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GUARANTEED HIGHER STRENGTH PROPERTIES

ASME STANDARDS TECHNOLOGY, LLC

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FOREWORD

This document was developed under a research and development project which resulted from ASME Pressure Technology Codes & Standards (PTCS) committee requests to identify, prioritize and address technology gaps in current or new PTCS Codes, Standards and Guidelines. This project is one of several included for ASME fiscal year 2008 sponsorship which are intended to establish and maintain the technical relevance of ASME codes & standards products. The specific project related to this document is project 07-07 (BPVC#4), entitled, "Guaranteed Strength Properties."

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ABSTRACT

This report discusses the various aspects related to the tensile properties in plates and forgings, including the feasibility of using guaranteed tensile values that exceed the specified minimum tensile strength in the material specifications, and provides recommendations for design stresses and Code construction based on the higher guaranteed tensile and yield strength values.

The issues discussed in this report apply mainly to tensile strength values higher than the minimum specification values since the tensile strength generally governs the Code allowable stresses for carbon and low alloy steels for Section VIII, Division 1 construction. However, with the increase in tensile strength there is also an increase in the yield strength. The yield strength may govern the Code allowable stresses for Section VIII, Division 2 and 3 construction

1 INTRODUCTION

Material specifications list the specified minimum yield strength, minimum and, in most cases, maximum tensile strength and values for materials and grades covered by the specification. The tensile properties for a particular material and grade are based on chemical composition, heat treatment, thickness and production data. The tensile properties can also be influenced by the amount of work (reduction) during the rolling process, resulting in higher values for thin plates than for thick plates. The mill production data must show that all tensile strength values are within the specified tensile strength ranges and that the yield strength values exceed the specified minimum values to make it commercially acceptable for the producer of that material. Increasing the specified minimum tensile strength or yield strength would involve a commercial decision by the material producer, based on his production data and the expected rejection rate, as to what minimum specified tensile properties above the specification values are acceptable to that producer.

Improved melting practices, chemistry controls and rolling practices can result in improved notch toughness and tensile properties. Typical production data indicate that often the actual tensile properties (tensile strength and yield strength) significantly exceed the specified minimum properties, particularly in thinner plates. Some industry standards (e.g., API 650, Welded Steel Tanks for Oil Storage, CODAP) recognize this and include provisions for use of higher tensile properties. API 650 permits an increase up to 5 ksi above the specified minimum values for certain carbon steels. These higher tensile strength values are subject to agreement between the purchaser and the material producer. The use of higher guaranteed tensile properties (where this is feasible) reduces the weight of the vessel component, resulting in savings to the vessel manufacturer and the owner.

2 MATERIAL SPECIFICATIONS

Some typical carbon and carbon-manganese pressure vessel steel specifications are:

(a) SA-105, Specification for Carbon Steel Forgings for Piping Applications.

(b) SA-106, Grades A, B and C, Specification for Seamless Carbon Steel Pipe for High-Temperature Service.

(c) SA-182, Grade F11, Classes 1, 2 and 3, Grade F12, Classes 1 and 2 and Grade F22, Classes 1 and 3, Specification for Forged or Rolled Alloy and Stainless Steel Pipe Flanges, Forged Fittings and Valves and Parts for High-Temperature Service.

(d) SA-285, Grades A, B, C and D, Standard Specification for Pressure Vessel Plates, Carbon Steel, Low and Intermediate Tensile Strength. This steel may be semi-killed or fully killed, and is normally supplied in the as-rolled condition. The maximum thickness is limited to 2 inches.

(e) SA-299, Grades A and B, Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service. Both Grades have the same chemical composition. Grade A has a specified minimum tensile strength of 75 ksi, and Grade B, 80 ksi. Plates over 2 inches thick shall be normalized.

(f) SA-333, Grades 1 and 6, Specification for Seamless and Welded Steel Pipe for Low-Temperature Service.

(g) SA-335, Grades P11, P12, P21 and P22, Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service.

(h) SA-336, Grade F11, Classes 1, 2 and 3, Grade F12, Grade F21, Classes 1 and 3 and Grade F22, Classes 1 and 3, Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts.

(i) SA-350, Grades LF1 and LF2, Specification for Carbon and Low-Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components.

(j) SA-387, Grades 11, 12, 22 and 21, Classes 1 and 2, Standard Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum. The lower strength Class 1 plates may be supplied in the annealed or in normalized and tempered (NT) condition, and the Class 2 plates in the normalized and tempered (NT) or in the quenched and tempered (QT) condition.

(k) SA-516, Grades 55, 60, 65 and 70, Standard Specification for Pressure Vessel Plates, Carbon Steel, Manganese-Silicon. The grade designations correspond to the specified minimum tensile strength in ksi. Plates over 1½ inches thick shall be normalized. SA-20 also permits quenching and tempering of pressure vessel plates when agreed to by the purchaser.

(l) SA-537, Classes 1, 2 and 3, Standard Specification for Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel. All Classes of plate are supplied to the same chemical composition. Class 1 plates are normalized, and Classes 2 and 3 plates are quenched and tempered. Class 1 plates have a specified minimum tensile strength of 70 ksi and Classes 2 and 3 plates have 80 ksi minimum tensile strength in thicknesses up to and including 2½ inches. Thicker plates have lower tensile strength and yield strength.

(m) SA-612, Standard Specification for Pressure Vessel Plates, Carbon Steel, High Strength, for Moderate and Lower Temperature Service. Plates 0.5 inch thick and thinner have a specified minimum tensile strength of 83 ksi and those over 0.5 inch have 81 ksi minimum tensile strength. The maximum thickness plate supplied to this specification is 1 inch.

(n) SA-737, Grades B and C, Standard Specification for Pressure Vessel Plates, High-Strength, Low-Alloy Steel. Both these grades are supplied in the normalized condition. Grade B is carbon-

manganese-columbium steel with 70 ksi specified minimum tensile strength, and grade C is carbon-manganese-vanadium steel with 80 ksi specified minimum tensile strength.

(o) SA-738, Grades A, B, C, D and E, Standard Specification for Pressure Vessel Plates, Carbon Steel, Manganese-Silicon. Grade A has a specified minimum tensile strength of 75 ksi, Grade B has an 85 ksi minimum tensile strength, Grade C has an 80 ksi minimum tensile strength, Grade D has an 85 ksi minimum tensile strength and Grade E has a 90 ksi minimum tensile strength. Grade A shall be normalized or quenched and tempered in thicknesses up to and including 2½ inches. Thicker Grade A plates and Grades B, C, D and E plates in all thicknesses shall be quenched and tempered. Only Grades A, B and C have been approved for pressure vessel construction.

(p) SA-765, Grades I, II and IV, Specification for Carbon Steel and Low-Alloy Steel Pressure-Vessel-Component Forgings with Mandatory Toughness Requirements.

Material specifications list the minimum specified yield strength, the specified minimum tensile strength and, in most cases, maximum tensile strength values. The specified tensile strength range for pressure vessel plates typically is 20 ksi (138 MPa) and 25 ksi for (172 MPa) for forgings and fittings. However, some forging specifications (SA-105, SA-182) specify a maximum hardness to control the maximum strength. Several forging specifications do not list a maximum tensile strength or hardness (SA-522, SA-723). Also most pipe and tube specifications do not list a maximum tensile strength or maximum hardness.

The aim tensile properties are established from production data to ensure a minimum rejection rate. The steel producer would generally have to accept a greater risk of rejection by agreeing to a higher minimum tensile strength than those listed in the material specification; therefore, the acceptance of a higher tensile strength is a commercial decision by the steel producer based on his ability to meet the higher minimum tensile properties while staying below the maximums.

It may be easier for the mill to accept a greater minimum tensile strength for thinner as-rolled plates than for thicker plates. The tensile strength is generally higher in thinner plates because of the greater reduction in thickness (more work) during the rolling of the plate and faster cooling rate in thinner plates. However, for light gage as-rolled plates there is considerably more variability, and increasing the minimum tensile strength, while having the same maximum tensile strength, introduces a greater risk of exceeding the maximum specified tensile strength values.

Increasing the minimum tensile strength for a particular grade of steel decreases the spread between the specified minimum and maximum tensile strength. This increases the risk of a higher rejection rate. This may require tighter production control by the steel producer to ensure that the material meets the more restrictive range. One alternative would be to permit an increase in the maximum tensile strength as well, to keep the range the same; however, that may necessitate a new grade designation.

3 FACTORS THAT AFFECT TENSILE PROPERTIES OF CARBON AND LOW ALLOY STEELS

There are several factors that affect the tensile properties. The more important ones are discussed below.

3.1 Chemical Composition – Alloying Elements

Common elements that are present in carbon and low alloy steels are carbon, manganese, silicon, phosphorus and sulfur. The carbon content probably has the most significant effect on hardness and strength of all the elements present in carbon and low alloy steels. However, the increase in carbon content also reduces notch toughness and weldability. Manganese is essential to steel production, not only in melting, but also in rolling and other processing operations. Increasing the manganese/carbon ratios also improves notch toughness. Silicon increases hardenability and strengthens low alloy steels.

