STP-PT-033

DEGRADATION OF NOTCH TOUGHNESS BY A POST WELD HEAT TREATMENT (PWHT)

ASME STANDARDS TECHNOLOGY, LLC

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FOREWORD

This report is a natural follow-up to three major studies sponsored by the ASME that address a number of Post Weld Heat Treatment (PWHT) issues. It should be noted that early publications identified a PWHT as a highly desirable treatment for weldments. As will become evident from the review that follows and the summary of key observations, this recommendation is suitable for some steels and unsuitable for others. The purpose of the report is to provide information and recommendations for consideration by the ASME Code writing committees. The observations made in the various documents reviewed, summarized as "Key Observations," are the bases for the recommendations that are made for possible revisions in ASME Code rules for PWHT practices.

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ABSTRACT

This report is a review of the literature on post weld heat treatment of steels used in ASME Code construction. Based on this review, recommendations are made for use by the ASME Code writing committees on issues that these committees should consider. Examples of changes include the elimination of a mandatory PWHT for steels used in all lethal service and the use of fracture mechanics studies to justify departures from present ASME Code rules when a PWHT is not needed to address issues such as dimensional control and/or stress corrosion cracking.

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1 INTRODUCTION

This report is a natural follow-up to three major studies sponsored by the ASME. In the first, Stout [1] outlined the metallurgical factors concerning PWHT. The second Spaeder-Doty report [2] focused on ASME Code-related issues. The Uptis-Mokhtarian [3] studies on design margins for the Section VIII of the ASME Code are relevant to this report. This study includes a comparison of ASME PWHT rules with major European Codes. It is a “stand alone” document that is useful for assessing recommendations that are presented in the report.

The Appendix A contains a comprehensive review of ASME Code PWHT issues related to quenched and tempered steels including early references (1955) to what was referred to as “reheat cracking” or “stress relief cracking.” Note that it also reports on full size testing of pressure vessels fabricated from 100 Ksi yield strength steels and subjected to impact loading at cryogenic temperatures. It should be noted that these full scale tests were conducted on vessels that were fabricated from ½-inch thick plate; the relatively thin plate is beneficial in terms of ductile behavior.

The information provided in the Appendix A is part of the database used for developing recommendations contained herein.

It should be noted that early publications [4] identified a PWHT as a highly desirable treatment for weldments. As will be evident from the review that follows and the summary of key observations, this recommendation is suitable for some steels but unsuitable for others.

There are a number of other reports [5] through [30] that address key technical issues related to a PWHT. A review of the authors of these references points to large amounts of research conducted on the PWHT issues over about 60 years.

There are two primary reasons for a PWHT of weldments: (1) The reduction of residual stresses and (2) the reduction of hardness (usually by a tempering reaction) of the microstructure developed by welding. These two benefits are especially applicable to the early steels (often relatively high carbon in comparison to modern steels) used when welding replaced riveting as the preferred method of fabricating steel structures. There is no exact date for this replacement but the developments associated with the building of World War II Liberty Ships resulted in many developments including understanding the role of residual stresses, hydrogen cracking, and brittle fracture as related to fracture mechanics. Some engineers have taken the position that a PWHT should be applied to all/most weldments. These views may reflect “poor teaching” by the academic community.

However, the present understanding of the interrelationships among key factors such as design, notch toughness, and stress level including residual stresses makes it clear that the decision to require a PWHT should be based on the specific of component characteristics in relation to the service conditions.

A reduction in residual stresses can be important in preventing distortion following machining of weldments and in the prevention of stress corrosion cracking under specific conditions [5]. A PWHT can have the desirable effect of also out gassing hydrogen, but in certain steels, it may introduce reheat cracking and/or a reduction in notch toughness. As noted above, hardness is sometimes used as an index of susceptibility to stress corrosion in certain environments and may require that an otherwise satisfactory weldment be PWHT to reduce hardness below a critical level, often about 20 Rockwell C. In general, propensity for stress corrosion cracking increases with hardness level.

