgings include other criteria, e.g. percent shear appearance, mils lateral expansion, etc.</td></tr>
<tr><td colspan="3"><u>Summary of Comments on Topic 12, Question (1):</u>
1. One respondent listed 8 in. (200 mm) maximum thickness for forged vessels to be able to achieve proper microstructure with pearlite, ferrite, and bainite.
2. Another respondent gave about 4 in. (100 mm) maximum thickness (to avoid ferrite islands at the core).

<u>Summary of Comments on Topic 12, Question (2):</u>
1. Proper chemical composition, forging ratio, and heat treatment should be considered.
2. Grain size should be smaller than 4 for forging and 5 for plates

<u>Summary of Comments on Topic 12, Question (3):</u>
See comments on Topic 11.

<u>Summary of Comments to Topic 12, Question (4):</u>
Useful for information. The percent shear appearance and mils lateral expansion should be measured in order to determine the minimum pressure temperature (MPT).</td></tr>
</table>

#	Topic	Background	Questions
13	**2 ¼ Cr – 1 Mo forgings**	*Some fabricators are advocating the use of 2¼Cr-1Mo forgings with 1¼Cr-½Mo vessels.*	*(1) Do you see any difficulties with using 2¼Cr-1Mo forgings with 1¼Cr-½Mo vessels in refinery service?* *(2) What additional procedures are necessary in vessel fabrication when using 2¼Cr-½Mo forgings with 1¼Cr-½Mo vessels.*

Summary of Comments on Topic 13, Question (1):

Several respondents expressed concerns with using of 2¼Cr-1Mo forgings with 1¼Cr-½Mo vessels for the following reasons:

1. It may lead to problems during vessel fabrication or vessel service.
2. Different allowable stresses in these materials.
3. Different PWHT temperatures for 2¼Cr-1Mo and 1¼Cr-½Mo steels.
4. Different creep rates in base metals and welded joints, which may cause different stress distribution at nozzles in vessels operating in creep range. This would need to be considered in the design.
5. The need to consider the different potential problems for each material and welded joints, e.g. temper embrittlement, creep embrittlement, etc.

Summary of Comments on Topic 13, Question (2):

1. Use 2¼Cr-1Mo steel if the thicker part, such as 1¼Cr-½Mo nozzle forging, does not meet the required mechanical properties.
2. If PWHT temperature of 2¼Cr-1Mo is higher than 1¼Cr-½Mo; then, the higher temperature should be applied for both materials.
3. The use of the two different materials may lead to problems during vessel fabrication or vessel service. If necessary to use 2¼Cr-1Mo vessel shell or forgings, it is better to use all 2¼Cr-1Mo construction in that part of the vessel.

#	Topic	Background	Questions
14	**Temper embrittlement**	*It is generally understood that there is less significant temper embrittlement in 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo materials than in 2$^{1}/_{4}$Cr-1Mo materials; however, some Users still impose requirements to minimize the risk of temper embrittlement, such as a maximum J-factor, X-bar, or step cooling. Step cooling is expensive and does not seem to be warranted for the 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels. The X-bar factor was developed for welds. The J-factor was developed for 2$^{1}/_{4}$Cr-1Mo base metal.*	*(1) Is it relevant to impose any special requirements to minimize the risk of temper embrittlement in 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo materials?* *(2) If so, what criteria have the best correlation with TE in these steels? (X-bar, J-factor, step cooling, or limitations on chemical composition, such as P, Cu, Ni, content, etc.)* *(3) What limitations should be specified to limit the TE in 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo base metals and welds?* *(4) What maximum X-bar requirements can be met in the 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo base metal and in weld metal?*

Summary of Comments on Topic 14, Question (1):

Temper embrittlement in 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels is lower than in 2$^{1}/_{4}$Cr-1Mo steels and generally not of concern; however, several respondents felt that some guidelines are necessary. These respondents suggested the following guidelines:

1. Reduce the P and Sn contents.
2. Control the X-bar value in the base metal and in welded joints. One respondent suggested X-bar < 15 and $J < 100$. Another respondent stated that J-factor is totally unwarranted in these steels.

Summary of Comments on Topic 14, Question (2):

1. The consensus of the responses was that step cooling is not necessary since the susceptibility of the 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels to temper embrittlement is negligible.
2. There is no need for step cooling tests for these materials.
3. Two respondents suggested to control the J-factor only for the base metal and X-bar (15 max) for the weld metal.