Other common elements that may be present in steels are chromium, nickel, molybdenum and copper. Chromium is essentially a hardening element but may also be used in combination with nickel to improve tensile properties. Nickel increases strength and toughness, particularly in heat treated steels. Molybdenum increases strength, and is commonly used to increase elevated temperature tensile properties and creep strength, often in combination with chromium. Both nickel and molybdenum have more effect on hardenability in heat treated steels, which improves the ability to produce thicker plates. Copper in certain alloys increases resistance to atmospheric corrosion and increases yield strength.

Some steels may also contain microalloying elements such as vanadium, columbium (niobium) and titanium. These are almost always deliberate additions to improve strength, particularly yield strength. They have little effect on carbon equivalent (CE). They may also be added as gain refining elements. Vanadium may also be added to increase the elevated temperature properties of materials and provide more resistance to tempering. However, excessive amounts of these microalloying elements may cause carbide precipitation along the grain boundaries in the heat affected zone and loss of toughness under high heat input welding and during PWHT, and provide resistance to tempering.

The maximum amounts of elements that may be present in the steel are listed in the material specification for that steel and grade. ASME SA-20, Table 1 lists the maximum limits for unspecified elements, those that may be present in the steel but are not listed in the chemical composition tables in the material specification as having no requirement. ASME SA-20 requires reporting for each heat of steel, the percentages by weight of carbon, manganese, phosphorus, sulfur, silicon, nickel, chromium, molybdenum, copper, vanadium, columbium and any other element that is specified or restricted by the applicable material specification or listed in Table 1 of SA-20 as an unspecified element.

3.2 Chemical Composition – Carbon Equivalents

Increasing the carbon content or some of the alloying elements also increases the carbon equivalent, which generally decreases the weldability and notch toughness.

A commonly used formula for weldability is the IIW carbon equivalent formula:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}, \% \tag{1}$$

This formula contains the most commonly used alloying elements and can also be used to correlate to the tensile strength of the material. Figure 1 [2] plots the IIW carbon equivalent CE vs. tensile strength of 1.5 – 3.0 in. (38 – 75 mm) thick normalized SA-516, Gr. 70 plates. It shows that it would be necessary to increase the CE in the normalized plate by about 0.05% to increase the tensile strength by 5 ksi, i.e., from 70 ksi to 75 ksi (485 – 515 MPa).

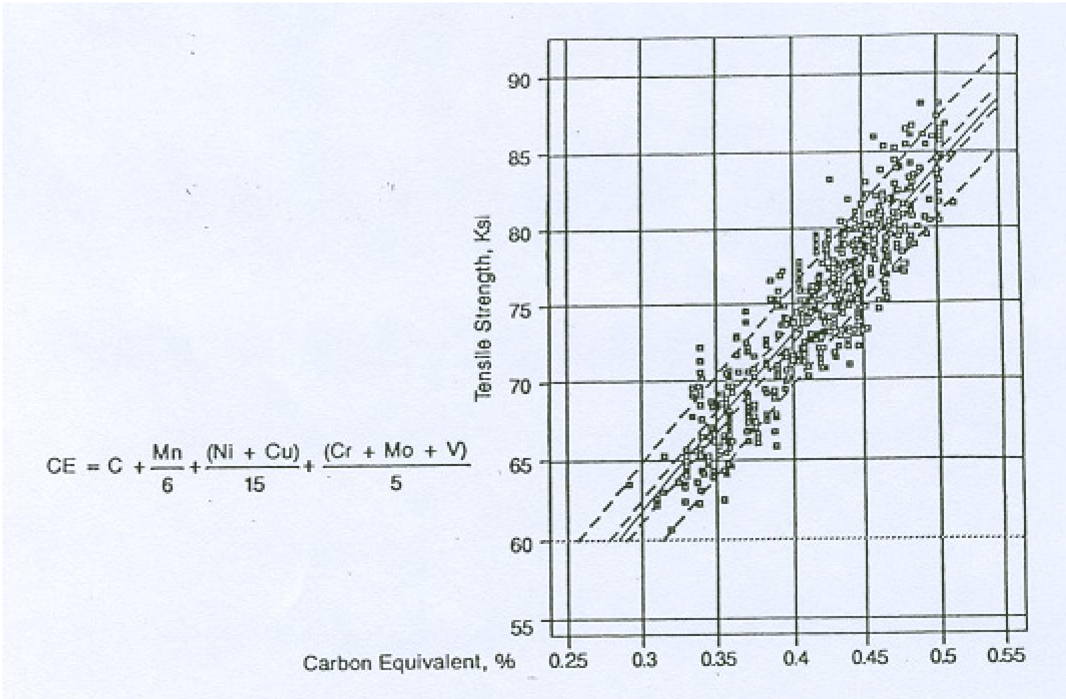

Figure 1 - SA-516, Grade 70 Normalized Plates over 1.5 in. to 3 in. (38 – 75 mm) Thick

One element that may be present as an unspecified element but is not listed in SA-20, Table 1, is boron. Boron increases hardenability and strength of the steel but excessive amounts of boron (e.g., a boron content above 0.0005 %) can significantly increase hardness and decrease notch toughness in welded joints. Boron is not included in the IIW CE formula, above, but it is included in another carbon equivalent formula by Ito and Bessyo, called P_{cm}, which is considered more applicable for weldability of steels with carbon content less than 0.18 %, where:

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B, \% \tag{2}$$

The specified chemical composition in the material specification for a particular grade of steel does allow for adjustments (within the specified composition ranges) to increase tensile strength, particularly where a higher initial strength is needed to account for losses in tensile properties due to high PWHT temperatures and/or long hold times at the PWHT temperature. However, this reduces the weldability and may require additional precautions to avoid cracking of welded joints, such as higher preheat temperature, dehydrofenation heat treatment (DHT) or intermediate PWHT for highly restrained welds where that would not be required with lower carbon equivalents.

Figure 2 [11] shows the effect of carbon equivalent (CE) on normalized and tempered A-387, Grade 11 steel. This shows that an increase in of 0.1 % in the carbon equivalent can result in an increase of about 10 ksi tensile strength.

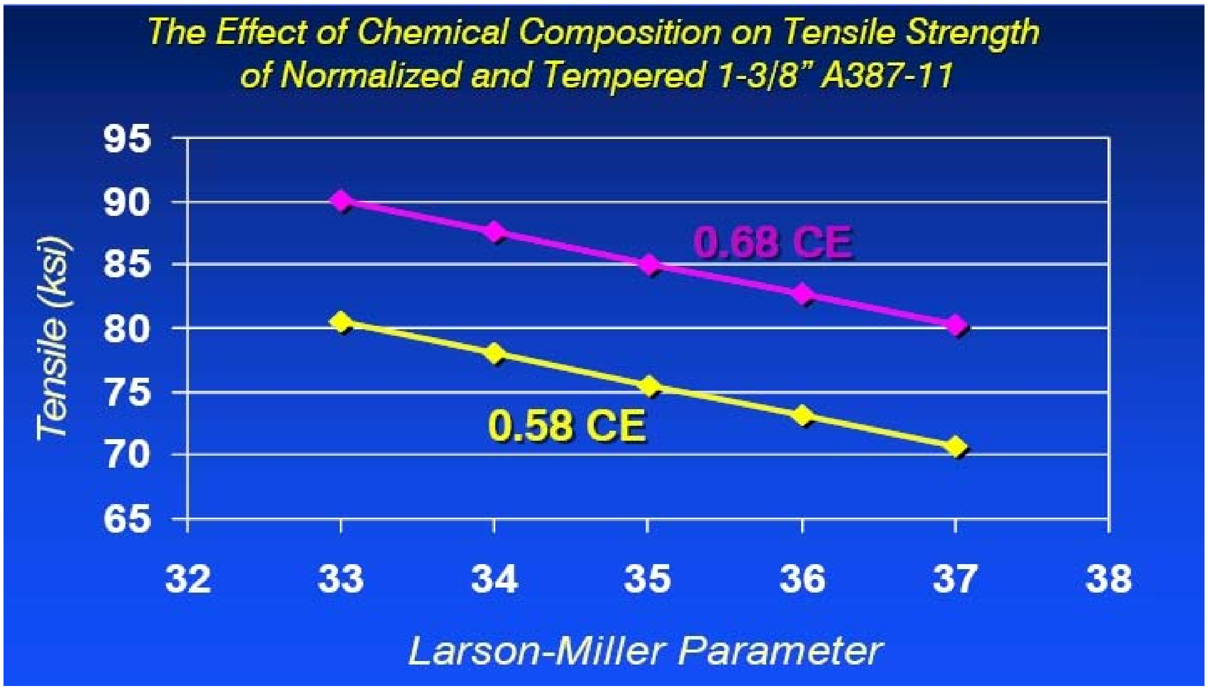

Figure 2 - The Effect of Carbon Equivalent on Tensile Properties of N&T A-387 Gr. 11 Steel and as a Function of the Tempering Parameter (LMP)

The total parameter LMP is a combination of the time at the PWHT temperature and any other heat treatments above 900°F. LMP is given by the following formula.

$$LMP = T(C + \log t) \tag{3}$$

where:

T = °R

°R = (°F + 460) for the LMP values in Figure 2, Figure 3, Figure 4 and Figure 6

C = 20

t = time at temperature, hours.