Other properties that are related to hardness include the creep-rupture properties. At high hardness levels, some steels exhibit notch weakening in stress rupture tests. Unpublished studies by the senior author of this report indicate that certain quenched and tempered high strength steels should not be used at service temperatures exceeding about 700° F. Studies by Swift [6] identified notch weakening in stress rupture tests as being associated with stress relief cracking. The present report does not focus on the effect of PWHT on service performance at temperatures where design is based on creep and creep-rupture properties. However, given the importance of this issue, a general overview is presented for steels specifically designed for enhanced creep and creep-rupture properties. The heat treating practices and steel chemical compositions that provide the optimum creep-rupture properties are often not compatible with good notch toughness. As will be covered in a subsequent section, PWHT may be needed to prevent brittle behavior and when there is susceptibility to stress corrosion cracking.

The undesirable effects of introducing reheat cracks is of special concern because the nature of these micro cracks is that they may not be detected by routine nondestructive testing such as radiography. Moreover, the reheat cracks are typically found in the coarse-grained region of the heat affected zone (HAZ) of a weldment. The properties (including notch toughness) and microstructure of the HAZ are strongly dependent on welding parameters such as preheat and heat inputs. Thus, the ASME Code should recognize the importance of a careful consideration of both the desirable and the potential harmful effects before mandating a PWHT.

The PWHT practice cannot only introduce cracks that may go undetected but also degrade notch toughness thereby reducing the tolerance for cracks.

It is also important to recognize that the microstructure and residual stress characteristics developed in the weldment are dependent on the specific chemical composition of both the base metal and weld metal and the welding parameters. In effect, there are an infinite number of combinations of HAZ characteristics; thus, it is easy to identify steels that are prone to reheat cracking but difficult to rule out with certainty that a grade of steel is fully immune to reheat cracking. As noted above, there are steels, modern or not, that require a PWHT to prevent susceptibility to brittle fracture and stress corrosion cracking.

Thus, it is clear that a PWHT is neither universally good nor bad. The purpose of the present report is to sort out these issues to provide information and recommendations for consideration by the ASME Code writing committees. The observations made in the various documents reviewed, summarized as "Key Observations," are the bases for the recommendations that are made for possible revisions in ASME Code rules for PWHT practices.

In 2006 [7], work from The Welding Institute (TWI) was presented reviewing some of the topics covered in this report. The Electric Power Research Institute (EPRI) has also conducted proprietary studies on PWHT issues.

2 APPLICATION OF IMPROVEMENTS IN TECHNOLOGY

Improvements in production practices for materials used in ASME Code applications, especially in terms of notch toughness, make a periodic review of ASME Code requirements highly desirable. It is especially important to keep the ASME Code practices cost-effective and consistent with the properties of modern steels.

The writings of Barsom [8] [9] provide clear practical guidelines on a methodology [9] to integrate notch toughness considerations into welding Codes. This methodology is summarized as a Fracture Control Plan (FCP). The Barsom writings are especially useful in that they serve as a teaching tool to bring engineers without a detailed background in fracture mechanics to a satisfactory level of understanding this complex field.

One historical note is that the 1954 studies [10] conducted after the catastrophic failure of Liberty ships during World War II found that residual stresses were not nearly as important as had been expected. The following is a direct quote [11] from the British Admiralty:

> "Residual stresses were originally thought to be an important contributory cause of the failure of welded ships, but extensive investigations have not confirmed this. It was inferred that in order to produce brittle failure in a ductile material, the residual stress would have to be triaxial—biaxiality would not be sufficient; but triaxiality could occur only locally, whereas the fractures were extensive.
>
> It was therefore concluded that residual stresses do not impair the strength provided the material is in a notch ductile condition, but may lead to brittle fracture if the material is in a notch brittle condition. Material in the latter condition would, however, be liable to brittle fracture even if there were no residual stresses."

It follows that residual stresses can be tolerated from a brittle fracture point of view if the steels exhibit sufficient notch toughness. Pellini studies [12] related brittle fracture and residual stresses to the Nil Ductility Temperature (NDT). Service at temperatures above the NDT typically minimizes brittle fracture.