Summary of Comments on Topic 14, Question (3):

1. Several respondents suggested to control J-factor for base metal and X-bar for the weld metal.
2. One respondent stated that the Japanese Petroleum Institute recommends the following limitations:
   a. X-bar: less than 15.
   b. $P < 0.010$ %; $S < 0.008$ %.

Summary of Comments on Topic 14, Question (4):

1. Two respondents stated that it is possible to meet J-factor = 150 (max) for the base metal and X-bar = 15 max for the weld metal.
2. Two other respondents stated that with special considerations it may be possible to meet X-bar = 12 max.

#	Topic	Background	Questions
15	**Other forms of embrittlement**	*It has been reported in the literature that other forms of embrittlement are possible in 1 1/4Cr-1/2Mo and 1Cr-1/2Mo steels that may be irreversible by lower temperature heat treatment and may require higher temperature heat treatment such as normalizing. In one case CVN samples were found to have high energy CVN energies and a brittle appearance, i.e. "high energy cleavage."*	*(1) Do you have any information on such forms as "irreversible" or "stress relief" embrittlement?* *(2) Have you ever seen "high energy cleavage"?* *(3) Do you believe a requirement for lateral expansion of CVN samples is justified?*

Summary of Comments on Topic 15, Question (1):

One respondent provided the following comment:

1. Irreversible (or stress relief) embrittlement is characterized by a big scatter in CVN results. From 3 specimens tested at the same temperature it is possible to have two values at 300 J and one value at 10 J.

Summary of Comments on Topic 15, Question (2):

Only one respondent provided a comment: "There have been cases where the test results show good impact test values but poor shear appearance, which may indicate that the tests were performed in the transition region of a material with high upper shelf energy." Others had no comments.

Summary of Comments on Topic 15, Question (3):

Most respondents had no comments on this question. One respondent provided the following comment: "ASME specifies a mills lateral expansion criteria for carbon and low alloy steels with minimum specified UTS greater than 95 ksi."

#	Topic	Background	Questions
16	**Creep embrittlement and cracking**	*There has been a significant amount or research on creep embrittlement (above 850 °F) and cracking and a number of reports and recommendations to minimize the risk of creep embrittlement and cracking.* *These recommendations include limitations on chemical composition (maximum P, S, Cu, As, Sn, Sb, contents, etc.), use of the lower strength Cr-Mo steels materials with Class 1 properties, and on fabrication (use of temper bead techniques to ensure fine grain in the HAZ, avoiding notches and other stress raisers at welds, use of 1300 °F minimum PWHT temperature, use of Cr-Mo steels with Class 1 properties and lower carbon contents, and X bar, and MPC factors).*	*(1) What chemical composition limitations are most effective in reducing the risk of creep embrittlement and cracking?* *(2) Concerns with X bar and MPC factors.* *(3) Concerns with 1300 °F minimum PWHT.*

<u>Summary of Comments on Topic 16, Question (1):</u>

1. Low P (0.015 %) and low S (0.005 %) are effective.

2. $2^{1}/_{4}$Cr-1Mo is recommended above 900 °F (482 °C).

3. On respondent felt that the WRC Bulletin 409 and 411 based studies are flawed.

4. Another respondent stated that they have encountered problems in the older stacked platform reactors. Cracks were found at weld discontinuities at nozzles and supports. They have not encountered any recent creep embrittlement and cracking problems in their reactors operating in creep range after instituting certain requirements for $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo vessels operating in the creep range:

(a) Limit the materials to those with Class 1 properties.

(b) Specify C $\leq$ 0.13 for design temperatures above 850 °F (454 °C).

(c) PWHT the Class 1 vessels at 1275 °F ± 25 °F

(d) Use flared (contour) nozzles for vessels operating in the creep range, which permits butt welded joints for nozzle attachment welds.

(e) Provide generally a smooth contour for all welded joints. Blend grind all butt joints in fatigue service.

(f) 100 % RT all butt welded joints in the vessel and all nozzle attachment welds. MT or PT all other attachment welds.

<u>Summary of Comments on Topic 16, Question (2):</u>

1. Most respondents stated that in their opinion that X-bar or MPC factors are not necessary for $1^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo steels and not commonly used.

2. One respondent stated" "MPC factor can be of concern. The weight of Nb is very high in the factor. It should be necessary to limit the Nb content below 0.002 %."

3. Another respondent stated: "X bar is OK if one insists it makes sense, and we have no problem meeting current demands. MPC factors require a level of detection for minor elements that are not commercially practical during melting of steel. Issuance of weight factors like 1000 for Nb is ridiculous when you cannot accurately analyze below 0.002. We have reanalyzed Nb using ICMP spectroscopy at a university and found actual levels two complete orders of magnitude lower."