3.3 Temper Embrittlement and Creep Embrittlement of Cr-Mo Steels

The concerns about temper embrittlement and creep embrittlement of Cr-Mo steels in high temperature service have led to several additional chemical composition requirements and controls to reduce the susceptibility of the Cr-Mo steels to embrittlement. Several API Recommended Practices, such as RP 934A, RP 934 C and RP 934E [5], [6], [7], [8] include specific recommendations for use of Cr-Mo materials in high pressure, high temperature refinery service, including chemical composition. The ASME Code does not include specific requirements for in-service degradation of materials. However, Nonmandatory Appendix A in Section II, Part D does include comments on some of the effects of processing history, heat treatment, melting practices, the level of microalloying elements and service exposure on material properties.

3.3.1 Temper Embrittlement

The 2¼Cr-1Mo steels, and to a lesser degree the 1¼Cr-½Mo steels, are subject to temper embrittlement. Temper embrittlement occurs when the material is exposed for a prolonged time (e.g., over 1000 hr) in the temperature range of about 650°F to 1000°F (343°C – 538°C). Temper embrittlement causes a large increase of the ductile-to-brittle transition temperature and fracture along the prior austenite grain boundaries, but does not have a significant effect on tensile strength. API RP 934A [5] includes special requirements for 2¼Cr-1Mo steels on chemical composition for base metal (maximum J-factor) and weld metal (maximum X-bar factor) to reduce the effects of temper embrittlement. The J-factor and X-bar factors are defined below:

J-factor = (Si + Mn) x (P + Sn) x $10^4 \leq 100$, and

X-bar = (10P + 5SSb + 4Sn + As)/100 ≤ 12, where P, Sb, Sn and As are ppm

The test coupons are also subjected to step cooling tests to develop impact test transition curves in the minimum PWHT condition and in minimum PWHT condition plus step cooling treatment. The 40 ft-lb transition temperature shall not exceed 50°F, where the shift is defined by the following equation:

CvTr40 + 2.5 ΔCvTr40 ≤ 50°F, and

CvTr40 = 40 ft-lb transition temperature of material subjected to the minimum PWHT only

ΔCvTr40 = the shift of the 40 ft-lb transition temperature of material subjected to the minimum PWHT plus the step cooling heat treatment.

The test coupons must be subjected to all the above heat treatments. Separate test coupons must be subjected to the maximum heat treatment for fabrication and any repairs.

3.3.2 Creep Embrittlement

The 1¼Cr-½Mo and 1Cr-½Mo steels are subject to creep embrittlement after long time exposure to temperatures above about 825°F. This damage mechanism occurs in the form of HAZ creep damage, as well as intergranular fracture along the grain boundaries, mainly in the coarse grain HAZ. API RP 934E [8] lists the following chemical composition requirements to minimize the risk of creep embrittlement and cracking:

C = 0.15 % max.	Cu = 0.20 % max.
P = 0.015 % max.	Ni = 0.30 % max.
S = 0.007 % max.	X-bar = 15 ppm max.

The material should also be vacuum degassed and the welded joints should be stress relieved above 1275°F, but not above 1350°F. The allowable design stresses for 1¼Cr-½Mo and 1Cr-½Mo steels at design temperatures in the creep range are the same for Class 1 and Class 2 properties; therefore, there is no need to use plates to the higher strength Class 2 properties, as the use of the lower strength steels with Class 1 properties results in the same thickness. However, the restriction of the maximum carbon content to 0.15% may require quenching and tempering thicker plates to meet the strength and toughness requirements after long time PWHT (e.g., three PWHT cycles) at high PWHT temperatures.

3.4 Thickness

It is easier to achieve the specified tensile properties in thinner plates than in thicker plates. That is because of less reduction (work) during rolling and slower cooling rates in thicker plates during the heat treatment. Some specifications increase the carbon and manganese contents to meet the specified tensile strength in thicker plates (e.g., SA-516). Other specifications decrease the specified minimum tensile strength and yield strength for thicker plates in specifications that list the same chemical composition limits for all thicknesses (e.g., SA-537).

ASME SA-20 requires tension tests and impact tests to be taken from the ¼ T location in the plate. However, some users and specifications, particularly for thick Cr-Mo low alloy steel plates, require the mechanical tests to be performed on test specimens taken from the ½ T location of the plate. This generally results in lower tensile strength and impact test values than at the ¼ T location, because of the slower cooling rate, depending on thickness and degree of inherent hardenability. It is a common practice to require ½ T testing for Cr-Mo materials for petroleum refinery service, which is included in API RP 934A, RP 934B, API 934 C and API RP 934E. 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 thicker plate or forgings.

The maximum thickness of 1¼Cr-½Mo and 1Cr-½Mo plates is limited because of this alloy's hardenability properties, which leads to lower toughness than the 2¼Cr-1Mo plates. The addition of Cr and Mo aid in increasing the hardenability of the material by forming carbides. As a general rule, as the Cr content increases, the materials hardenability increases. The 2¼Cr–1Mo steels have higher hardenability and, therefore, are used in greater thicknesses than the 1¼Cr-½Mo steels. The 1¼Cr-½Mo and 1Cr-½Mo plates and forgings are generally limited to about 4 in. (100 mm) maximum thickness with Class 2 and Class 3 properties because of an inability to achieve the required tensile properties for Class 2 tensile properties in plates and Class 3 properties in forgings and the required notch toughness in thicker sections.

As specified in SA-20, the tension tests conforming to 0.500 in. (12.5 mm) diameter test specimens generally are taken from the ¼ t location in the plate. The provisions for ½ T testing are included in A/SA-387, Supplementary Requirement S53, which permits the tensile specimens to be taken from the ½ T location in lieu of the ¼ T location, when specified by the purchaser, which eliminates the need for tests at both locations. Generally, full thickness tension test specimens are used for plates less than 1½ in. thick, therefore, the consideration for ½ T vs. ¼ T testing becomes a consideration for plates over 1½ in. thick.

The cooling rate from the austenitizing temperature during a heat treatment has a significant effect on the mechanical properties of the material. Because of this and because of multiple PWHT cycles at 1275°F (690°C) (or above) the 1¼Cr-½Mo and 1Cr-½Mo materials generally need to be quenched and tempered in thicker sections to achieve the specified tensile properties and to meet the notch toughness requirements. Figure 3 [4] illustrates how a significant improvement in tensile strength can be realized by way of quenching and tempering for A-387 Grade 12 and Grade 22 steels.

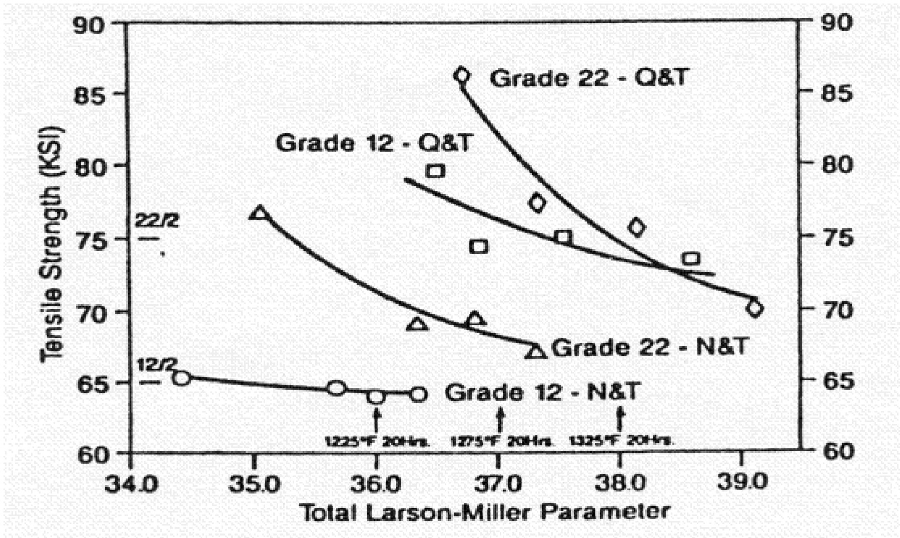

Figure 3 - The Effect of Stress Relief on Tensile Strength of 2 in. (50 mm) Thick A-387, Gr. 12 and Gr. 22 Plates as a Function of Larson-Miller Parameter (LMP)

3.5 Heat Treatments (normalizing, quenching and tempering, etc.)

Commonly used heat treatments are normalizing, normalizing and tempering (N & T), quenching and tempering (Q & T) and thermo-mechanical control processing (TMCP for SA-841 plates), which involves accurate control of both the steel temperature and rolling reduction without or with subsequent heat treatment (such as direct quenching and tempering). Quenching and tempering results in higher tensile and yield strength than normalizing of a steel with the same chemical composition and improves notch toughness. Q & T is allowed by SA-20, paragraph 6.6 in lieu of other heat treatments, if approved by the purchaser. This is another way to achieve higher tensile strength and yield strength. The tensile strength after quenching is reduced by tempering so that it is within the limitations for a normalized plate, but the ratio of yield strength to tensile strength will be higher in Q & T plates than in normalized plates.