There are also detailed practices that can be used to greatly reduce the need for a PWHT and characteristics of weldments that eliminate the need for this treatment. For example, controlled deposition, in conjunction with other limits, are routinely used in post construction ASME Codes such as the National Board Inspection Code (NBIC). The NBIC Code includes rules that permit the PWHT to be replaced with other practices.

By definition, a PWHT can include every heat treatment ranging from a sub-zero cycle to effect transformation of austenite to martensite in certain steels to a full anneal. The term PWHT has different meanings depending on the specific material and its intent. As already noted, intent can include dimensional stability following machining, prevention of stress corrosion cracking, and preventing brittle fracture.

Other issues include the deliberate additions of bismuth to facilitate the removal of flux following flux cored arc welding. Reheat cracking from the bismuth [13] addition are a form of liquid metal embrittlement.

It follows from the previous paragraph, that there is no single mechanism for reheat cracking. Lundin and Khan [14] have conducted fundamental studies of reheat cracking of the Cr-Mo steels; their work provides a comprehensive review and details the complexity of this subject. This work was preceded by the Erwin and Kerr work [15].

For steels produced to nominal yield strength of 100 Ksi, the mechanism [1] of reheat cracking is as follows:

(a) The welding operation produces a coarse-grained HAZ near the fusion line where the carbon and alloying elements are taken into solution at the high temperature.

(b) During cooling, transformation to martensite or lower bainite occurs with most of the alloying elements in solution. Thermal contraction during cooling sets up high tensile residual stresses.

(c) If the weldment is heated, the residual stresses induce plastic strains as the strength of the steel decreases.

(d) At temperatures ranging from 400° to 550° C (750° to 1025° F), the carbide-forming elements, such as Cr, Mo, Nb, and V, undergo precipitation as carbides, displacing Fe_3C. Some form a fine dispersion within the grains thus strengthening them, while a portion migrates to the grain boundaries to form films or nodules.

(e) Because the boundaries become weaker than the dispersion-hardened grains, most of the creep strain occurs in the boundary region, which are limited by the coarse-grain size.

(f) Rupture occurs in the boundaries by a triple point or a cavitation process.

Early considerations of the PWHT question by the ASME Code focused on high strength alloy steels, but it is clear that the PWHT issues embrace a wide range of steels as well as non-ferrous alloys. It is important to recognize that there are certain steels that are especially prone to reheat cracking; examples are SA 517, Grade F, and SA 737, Grades B and C. Listed below are ferrous alloys from a 1974 NBIC publication that demonstrate the wide range of steels that exhibit reheat (stress rupture) cracking.

Table 1 - Proceedings - Forty-Third General Meeting

The National Board of Boilers and Pressure Vessel Inspectors

May 6-10, 1974, New Orleans, LA

Nominal Designation	Observations
½Cr-1/2Mo-V	Cracked
1Cr-1Mo-V	Cracked
1 Cr-1/2Mo	Cracked
2 ¼ Cr-1Mo	Cracked
½Mo-B	Cracked
1 ¼Mn-1/2Mo	Borderline
0.8Mn-0.5Cr-0.2Mo-V-B	Cracked
1.7Cr-0.5Mo-V-B	Cracked
0.8Mn-0.8Ni-0.5Cr-0.5Mo-V-B	Cracked

As detailed in Lancaster [16], equations have been developed to quantify the effect of specific alloying elements on reheat cracking:

$$\text{Reheat Cracking Index} = \%Cr + 3.3\,(\%Mo) + 8.1\,(\%V) - 2$$

If the Index is above 0, reheat cracking may be observed. Note the powerful effect of vanadium on the susceptibility of steels to reheat cracking. Copper is also known to promote reheat cracking.

More recent reviews [7] indicate that reheat cracking should not be unexpected for a wide range of steels and other alloys. The reheat cracking issue is a potential issue with low alloys steels, the 300 series stainless steels, and super alloys such as Alloy 800H. Unpublished studies at U.S. Steel indicated that changes in chemical composition alone can reduce but not eliminate reheat cracking.