<u>Summary of Comments on Topic 16, Question (3):</u>

1. All respondents expressed concerns with the ability to guarantee the required strength and toughness with 1300 °F minimum PWHT. The main concern will be degradation of notch toughness.

2. One respondent stated that it is not possible to have at the same time good creep embrittlement resistance and good toughness properties.

#	Topic	Background	Questions
17	**Reheat cracking**	*This issue is addressed in WRC Bulletin 409, by Lundin and Khan as well as numerous papers in the literature.*	*Can you provide examples of where this problem has been experienced in $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo materials?*
	Summary of Comments on Topic 17: 1. Most respondents stated that they have not experienced reheat cracking. 2. One respondent stated that his company has experienced reheat cracking at toes of fillet welds. 3. Another respondent stated that, as a producer, his company cannot work to any of the MPC factors detailed in any of the literature. He suggested a low carbon, QT Class 1 material, place restrictions on the welding, and not on the base plate, and PWHT at reasonable temperatures to avoid this problem.		

#	Topic	Background	Questions
18	**Hot tensile tests**	*The ASME Code allowable stresses in Section II, Part D, Tables 1A (for Division 1 construction) and 5A (for Division 2 construction) are based on the trend curve information obtained from hot tensile tests from at least three heats of steel. The trend curve data is used to develop the elevated temperature tensile strength values in Table U and the yield strength values in Table Y-1 of Section II, Part D. ASME Code does not require hot tensile tests; however, these are sometimes specified by Users. The European EN pressure vessel standards require guaranteed elevated temperature properties.*	*(1) Are the steel producers willing to guarantee 90 % of the tensile strength values in Table U of Section II, Part D?* *(2) If not, what are the concerns and limitations (e.g., maximum PWHT temperature and hold times, in terms of LMP, etc.)*
	Summary of Comments on Topic 18, Question (1): The following lists several comments: 1. Because the allowable stress of both ASME Section VIII, Div.2, 2007 Edition and EN Pressure Vessel Standard are established based on Yield Strength at elevated temperature, thus, we think it is not necessary to guarantee the tensile strength at elevated temperature. 2. No. It can be a problem for he thicker plates for which there is not full bainitic microstructure. 3. Not if someone wants to PWHT at excessively high temperatures with long hold times and thereby cause the material to be on the bottom of guaranteed tensile properties. It helps to use Q&T material. 4. We do not require the mills to guarantee elevated temperature tensile properties in Section II, Part D (or 90 % of such values). In summary, some respondents were willing to and some were not willing to guarantee 90 % of the tensile strength values in Table U of Section II, Part D. Summary of Comments on Topic 18, Question (2): 1. The concern can be both LMP and microstructure. 2. In order to guarantee the tensile property, PWHT cycle and temperature have to be properly limited. 3. The concerns are PWHT and use fine grain practice. Were the trend curves based on coarse grain 1950s material with no low temperature toughness? The concerns are mainly with the maximum PWHT temperature, hold times, LMP, and plate thickness. Quenching and tempering helps to achieve higher tensile properties.		

#	Topic	Background	Questions
19	**Maximum hardness requirement**	*Generally it is necessary to PWHT at 1250 °F minimum (1275 °F ± 25 °F) to achieve both a maximum hardness of 225 BNH and 40 ft-lb at 32 °F or 0 °F.*	*(1) The Users require a maximum surface hardness for the 1Cr-$^{1}/_{2}$Mo and 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo welds (e.g. 225 BHN on surface). Please state what difficulties are encountered in achieving this result.*

Summary of Comments on Topic 19:

1. We can guarantee the hardness if the condition of 1275 °F ± 25 °F (690 °C ± 14 °C) x 2 hours (min) is applicable.

2. Our practice is that the PWHT temp. has to be controlled with 680 °C (1256 °F), and not exceed 690 °C (1274 °F) in order to maintain the mechanical properties for thickness over 4 in. The hardness criteria will be 225 BHN as maximum with proper PWHT and holding time.

3. This applies to HAZ, and making this any part of a product specification for base plate would be a waste of money and time. 100 ksi max tensile for Class 2 is a maximum of about 200 HBN, so why require it. And again, the PWHT is needed to get toughness in the weld or HAZ, not in the base plate.