SA-537 plates are produced to Class 1 and Class 2 tensile properties. Both have the same chemical composition, but Class 1 plates are normalized and have 70 ksi minimum tensile strength, whereas the Class 2 plates are quenched and tempered and have 80 ksi minimum tensile strength.

The Cr-Mo plates and forgings to Class 1 tensile properties are produced in the annealed or in the normalized and tempered (N & T) condition and 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.

The Cr-Mo plates to Class 2 tensile properties and forgings to Class 2 and Class 3 tensile properties generally are supplied in the quenched and tempered condition, particularly in thicknesses over about 2 inches (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.

3.6 Variability of Tensile Properties in Plates (inc. test specimen location and heat treatment)

For other than quenched and tempered plates, one tension test coupon is required from one corner of the as-rolled plate. For quenched and tempered plates, two test coupons shall be taken from the opposite ends of the plate. The results shall meet the properties specified in the material specification. The amount of testing should not be less for plates produced to guaranteed properties that are higher than the values listed in the material specification.

It is well known that the chemical composition (as determined by product analysis) can vary within the plate. Also, the tensile properties vary within the plate as a function of chemical composition, processing, testing procedure and other factors, and may be different than the results shown on the test report. A survey of the variations in tensile strength was conducted by the American Iron and Steel Institute, and are published in “The Variation of Product Analysis and Tensile Properties – Carbon Steel Plates and Wide Flange Shapes” (SU/18, SU/19 and SU/20) published in September 1974 [9]. Likewise, there are variations in Charpy V-Notch impact test properties in steel plates [3]. These variations have been considered acceptable for pressure vessel plates and should also be acceptable for plates with higher guaranteed tensile properties.

3.7 Fabrication Heat Treatments (postweld heat treatments)

The ASME Code requires the test specimens to be obtained from test coupons that have been heat treated in the same manner as the material, including all fabrication heat treatments above 900°F (482°C), such as postweld heat treatment (PWHT). Section VIII, Divisions 1 and 2 exempt the P-No. 1, Groups 1 and 2 materials from this requirement. However, it is also known that postweld heat treatments, especially if the material is subjected to several PWHT cycles, reduce the tensile properties and notch toughness. Figure 4 [3] plots tensile strength vs. Larson-Miller Parameter (LMP) for a 3 inch (75 mm) thick normalized SA-516, Grade 70 plate (ASME P-No. 1, Group 2 material).

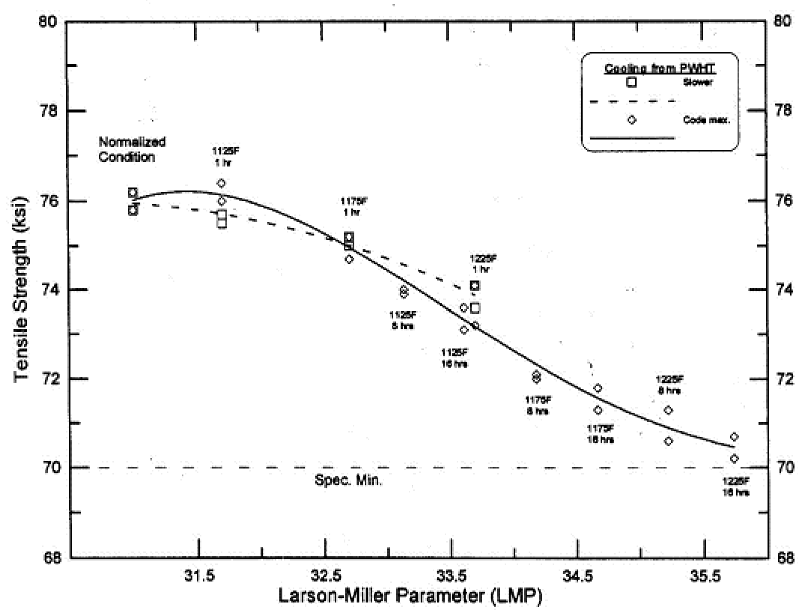

Figure 4 - The Effect of PWHT on SA 516 Gr. 70 Plate Tensile Strength

Figure 4 shows an average tensile strength of about 76 ksi (524 MPa) at room temperature in 3 inch (75 mm) thick SA-516, Gr. 70 plate. This figure shows that the tensile strength of this plate has only a margin of about 1 ksi (6.9 MPa) for reduction by PWHT to a guaranteed tensile strength of 75 ksi (517 MPa), which is a 5 ksi (34.5 MPa) increase over the specified minimum UTS. This would occur by subjecting it to LMP of about 32,750, which corresponds to about 4½ hours at 1125°F (607°C). One PWHT cycle for 3 inch (75 mm) thick plate requires a 2½ hour hold time at 1100°F (593°C) minimum PWHT temperature, which typically would be done in a shop at 1125°F (607°C) nominal ± 25°F (14°C). It would be necessary to supply this plate with higher carbon content or more residual elements (Cr, Ni, etc.), or in the Q & T condition to increase its strength. Therefore, it is necessary to ensure that the plate meets the higher tensile after all fabrication heat treatments.

The 2¼Cr-1Mo materials are ASME P-No 5A, Group 1 materials. The Code requires these materials to be stress relieved at 1250°F (677°C) minimum for 1 hour/in. for thicknesses up to and including 5 inches (125 mm) and 5 hours plus 15 minutes for each additional inch of thickness over 5 in. (125 mm). Test coupons for Cr-Mo vessels typically are subjected to three PWHT cycles to simulate all fabrication heat treatment (including intermediate stress relief) to allow for two fabrication PWHT cycles plus a repair cycle. 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 5 [10] plots the test data (tensile strength and yield strength) vs. Larson-Miller parameter (LMP) for A-387, Grade 22, Class 2. This illustrates the combined effect PWHT temperatures and hold times on tensile properties of the 2¼Cr-1Mo steel.

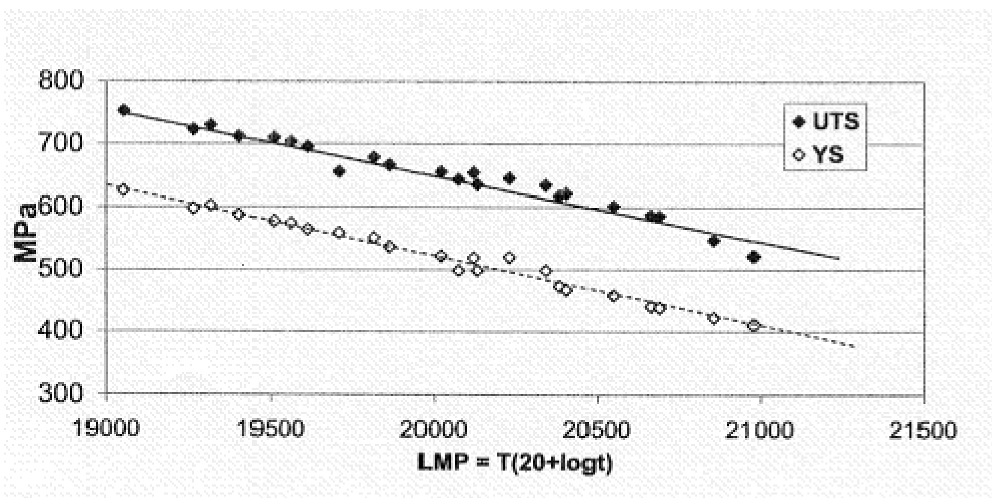

Figure 5 - Tensile Strength and Yield Strength of A-387, Grade 22, Class 2 vs. Larson-Miller Parameter

(LMP is given in terms of °C; This data includes one initial tempering cycle)

$$LPM = T(C + \log t) \tag{4}$$

Where:

T = °K

°K = °C + 273 for the LMP values in Figure 5

C = 20

t = time at temperature, hours.

SA-387, Gr. 22, Class 2 plates have a specified minimum tensile strength of 75 ksi (515 MPa) and 45 ksi (310 MPa) minimum yield strength at room temperature.