The format of this report is to supplement this background section with a summary of key documents and then outline issues that the authors recommend the ASME Code consider for possible revision. Before discussing these key documents, it is useful to outline key elements of notch toughness as presented by Barsom [8].

3 BASICS OF NOTCH TOUGHNESS [8]

The following graph is presented on the cover of the Barsom- Rolfe text:

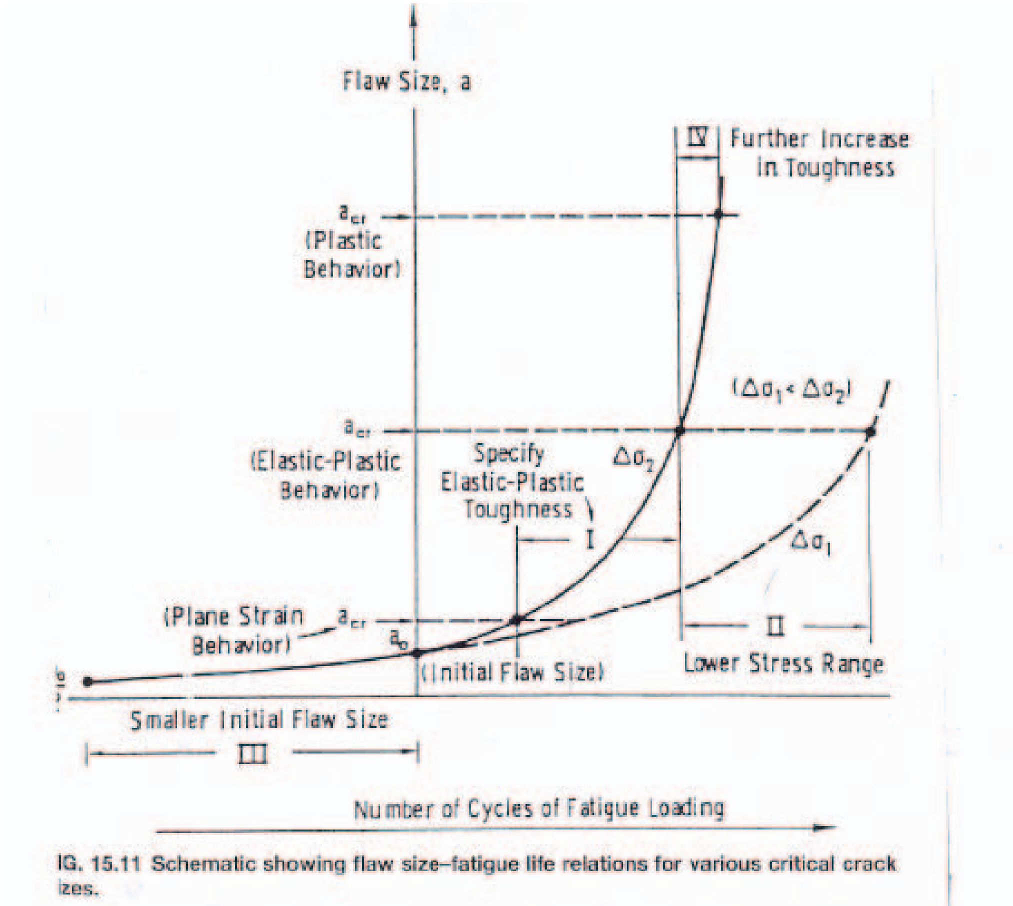

Figure 1 - Flaw Size-Fatigue Life Relations for Various Critical Crack Sizes

Inspection of this schematic graph shows the following:

(a) The number of cycles of fatigue loading (horizontal axis) that can be sustained is dependent on the critical flaw size (vertical axis) and the stress levels; two stresses ranges are shown, sigma 1 and sigma 2. The critical flaw size, a, is in turn controlled by the level of toughness and stress level. For a given stress, the critical flaw size increases with toughness level. Toughness is strongly dependent on strain rate and temperature especially for the type of steels used in structures. Strain rate effects are much higher for low strength steels than for high strength steels; above 140 Ksi the effect is small. Special Note: The development of high performance (low carbon martensitic microstructure) steels makes the availability of steels that exhibit both high strength and excellent notch toughness possible; see ASTM A709.