4. One respondent stated that his company requires the welded joints to meet 225 BHN maximum surface hardness after the final heat treatment (PWHT) of the vessel or component. No requirement for hardness tests on the cross-section of the welded joints.

The respondents indicated that they can achieve both a maximum hardness of 225 BNH and 40 ft-lb at 32 °F in welded joints; however, the maximum hardness is affected by the welding conditions and PWHT.

#	Topic	Background	Questions
20	**DHT and ISR**	*ISR and DHT are used to remove hydrogen from welds and to minimize the risk of hydrogen cracking. However, DHT may not be appropriate for highly restrained welds (such as nozzle forging welds) in some Cr-Mo welds.*	*When is ISR and when is DHT appropriate for 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo materials?*

Summary of Comments on Topic 20:

The respondents felt that ISR is not necessary for 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo materials and offered the following comments:

1. As per our past experiences, we think that ISR is not necessary for 1$^{1}/_{4}$Cr-$^{1}/_{2}$Mo and 1Cr-$^{1}/_{2}$Mo materials, because hydrogen cracking is avoidable sufficiently by DHT method, and residual stress is also reduced sufficiently during final PWHT application.

2. Nozzle attachment welds are heat treated by ISR after welding of Cr-Mo-V steels. Other conventional Cr-Mo welds are heat treated by DHT condition after welding without any additional ISR.

3. We suggest ISR only for very high restraint condition and when two weld joints are very close other. Also, proper laboratory tests to estimate H_2 content are useful.

4. Normally, DHT is applied for all weld seams (including nozzle attachment welds) at 572 °F (300 °C) for 1 hr minimum.

#	Topic	Background	Questions
21	**Weld overlay and clad plate disbonding**	*Clad plates may be appropriate for certain $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo applications, particularly for those in high temperature high pressure hydrogen service. Many $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo vessels are of clad plates, such as coke drums, etc.*	*(1) Are weld overlay disbonding tests necessary for $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo applications?* *(2) How do the test results on these Cr-Mo steels compare with those on $2^1/_4$Cr-1Mo steels?* *(3) Roll bonded vs explosively clad plates (maximum thickness, resistance to disbonding, etc.).*

Summary of Comments on Topic 21, Question (1):

1. No. If $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo are selected according to Nelson Curve, we think no disbonding will occur due to vessel operating condition and, therefore, we think disbonding test is not necessary for such material application.

2. Weld overlay disbonding tests are only necessary for austenitic stainless steel weld overlay in high temperature hydrogen service for use temperatures over 700 °F (371 °C).

3. We seriously doubt it because they wouldn't be used in the temperature and hydrogen pressure regimes that Grade 22 or 23 would see.

4. Based on characteristic of materials, disbonding test should be required depending on hydrogen service.

Summary of Comments on Topic 21, Question (2):

Most respondents stated that they do not have weld overlay disbonding test data on $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo steels. Two respondents offered the following comments:

1. We did disbonding tests on both materials; no problems if proper weld procedures are used.

2. Grade 11 is more sensitive to disbonding than Grade 22.

Summary of Comments on Topic 21, Question (3):

1. One respondent stated: We have not seen significant differences regarding disbonding resistance".

2. One user generally prefers explosively clad plates because of their better bond strength.

3. Another respondent stated: "This is trying to compare apples and oranges. Explosive bonded clad competes with overlay for heavy wall vessels and not light gage clad except in some circumstances such as coke drums when availability is an issue. There is no data to suggest that in the ranges where roll-bonded clad is used it is subject to disbonding due to hydrogen issues, and in fact the disbond test procedure doesn't even cover plates that are roll bonded (e.g. < 2 in.)."

#	Topic	Background	Questions
22	**MPT (minimum pressurizing temperature)**	*Many users of vessels in refinery services with high pressure hydrogen, such as hydrofiners are having difficulty in establishing an minimum pressurizing temperature (MPT).*	*Do you have any guidelines for establishing MPT for high pressure hydrogen pressure vessels such as hydrofiners?*
	Summary of Comments on Topic 22: 1. Although we do not have sufficient temper embrittlement (step cooling) data for $1^1/_4$Cr-$^1/_2$Mo, same guideline can be applied for it. 2. Based on Kv and SC test we can assume that MPT is about 40 °C (104 °F). 3. Creep embrittlement may cause loss of notch toughness in improperly heat treated vessels. We do not specify MPT for $1^1/_4$Cr-$^1/_2$Mo and 1Cr-$^1/_2$Mo vessels; however, some operators do use MPT these vessels.		

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