The following lists Larson-Miller parameters for 2, 3, 4, 5 and 6 inch (50, 75, 100, 125 and 150 mm) thick vessels when subjected to three PWHT cycles at 1275°F (690°C) for vessel fabrication (not including the initial temper):

T = 2 in. (50 mm): LMP = 36.05 x 10^3 (20.02 x 10^3, °C) [6 hours at 1275 °F (690°C)]

T = 3 in. (75 mm): LMP = 36.36 x 10^3 (20.14 x 10^3, °C) [9 hours at 1275 °F (690°C)]

T = 4 in. (100 mm): LMP = 36.57 x 10^3 (20.31 x 10^3, °C) [12 hours at 1275 °F (690°C)]

T = 5 in. (125 mm): LMP = 36.74 x 10^3 (20.41 x 10^3, °C) [15 hours at 1275 °F (690°C)]

T = 6 in. (150 mm): LMP = 36.78 x 10^3 (20.43 x 10^3, °C) [15.75 hours at 1275 °F (690°C)]

The 1¼Cr-½Mo and 1Cr-½Mo steels are ASME P-No. 4, Group 1 materials. ASME requires PWHT at 1200°F (649°C) of these materials with 1 hour/inch hold time for thicknesses up to and including 5 inches (125 mm), and 5 hours plus 15 minutes/in. (15 minutes/25 mm) for thicknesses exceeding 5 inches (125 mm) [2]. However, there has been a trend to higher PWHT temperatures to soften hard heat affected 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 1¼Cr-½Mo and 1Cr-½Mo steel vessels are generally stress relieved at 1225°F (663°C) minimum, typically 1250°F ± 25°F (677°C ±14°C) for at least three PWHT cycles (two for vessel fabrication and one for repairs) for service temperatures at or below 850°F (454°C) (below the creep range) and at 1275 ± 25°F (690°C ±14°C) above 850°F (454°C) (within the creep range).

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

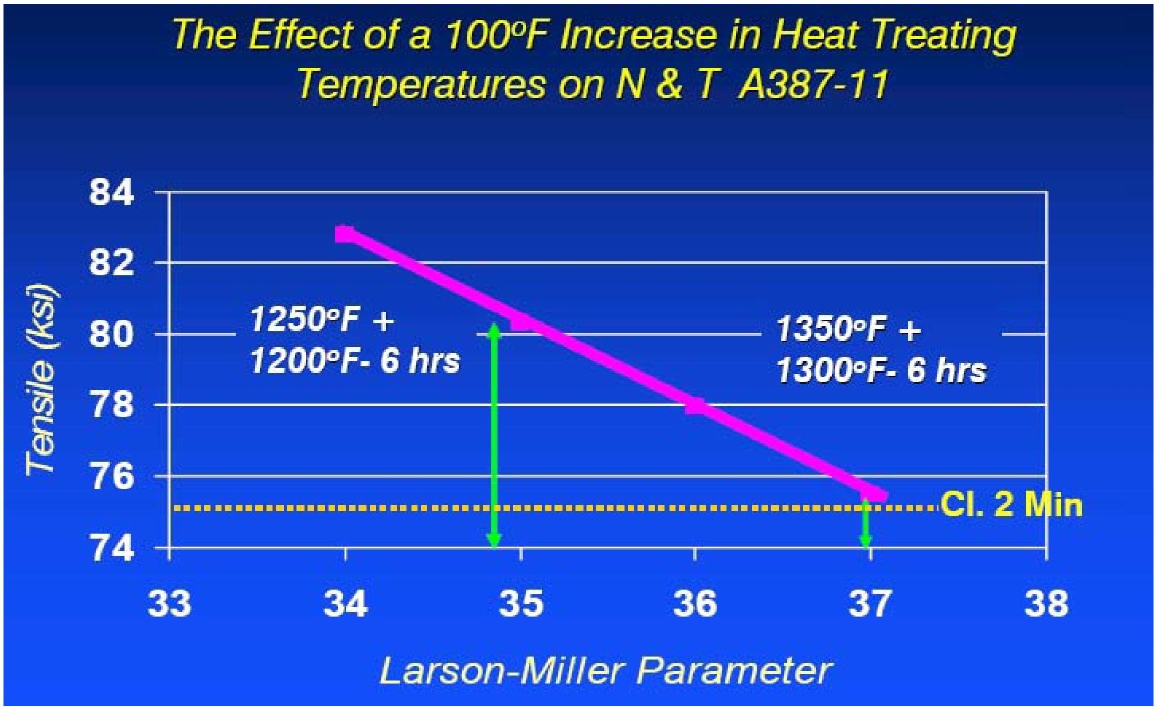

Figure 6 - The Effect PWHT Temperature on Tensile Properties of N&T SA-387, Gr. 11 Steel as a Function of Tempering Parameter (LMP)

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

The usual practice is to require tempering of the material at least 50°F (28°C) above the maximum PWHT temperature. However, each PWHT cycle is part of the total temper of the material; therefore, the final PWHT can also be used as the final temper, which reduces the maximum tempering parameter (LMP). In this case the final temper establishes the final properties of the material and, therefore, should be done only with prior agreement by the material manufacturer and by the vessel manufacturer, and with proper heat treatment controls by the vessel manufacturer. The test coupons should be stress relieved with the nominal temperature at or near the upper limit of the PWHT temperature and simulate the cooling rates that will occur in the vessel. The test specimens should be obtained from test coupons that have been heat treated in the same manner as the vessel materials during the vessel fabrication, preferably together with the vessel part which is stress relieved.

3.9 Other Factors

The specified minimum and maximum tensile properties in the material specification are established from typical production data that minimizes the rejection rate for the particular grade of steel and thickness. The steel producer will need to supply the material with tensile properties in the upper part of the tensile strength range and may need to increase the carbon content or some of the alloying elements to achieve the higher strength and reduce the risk of rejection. Thus, the higher tensile properties may result in higher carbon equivalents and require more preheat and/or other precautions by the vessel fabricator to avoid the risk of cracking in welded joints.

4 CURRENT PRACTICES IN USE OF HIGHER GUARANTEED TENSILE PROPERTIES

It is well recognized that there is a margin in tensile properties, particularly in thinner plates, which may warrant an increase in the minimum tensile properties for certain applications. Some examples of the use of higher tensile properties are:

(a) API Standard 650 permits a 5 ksi increase in the specified tensile properties for design of ambient temperature storage tanks.

(b) The French pressure vessel code, CODAP, permits the use of higher tensile properties in the calculations provided that the values have been established in the purchase order and are affirmed by the material producer in the test certificate with the specific inspection (3.1 or 3.2 of EN 10204).

(c) Some users and vessel fabricators have established in-house rules for use of higher tensile properties, when agreed to by the steel producer, for the design of pressure vessels when higher tensile properties are permitted by the local jurisdictions or by the applicable codes.

(d) Dual certification. Some of the A 516 and SA-516 plates supplied to service centers are dual certified as Grades 60/70, which limits the Grade 70 tensile strength to the maximum tensile strength of 80 ksi for Grade 60. The plates must also meet the more restrictive chemical composition limits of Grade 60 and Grade 70.

(e) Addition of a higher strength grade to the material specification. An example of this is SA-299, Grade B. The use of scrap metal in electric furnaces generally increases the residual elements (e.g., Cr, Mo, Cu) in the steel, which results in higher tensile properties for A 299. This justified a new grade B with 80 – 100 ksi specified tensile strength and 47 ksi minimum yield strength without a change in the specified chemical composition or heat treatment. Thus, a new Grade B of steel was created without adjusting the mill practices. The previous SA-299 was re-designated as Grade A with 75 – 95 ksi specified tensile strength and 42 ksi specified minimum yield strength. Although both grades have the same chemical composition limits, Grade A permits a leaner chemical composition (and a lower carbon equivalent) to meet its tensile properties.

The higher tensile properties should be agreed to, and guaranteed by, the steel producer. The steel producer must also know any additional requirements that may affect the material properties, such as the PWHT temperatures and times, notch toughness requirements and any limitations on chemical composition (other than those in the applicable material specification).

5 THE EFFECT OF HIGHER GUARANTEED TENSILE PROPERTIES FOR CARBON AND LOW ALLOY STEELS IN FABRICATION AND SERVICE CONSIDERATIONS

(a) Weldability. As discussed above, the guaranteed higher tensile properties may require the steel producer to increase carbon content or to increase the alloying elements to be able to meet the higher strength. This, in turn, may increase the carbon equivalent and decrease the weldability, requiring higher preheat temperatures or other precautions to avoid any potential cracking problems during welding.

(b) Service considerations. Higher tensile strength may necessitate an increase in the alloying elements to meet the higher strength requirement, which may result in higher carbon equivalent. This may also increase the hardness in welded joints and make the steel more susceptible to certain types of service induced cracking, such as hydrogen induced cracking (HIC) or stress oriented hydrogen induced cracking (SOHIC) of carbon steels. It is, therefore, important to consider any service related conditions and special requirements for the base metal and welded joints (such as the PWHT requirements and maximum hardness in welded joints) before deciding to specify higher tensile strength.

(c) The effect of multiple postweld heat treatments on tensile properties, particularly at higher PWHT temperatures. The effects of multiple heat treatments (temperature and time) are usually evaluated by use of Larson-Miller parameters (LMP). As shown in Figure 4, Figure 5 and Figure 6, and discussed above, a higher guaranteed tensile strength may limit the maximum PWHT time for construction of vessels of carbon steels and for low alloy steels (such as the SA-516, Gr. 70, and the 2¼Cr-1Mo and 1¼Cr-½Mo steels) unless the material is produced with even higher tensile properties by increasing the carbon equivalent (CE) or by quenching and tempering, to provide a greater margin for loss of strength due to PWHT.