(b) Specific observations include:

(1) A reduction in the initial flaw sizes increases the number of fatigue cycles in a substantial fashion. See Zone III on graph. Producing materials with very small sizes of imperfections is costly and is used only in limited applications such as jet engines. It is also important to

recognize that fabrication is a likely source of imperfections especially for welded construction.

(2) Reduction in the stress range level increases the number of fatigue cycles that can be sustained. Because fatigue crack growth rate is proportional to the stress range raised by the power of 3, a small reduction in stress range has a marked effect on fatigue life. Underestimating the level of these tensile stresses can result in a substantial reduction in the life of the component.

(3) When the toughness is low and the stress state described as "plane strain," the critical flaw size is very small. This is the condition for brittle fracture and a catastrophic event. Plain strain is associated with large thickness of the product. Brittle fracture can occur in relatively tough steels with severe triaxial stress loading.

(4) When the toughness is moderate and the stress state described as "elastic plastic," a relatively large number of fatigue cycles are required for failure. This is the level of toughness that is required in most construction Codes such as bridges.

(5) Increasing the toughness to a stress state described as "plastic" has only a modest effect on increasing the number of stress cycles to failure. However, this stress is a state that allows for a special condition where "crack arrest" is a possibility. Crack arrest is used in the design of deep diving submarines. The technology for crack arrest is proposed for certain critical components of vessels, where failure could result in a catastrophic event. An example of an application where crack arrest technology might be applied concerns vessels containing liquefied flammable gases where a large release could result in a vapor cloud, which if ignited, might result in a number of fatalities.

(c) Other Information

(1) The role of PWHT on the diagram is complex and difficult to predict. A PWHT may be required to mitigate stress corrosion cracking. A PWHT can under certain conditions improve fatigue life. However, it is unlikely that a PWHT will eliminate residual stresses completely. There are special practices that can be used to improve fatigue life by selected use of residual stress. However, the necessary practices, such as peening, are difficult to apply on a consistent and routine basis.

(2) Crack arrest is affected by the rate of energy released; for high levels of energy release, crack arrest cannot be achieved by simply specifying the use of high toughness steels.

4 STOUT WRC 302 [1]

This 1985 review of PWHT issues provides a comprehensive review of the metallurgical effects of a PWHT. The following is a brief summary of the section, "Basis for defining conditions requiring a PWHT":

(a) A PWHT can be a "mixed" blessing, because it can be beneficial by reducing residual stresses and hardness but at the expense of notch toughness.

(b) The need for PWHT treatment can be offset by practices that minimize the region in the weldment where reheat cracking occurs and by techniques that reduce the propensity for reheat cracking. Specific factors include 1) controlled weld bead size thereby limiting grain coarsening, 2) keeping hydrogen levels below the threshold values for delayed cracking, 3) quality control that avoids stress raising details of weldments, 4) good inspection practices, and 5) practices that reduce the level of residual stresses.

(c) Addressing the specific service requirements is critical for assessing the needs for a PWHT. The assessment includes the service stresses and lowest temperature, rate of loading, and consequence of failure.

(d) Weldment characteristics such as section thicknesses, tensile properties, fracture toughness, maximum flaw size, and weld contours all play important roles in decisions on the PWHT requirements.

5 SPAEDER-DOTY WRC 407 [2]

WRC 407 included recommendations for action by ASME Code committees; any action that has been taken is shown in parentheses. The conclusions from this report are as follows:

(a) The present rules are generally suitable for relatively high carbon steel that are not produced to high notch toughness requirements. Modern steelmaking practices make it practical to produce steels with relatively high notch toughness.