(d) The effect of higher guaranteed tensile properties on notch toughness. Increasing the tensile strength should not necessarily reduce notch toughness. However, the impact test exemption curves in Section VIII, Divisions 1 and 2 also apply to welded joints (weld metal and HAZ); therefore, it would be necessary to evaluate the applicability of the impact test exemption curve for this material or require impact testing of the material and welded joints.

(e) Different allowable stresses for different vessel parts when using higher allowable stresses for different parts. There is no technical reason why one part of the vessel cannot be designed and constructed with a material with different tensile properties if it meets all other Code requirements.

(f) Potential problems in the bid stage. It may not be known in the bid stage what guaranteed tensile properties the steel producer will be willing to accept. The bidder/vessel contractor should preferably discuss and agree with the materials suppliers in the bid stage as to whether higher guaranteed properties are appropriate. However, higher guaranteed properties should not be used unless approved by the purchaser. Materials with higher guaranteed properties may not be acceptable for certain service conditions (e.g., wet H_2S service) as this may result in higher hardness in the HAZ of welded joints.

(g) P-No. designations and welding procedures. Increasing the minimum guaranteed tensile strength should not change the P-No. designation as the material would still be supplied to the same grade designation but with a higher guaranteed minimum tensile strength. However, it may require new welding procedure when different welding consumables are needed to meet the higher minimum tensile strength. For example, increasing the guaranteed minimum tensile strength for SA-738, Grade A from 75 ksi to 80 ksi may necessitate the use of E80XX electrodes instead of E70XX.

Likewise, increasing the specified minimum tensile strength for SA-738, Grade B from 85 ksi to 90 ksi may necessitate the use of E90XX electrodes instead of E80XX.

6 THE USE OF GUARANTEED STRENGTH PROPERTIES FOR CARBON STEELS AND CR-MO STEELS IN DESIGN AND CONSTRUCTION OF CODE VESSELS

6.1 Room Temperature Properties

Past experience indicates that there is a margin in tensile properties, particularly in thinner plates, that may permit the steel producer to guarantee higher minimum tensile properties at room temperature. The allowable design stresses at room temperature and up to 100°F should be established using the current Code rules.

6.2 Elevated Temperature Properties

The increased guaranteed tensile properties may result in some adjustments in chemical composition and heat treatment (Q & T instead of normalizing or N & T), particularly for Cr-Mo steels subject to multiple PWHT cycles at high PWHT temperatures. It would, therefore, be appropriate to require elevated temperature tension tests (in addition to the room temperature tension tests) to verify the room temperature and elevated temperature tensile properties agreed to between the purchaser and the steel producer and guaranteed by the steel producer. An alternative approach for certain grades of carbon steels (P-No. 1 materials) is suggested below.

Table 1 lists the tensile strength and yield strength ratios at room and elevated temperatures for some carbon steels (P-No. 1 materials) based on the values listed in Section II, part D, Tables U and Y-1. These ratios for the grades listed in Table 1 are essentially the same for the lower strength and higher strength grades in the same specification having the same chemical composition and heat treatment (as-rolled, normalized and quenched and tempered). These ratios are also the same for similar carbon steels in several different specifications (e.g., SA-285 and SA-516). It is, therefore, reasonable to use the same trend curve ratios to establish the allowable stresses for the same grades of carbon steels with higher guaranteed tensile properties at room temperature, provided that the increase in the guaranteed tensile properties is for the same grade of steel with the same heat treatment and is limited to no more than about 5 ksi. Based on the comparisons in Table 1 and the provisions in other standards (API 650), this appears a reasonable and more economical alternative approach for carbon steels as it eliminates the need for elevated temperature tension tests.

6.3 Properties in Creep Range

Section II, Part D, Table 1A lists allowable stresses based on time independent and on time dependent properties. No consideration is given in this report to higher guaranteed tensile properties for design of Code structures in the creep range.

6.4 Notch Toughness Considerations

The same notch toughness requirements should apply to materials with higher guaranteed tensile strength as for the same grade with originally specified values. However, consideration needs to be given to the following cases to comply with the Code requirements:

(a) Higher minimum average energy values based on increased yield strength when increasing the specified minimum yield strength to a higher value (Figure, UG-84.1 in Section VIII, Division 1, Figure 3.2 in Division 2).

(b) The mils lateral expansion (MLE) requirement instead of Charpy energy values for materials with guaranteed minimum tensile strength of 95 ksi (655 MPa) or higher.

6.5 Cr-Mo Steels

Typical low alloy steels used in thick wall construction are the SA-387 Cr-Mo steels. These steels are often used in thick wall pressure vessels that are subjected to multiple PWHT cycles at temperatures exceeding those in the ASME Code, Divisions 1 and 2.

The Code rules require tests on heat treated test coupons to simulate all fabrication and repair heat treatments to ensure that the required minimum tensile properties are being met in the base metal and welded joints. This results in high Larson-Miller parameters (LMP), which requires special consideration in production of such steels to achieve the desired properties. Although the Code does not require the materials manufacturer to guarantee elevated temperature properties, high PWHT temperatures and long hold times of thick wall vessels may make it difficult to guarantee the specified minimum tensile properties even at room temperature. These steels should require elevated temperature tension tests to verify the higher guaranteed tensile properties at temperatures above 100 °F (38 °C), in addition to the room temperature tension tests.

6.6 Stainless Steels

Several stainless steel producers have expressed no interest in guaranteeing higher tensile properties than those listed in the product specification. This should be included in a future project.

7 CONCLUSIONS AND RECOMMENDATIONS

Past experience and production data of carbon steel plates indicates that consideration may be given to allowable stresses based on higher guaranteed tensile properties than those listed in the product specifications for the carbon steels listed in Section II, part D for ASME Section VIII construction. However, additional precautions should be taken when the increase to a higher guaranteed minimum tensile strength leads to other concerns, such as higher carbon equivalents and reduced weldability, more difficulty in meeting the required tensile properties after PWHT, particularly after multiple PWHT cycles and increased rejection rate. The use of higher guaranteed tensile properties and allowable stresses should include the following considerations:

(a) The higher minimum guaranteed tensile properties by the steel producer at room temperature and at elevated temperatures should be subject to agreement by the steel producer and the purchaser.

(b) An increase in the guaranteed tensile strength may be used for carbon steels (ASME P-No. 1, Groups 1, 2 and 3 materials) and for commonly used Cr-Mo materials, such as the 2¼Cr-1Mo, 1¼Cr-½Mo and 1Cr-½Mo steels.

(c) Materials with higher guaranteed tensile properties for use at design temperatures above 100°F (38°C) should also be subjected to elevated temperature tensile tests to verify the guaranteed tensile properties at the intended use temperature.

(d) Any increase in guaranteed tensile strength of P-No. 1, Groups 1 and 2 materials should also require the test coupons to simulate all fabrication heat treatments.

(e) Consideration should also be given to weldability when the material is supplied with higher minimum guaranteed tensile strength.

(f) Consideration should be given to adding a new grade (e.g., Grade 75 to A 516) if it is feasible to do that with the same chemical composition of an existing grade (e.g., A 516, Grade 70). Another consideration is to add a new Supplementary Requirement to some material specifications that, subject to agreement between the purchaser and the supplier, would permit a 5 ksi increase to the specified minimum tensile strength, provided it meets all other requirements of the material specification and grade.

(g) Consideration may also be given to an alternative approach to permit a maximum increase in the guaranteed minimum tensile strength of ASME P-No. 1 materials not exceeding 5 ksi at room temperature without requiring elevated temperature tension tests, provided there is no change in the chemical composition and heat treatment. In that case the tensile strength and yield strength values for materials with increased guaranteed tensile properties may be based on the same trend curve factors as for the same specification and grade of steel in Tables U and Y-1.

(h) The use of materials with higher guaranteed tensile properties should be limited to design temperatures where time dependent properties do not govern the design.

8 RECOMMENDED CODE CHANGES

The following changes are recommended in Section VIII, Divisions 1, 2 and 3 for use of carbon and C-Mn steels (ASME P-No. 1 materials), 1¼Cr-½Mo and 1Cr-½Mo steels (P-No. 4, Gr. 1 materials) and 2¼Cr-1Mo steels (P-No. 5A, Gr. 1 materials):

(a) Permit the manufacturer, with the approval of the user, to specify minimum guaranteed tensile and yield strength properties which exceed the minimum values stated in the material specification for the material and grade. The maximum tensile strength shall not exceed the value listed in the material specification.

(b) The higher guaranteed tensile properties shall not be used at temperatures where time dependent properties govern the allowable design stresses.

(c) Tensile tests shall be in accordance with the applicable material specification and shall meet all requirements of the material specification for that grade, except for the minimum tensile strength and yield strength values.

(d) The tensile tests for use of the material at design temperatures above 100°F (38°C) strength shall be at the maximum design temperature for the structure.

(e) The provisions for impact test exemption shall not apply.

(f) Permit the manufacturer to derive allowable stresses for the material at the design temperature using the rules in the appropriate code section. If the allowable stress is governed by the tensile strength, the ratio of the increased allowable stress divided by the allowable stress from Section II, Part D shall not exceed the ratio of the increased tensile strength to the minimum tensile strength in the specification. If the allowable stress is governed by the yield strength, the ratio of the increased allowable stress divided by the allowable stress from Section II, Part D shall not exceed the ratio of the increased yield strength to the minimum yield strength in the specification.

(g) Tests on the tensile properties for comparison to the guaranteed minimum specified properties shall be done on coupons that have been exposed to all heat treatments, including the maximum number of expected PWHT cycles for the life of the vessel, that expose the material to a temperature greater that 900°F (482°C).

(h) If the maximum tensile strength does not exceed the values listed in the material specification, no additional requirements are necessary.

9 RECOMMENDED ALTERNATIVE CODE CHANGES FOR ASME P-NO. 1 MATERIALS WITH HIGHER GUARANTEED PROPERTIES NOT EXCEEDING 5 KSI

The following alternative changes in Section VIII, Divisions 1, 2 and 3 are recommended for P-No. 1, Group 1, 2 and 3 materials for use of higher guaranteed properties not exceeding 5 ksi (34.5 MPa) increase in the specified minimum tensile strength at room temperature:

The higher guaranteed tensile properties may be used only if the design temperature is limited to 50°F (28°C) below the temperature at which the allowable stress values in Section II, Part D are governed by time dependent properties, as indicated by the use of italics.

(a) Permit the manufacturer, with approval of the user, to specify minimum guaranteed tensile and yield strength properties as much as 5 ksi (34.5 MPa) above the values in the material specification. Require that all other requirements of the specification and the applicable construction code be met.

(b) Permit the manufacturer to derive elevated temperature tensile and yield strength values based on the same trend curve factors (ratios) as for the same specification and grade of steel in Tables U and Y-1. The trend curve factors can be derived from the tensile and yield strength values in Section II, Part D, Tables U and Y-1, respectively.

(c) Permit the manufacturer to derive allowable stresses for the material at the design temperature using the rules in the appropriate code section. If the allowable stress is governed by the tensile strength, the ratio of the increased allowable stress divided by the allowable stress from Section II, Part D shall not exceed the ratio of the increased tensile strength to the minimum tensile strength in the specification. If the allowable stress is governed by the yield strength, the ratio of the increased allowable stress divided by the allowable stress from Section II, Part D shall not exceed the ratio of the increased yield strength to the minimum yield strength in the specification.

(d) Tests of the tensile properties for comparison to the guaranteed minimum specified properties shall be done on coupons that have been exposed to all heat treatments, including the maximum number of expected PWHT cycles for the life of the vessel, that expose the material to a temperature greater that 900°F (482°C).

(e) If the maximum specified tensile strength does not exceed the value in the specification, no additional requirements are necessary.

REFERENCES

[1] ASME Section II, Part D, Properties (Customary), Materials, 2007.

[2] A 516 Steels, Technical Services Bulletin 778, Lukens Steel Co., Coatesville, PA, Rev. July 1993.

[3] K. Orie and C. Roper, The Effect of PWHT on Normalized Base-Metal Properties of ASTM A 516 Steel,Welding Research Council Bulletin 481, Part 1, May 2003.

[4] A. Wilson, C. Roper, K. Orie and F. Fletcher, Properties and Behavior of Modern A-387 Cr-Mo Steels, PVP-Vol. 239, 1992.

[5] Materials and Fabrication of 2¼Cr-1Mo, 2¼Cr-1Mo-¼V, 3Cr—1Mo & 3Cr-1Mo-¼V Steel Heavy Wall Pressure Vessels for High Temperature, High Pressure Hydrogen Service, API RP 934-A, 2nd. ed.

[6] Materials and Fabrication of 1¼Cr-½Mo Steel Heavy Wall Pressure Vessels for High Pressure Hydrogen Service, Operating at or Below 850 °F (454 °C), API RP 934C, 1st. ed.

[7] Technical Report on the Materials and Fabrication Issues of 1¼Cr-½Mo and 1Cr-½Mo Steel Pressure Vessels, API TR 934-D, 1st. ed. (under preparation).

[8] Recommended Practice for Materials and Fabrication of 1¼Cr-½MoSteel Pressure Vessels for Service Above 825 °F (441 °C), API RP 934E, 1st. ed. (under preparation).

[9] The Variation of Product Analysis and Tensile Properties – Carbon Steel Plates and Wide Flange Shapes, AISI Publications SU/18, SU/19 and SU/20, Sept. 1974.

[10] G. Masson, P. Bourges, L. Coudreuse, P. Toussaint and D. Cardamone, Considerations on PWHT Requirements and Their Effects, presented by Industeel, European Symposium on Pressure Equipment (ESOPE), Paris, 2007.

[11] J. Schick and K. Orie, API Round Table on 1¼Cr-½Mo Steels (A-387 Gr. 11), API Spring Refining Meeting, Atlanta, 2004.

[12] ASME Section VIII, Division 1, Rules for Construction of Pressure Vessels.

Appendix A - Comparison of Trend Curve Ratios and Allowable Stresses for VIII-1

Temp. °F	70	150	200	300	400	500	600	650	700	750	800	900	1000
SA-285, Gr. C													
UTS	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	54.3	50.5	41.1	31.7
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.987	0.918	0.947	0.576
YS	30.0	28.2	27.5	26.5	25.6	24.4	23.0	22.2	21.5	20.8	20.1	19.0	17.8
YS Ratio	1.0	0.940	0.917	0.883	0.853	0.813	0.767	0.740	0.717	0.693	0.670	0.633	0.593
Sa	15.7	15.7	15.7	15.7	15.7	15.7	15.3	14.8	14.3	*13.0*	*10.8*	*5.9*	
SA-516, Gr. 60													
UTS	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	59.3	55.1	44.8	34.6
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0				
YS	32.0	30.1	29.3	28.3	27.3	26.1	24.5	23.7	22.9	22.2	21.5	20.2	19.0
YS Ratio	1.0	0.941	0.916	0.884	0.853	0.816	0.766	0.741	0.716	0.694	0.672	0.631	0.594
Sa	17.1	17.1	17.1	17.1	17.1	17.1	16.4	15.8	15.3	*13.0*	*10.8*	*5.9*	*2.5*
SA-516, Gr. 65													
UTS	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	64.2	59.7	48.5	37.5
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.918	0.746	0.577
YS	35.0	32.9	32.1	31.0	29.9	28.5	26.8	25.9	25.1	24.2	23.5	22.1	20.8
YS Ratio	1.0	0.940	0.917	0.886	0.854	0.814	0.766	0.740	0.717	0.691	0.671	0.631	0.594
Sa	18.6	18.6	18.6	18.6	18.6	18.6	17.9	17.3	16.7	13.9	11.4	5.9	2.5
SA-516 Gr. 70													
UTS	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	69.1	64.3	52.3	40.4
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.987	0.919	0.747	0.577
YS	38.0	35.7	34.8	33.6	32.5	31.0	29.1	28.2	27.2	26.3	25.5	24.0	22.6
YS Ratio	1.0	0.939	0.916	0.884	0.855	0.816	0.766	0.742	0.716	0.692	0.671	0.632	0.595
Sa	20.0	20.0	20.0	20.0	20.0	20.0	19.4	18.8	18.1	*14.8*	*12.0*	*6.7*	*2.5*
SA-537, Cl. 1, 2½<t≤4"													
UTS	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	64.2	59.7	48.5	37.5
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.918	0.746	0.577
YS	45.0	42.3	41.2	39.8	38.4	36.7	34.5	33.4	32.2	31.2	30.2	28.4	26.7
YS Ratio	1.0	0.940	0.916	0.884	0.853	0.816	0.767	0.742	0.716	0.689	0.671	0.631	0.593
Sa	18.6		18.6	18.6	18.6	18.6	18.6	18.6	*16.9*				
SA-537, Cl. 1, t≤2½"													
UTS	70.0	70.0	70.0	69.1	68.4	68.4	68.4	68.4	68.4	67.7	65.4		
UTS Ratio	1.0	1.0	1.0	0.987	0.977	0.977	0.977	0.977	0.977	0.967	0.934		
YS	50.0	46.3	44.2	40.5	37.6	35.4	33.7	33.0	32.3	31.5	30.5		
YS Ratio	1.0	0.926	0.884	0.810	0.752	0.708	0.674	0.660	0.646	0.630	0.610		
Sa	20.0		20.0	19.7	19.5	19.5	19.5	19.5	*18.3*				
SA-537, Cl. 2, 2½<t ≤4"													
UTS	75.0	75.0	75.0	74.0	73.3	73.2	73.2	73.2	73.2	72.5	70.1		
UTS Ratio	1.0	1.0	1.0	0.987	0.977	0.976	0.976	0.976	0.976	0.967	0.935		
YS	55.0	51.0	48.6	44.5	41.3	38.9	37.1	36.3	35.5	34.6	33.5		
YS Ratio	1.0	0.927	0.884	0.809	0.751	0.707	0.675	0.660	0.645	0.629	0.609		