(b) The present rules are not well-suited for steels produced with high notch toughness requirements. For such steels, a PWHT is often not necessary from a service performance standpoint and might actually degrade the properties of the steel. There are, however, specific conditions in which a post-weld treatment may have to be imposed because of other considerations such as corrosion effects.

(c) The specific requirements for trade-off between time and temperature that are permitted for P-1 in Table UCS 56.1 steels are not consistent with the literature data. Similar problems exist for some of the minimum PWHT temperatures. This review should be made by ASME B31 and P&PV committees so that there is consistency in the PWHT practices. (This task has been undertaken by EPRI, but the results are not in the public literatures.)

(d) The development of new requirements that would relate PWHT requirements to notch toughness considerations would allow for economical fabrication for some pressure vessel applications. (This task has been undertaken by both the TWI and its sister organization, The Edison Welding Institute).

(e) The development of new rules should be based on studies that quantify the effects of PWHT on residual stress reduction, changes in notch toughness requirements, and the effect of PWHT treatment on the properties of the weldment.

Specific recommendations are listed below; more detail is presented in WRC 407.

(a) Re-examine the present minimum PWHT temperatures. (It is proposed that the ASME Code use the PWHT temperatures presented in the AWS Standard Welding Procedures.)

(b) Re-examine the thickness of various materials requiring PWHT. (This task has been addressed by both EPRI and the TWI; ASME Code committees need to obtain reports developed by the respective organizations.) See Reference [3]; it presents information on European Codes.

(c) Re-examine alternate PWHT requirements in Tables UCS-56.1 and AF-402.2.

(d) Promote the use of tempering parameters (such as the Larson-Miller parameter) for combining various PWHT cycles needed to simulate the cycles for fabricating vessels.

6 TWI STUDIES [19]

The information developed by the TWI is often proprietary; however, an excellent review of the important factors related to the PWHT issues are presented in the Job Knowledge Series [19], which is available on their website. There are also examples in proprietary reports outlining a protocol for using fracture mechanics to justify exemption from PWHT rules related to thickness.

7 EPRI STUDIES [21]

EPRI evaluated the properties of weldments made on a variety of materials (P No. 1, P No. 3, P No. 4, and P No. 5A). These studies suggest a reduction in the present requirements for the P No. 1 steels. Studies on the alloyed steels also suggest a need to revise the PWHT requirements.

8 STUDIES ON STEELS USED IN THE CREEP RANGE

The 9Cr-1Mo-V steel, designated as P91, is a martensitic-type low carbon steel that exhibits enhanced creep and creep-rupture properties that are achieved by a combination of alloy composition and heat treatment. These steels are referenced in Section IX of the ASME Code as creep-strength enhanced ferritic (CSEF) [22]. Specifically developed for service at temperatures where design stresses are limited by the creep and creep-rupture strengths, this steel exhibits poor notch toughness and susceptibility to stress corrosion cracking in the as-welded condition. In addition, the metallurgical characteristics require careful control of welding parameters to minimize hydrogen-induced cracking. P91 is only one example of steels that are part of the CSEF steels being promoted for service in the creep range.

Typical welding procedures employ relatively high preheat and control of interpass temperature. They also mandate a PWHT shortly after the completion of the weldment. These controls reflect the transformation characteristics of the steel in which the steel must be cooled sufficiently following welding to effect full transformation to the martensitic microstructure. A further complication is that the PWHT must be at a temperature that does not exceed the lower transformation temperature, A_1. This requirement adds restrictions to the composition limits to welding consumables. The details about the various factors that require careful consideration are outlined in proprietary reports from by EPRI. Newell's paper provides a general overview of the issues.

It also evident that a PWHT is often necessary to prevent notch weakening in stress rupture testing for steels such as 2-1/4Cr-1Mo steels produced to relatively high yield strengths. In general, welding practices need to use PWHT practices that keep the PWHT temperature below the lower critical for both the base metal and the welding consumables [22].

Lundin studies [14] [23] clearly identify key factors affecting the creep and creep-rupture properties of Cr-Mo steels.