Temp. °F	70	150	200	300	400	500	600	650	700	750	800	900	1000
Sa	21.4		21.4	21.1	20.9	20.9	20.9	20.9	*19.6*				
SA-537, Cl. 2, t≤2½"													
UTS	80.0	80.0	80.0	78.9	78.2	78.1	78.1	78.1	78.1	77.4	74.8		
UTS Ratio	1.0	1.0	1.0	0.986	0.978	0.976	0.976	0.976	0.976	0.968	0.935		
YS	60.0	55.6	53.0	48.6	45.1	42.4	40.5	39.6	38.7	37.7	36.6		
YS Ratio	1.0	0.927	0.883	0.810	0.752	0.707	0.675	0.660	0.645	0.628	0.610		
Sa	22.9		22.9	22.6	22.3	22.3	22.3	22.3	*19.6*				
SA-738, Gr. A													
UTS	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	74.1	68.9	56.0	43.2
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.919	0.747	0.576
YS	45.0	42.3	41.2	39.8	38.4	36.7	34.5	33.4	32.2	31.2	30.2	28.4	26.7
YS Ratio	1.0	0.940	0.916	0.884	0.853	0.816	0.767	0.742	0.716	0.693	0.671	0.631	0.593
Sa	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	*19.6*				
SA-738, Gr. B													
UTS	85.0	85.0	85.0	85.0	85.0	85.0	84.2	83.0	81.0	78.3	74.6		
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	0.991	0.976	0.953	0.921	0.878		
YS	60.0	56.9	55.2	52.3	49.9	48.0	46.3	45.4	44.5	43.5	42.4		
YS Ratio	1.0	0.948	0.920	0.872	0.832	0.800	0.772	0.757	0.742	0.725	0.707		
Sa	24.3	24.3	24.3	24.3	24.3	24.3	24.1	23.7					
SA-299, t > 1 in.													
UTS	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	74.1	68.9	56.0	43.2
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.917	0.747	0.576
YS	40.0	37.6	36.0	35.4	34.2	32.6	30.7	29.6	28.6	27.7	26.8	25.3	23.8
YS Ratio	1.0	0.940	0.900	0.885	0.885	0.815	0.768	0.740	0.715	0.693	0.670	0.633	0.595
Sa	21.4	21.4	21.4	21.4	21.4	21.4	20.4	19.8	19.1	*15.7*	*12.6*	*6.7*	*2.5*
SA-299, t ≤ 1 in.													
UTS	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	74.1	68.9	56.0	43.2
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.917	0.747	0.576
YS	42.0	39.5	38.5	37.2	35.9	34.2	32.2	31.1	30.1	29.1	28.2	26.5	25.0
YS Ratio	1.0	0.940	0.917	0.886	0.855	0.814	0.767	0.740	0.717	0.693	0.671	0.631	0.595
Sa	21.4	21.4	21.4	21.4	21.4	21.4	21.4	20.8	*19.6*	*15.7*	*12.6*	*6.7*	*2.5*
SA-737, Gr. B													
UTS	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	69.4	66.7	63.0	52.7	
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.991	0.953	0.900	0.753	
YS	50.0	47.9	45.8	41.4	37.7	35.3	33.9	33.4	32.9	32.2	31.2	28.1	25.9
YS Ratio	1.0	0.958	0.916	0.828	0.754	0.706	0.678	0.668	0.658	0.644	0.624	0.562	0.518
Sa	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	*19.6*				
SA-737, Gr. C													
UTS	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	79.4	76.3	72.0	60.3	
UTS Ratio	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.993	0.954	0.900	0.754	
YS	60.0	57.5	55.0	49.7	45.2	42.3	40.7	40.1	39.5	38.6	37.5	33.7	31.0
YS Ratio	1.0	0.958	0.917	0.828	0.753	0.705	0.678	0.668	0.658	0.643	0.625	0.562	0.517
Sa	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	20.0				
SA-612, ½<t ≤1"													

Temp. °F	**70**	**150**	**200**	**300**	**400**	**500**	**600**	**650**	**700**	**750**	**800**	**900**	**1000**
UTS	81.0	81.0	81.0	79.4	79.4	79.4	79.4	79.4	79.4				
UTS Ratio	1.0	1.0	1.0	0.980	0.980	0.980	0.980	0.980	0.980				
YS	50.0		44.1	40.6	37.5	35.3	33.9	33.0	32.1				
YS Ratio	1.0		0.882	0.812	0.750	0.706	0.678	0.660	0.642				
Sa	23.1	23.1	23.1	22.8	22.6	22.6	22.5	22.0	*19.6*				
SA-105													
UTS	70.0		70.0	70.0	70.0	70.0	70.0	70.0	70.0	69.1	64.3	52.3	40.4
UTS Ratio	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.987	0.919	0.747	0.577
YS	36.0	33.8	33.0	31.8	30.8	29.3	27.6	26.7	25.8	24.9	24.1	22.8	21.4
YS Ratio	1.0		0.917	0.883	0.856	0.814	0.767	0.742	0.717	0.692	0.669	0.633	0.594
Sa	20.0	20.0	20.0	20.0	20.0	19.6	18.4	17.8	17.2	*14.8*	*12.0*	*6.7*	*2.5*
SA-765, Gr. I													
UTS	60.0		60.0	60.0	60.0	60.0	60.0	60.0	60.0	59.3	55.1	44.8	34.6
UTS Ratio	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.917	0.747	0.577
YS	30.0	28.2	27.5	26.5	25.6	24.4	23.0	22.2	21.5	20.8	20.1	19.0	17.8
YS Ratio	1.0		0.917	0.883	0.853	0.813	0.767	0.733	0.717	0.693	0.670	0.633	0.593
Sa	17.1	17.1	17.1	17.1	17.1	16.3	15.3	14.8	14.3	*13.0*	*10.8*	*5.9*	*2.5*
SA-765, Gr. II													
UTS	70.0		70.0	70.0	70.0	70.0	70.0	70.0	70.0	69.1	64.3	52.3	40.4
UTS Ratio	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.987	0.919	0.747	0.577
YS	36.0	33.8	33.0	31.8	30.8	29.3	27.6	26.7	25.8	24.9	24.1	22.8	21.4
YS Ratio	1.0		0.917	0.883	0.856	0.814	0.767	0.742	0.717	0.692	0.669	0.633	0.594
Sa	20.0	20.0	20.0	20.0	20.0	19.6	18.4	17.8	17.2	*14.8*	*12.0*	*6.7*	*2.5*
SA-765, Gr. IV													
UTS	80.0		80.0	80.0	79.1	79.1	79.1	78.8	77.7				
UTS Ratio	1.0		1.0	1.0	0.989	0.989	0.989	0.985	0.971				
YS	50.0	47.6	45.8	43.5	41.4	39.7	38.2	37.7	37.1				
YS Ratio	1.0		0.900	0.870	0.828	0.794	0.764	0.754	0.742				
Sa	22.9		22.9	22.9	22.6	22.6	22.6	22.5	22.2				
SA-333, Gr. 1													
UTS	55.0		55.0	55.0	55.0	55.0	55.0	55.0	55.0	54.3	50.5	41.1	31.7
UTS Ratio	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.987	0.918	0.747	0.576
YS	30.0	28.2	27.5	26.5	25.6	24.4	23.0	22.2	21.5	20.8	20.1	19.0	17.8
YS Ratio	1.0		0.917	0.883	0.853	0.813	0.767	0.740	0.717	0.693	0.670	0.633	0.593
Sa	15.7		15.7	15.7	15.7	15.7	15.3	14.8	14.3				
SA-333, Gr. 6													
UTS	60.0		60.0	60.0	60.0	60.0	60.0	60.0	60.0	59.3	55.1	44.8	34.6
UTS Ratio	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.988	0.918	0.747	0.577
YS	35.0	32.9	32.1	31.0	29.9	28.5	26.8	25.9	25.1	24.2	23.5	22.1	20.8
YS Ratio	1.0		0.917	0.886	0.854	0.814	0.766	0.740	0.717	0.691	0.671	0.631	0.594
Sa	17.1	17.1	17.1	17.1	17.1	17.1	17.1	17.1	15.6	*13.0*	*10.8*	*5.9*	*2.5*

NOTE: The allowable stresses in Table 1 shown in italics are governed by time dependent properties.

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ABBREVIATIONS AND ACRONYMS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASME ST-LLC	ASME Standards Technology, LLC
CE	Carbon Equivalent
DHT	Dehydrofenation Heat Treatment
HAZ	Heat Affected Zone
LMP	Larson-Miller Parameter
MLE	Mils Lateral Expansion
N & T	Normalizing and Tempering
PTCS	ASME Pressure Technology Codes & Standards
PWHT	Post-Weld Heat Treatment
Q & T	Quenching and Tempering
TMCP	Thermo-Mechanical Control Processing

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