9 KEY OBSERVATIONS

The following are observations that form the basis of the recommendations to the ASME shown in the next section:

(a) A reduction in residual stresses is not required to prevent brittle fracture provided that service temperatures are above the NDT.

(b) A PWHT for a number of steels often introduces reheat cracks, and for certain steels, reduces notch toughness.

(c) Prolonged PWHT cycles can reduce the strength level of some steels to levels below that specified in the original purchase specification [27].

(d) Prevention of brittle fracture can be achieved in the as-welded condition by requiring sufficient notch toughness at the lowest service temperature for stresses corresponding to the maximum yield strength of the weldment and the maximum flaw size as defined by the non-destructive inspection practices used as the basis for determining the sufficient toughness.

(e) There are proprietary TWI studies demonstrating the use of fracture mechanics to justify exemptions from present ASME Code requirements for a PWHT based on thickness.

(f) Minimum PWHT temperatures presented in AWS Standard Welding Procedures are sometimes greater than the minimum presently specified in ASME Code requirements.

(g) Based on the wide variety of steels that are shown to have susceptibility to reheat cracking, it is difficult to rule out this form of cracking. This statement reflects the large number of combinations of residual stress patterns in the HAZ as a result of the effects of welding parameters on the characteristics of this zone.

(h) Changes in properties based on time and temperature follow a Larson-Miller type of parameter.

10 RECOMMENDATIONS FOR ASME CONSIDERATION

(a) The ASME Code should limit the mandate for a PWHT to those situations where there is a benefit to the service performance of the vessel. This requirement is especially applicable to steels produced to relatively high carbon content, which are found in older vessels in need of repair.

(b) The above recommendation requires eliminating a mandatory PWHT for all steels used in lethal service.

(c) The definition of lethal service should be expanded to include vessels containing liquefied combustible substances where a leaking vessel could produce a vapor cloud type of safety issue.

(d) The ASME Code should provide guidance for welding steels such as P91. This steel by virtue of its metallurgical characteristics requires a PWHT because of sensitivity to stress corrosion cracking and brittle fracture in the as -welded condition. There are also steels that exhibit notch weakening in stress rupture tests when produced to relatively high yield strengths. The issues related to service in the creep range are not addressed in detail in this report.

(e) The recommendations that have appeared in previous studies indicated a need to review the minimum PWHT temperatures for P4 and P5 type steels. It is proposed that the ASME Code consider making the minimum temperatures consistent with those prescribed in the AWS Standard Welding Procedures.

(f) The ASME Code should consider making provisions to mitigate the PWHT requirement when a fracture mechanics analysis shows that the structures have sufficient notch toughness in the base metal, HAZ, and weld metal at the lowest service temperature to tolerate the maximum flaw size at the yield strength of the weldment in the as-welded condition. This recommendation requires developing a protocol for carrying out this task.

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APPENDIX A

Origins of Post Weld Heat Treating and Origins of Reheat Cracking Issues in ASME Code Rules for Quenched and Tempered Steels

by W.D. Doty and C.E. Spaeder, October 21, 2007

In 1951 at an ASME conference in Tulsa, OK, Bibber, Hodge, Altman, and Doty presented a paper titled, "A New High-Strength Alloy Steel for Welded Structures" [31]. The steel was designated USS "T-1" Steel and was characterized by yield strength levels of 100,000 psi and above. The results of extensive testing of ½-inch and 1-inch thick plates in the unwelded and welded conditions were presented. Much attention was given to the determination of notch toughness and fracture appearance transition temperatures.

The subject of residual stress from welding and the need for post weld heat treatment (PWHT) were addressed in this paper. It was concluded that the transition temperatures were so low that the use of welded "T-1" steel should render stress relief annealing unnecessary for weldments at atmospheric temperatures and that weldments would be able to endure the necessary local redistribution of stresses. Therefore, studies were not conducted involving PWHT.

The 1951 paper described the use of "T-1" steel for buckets and dipper sticks for power shovels used in severe service in iron ore mines in northern Minnesota where service temperatures are sub-zero during winter operations. This application made use of all the characteristics of "T-1" steel including its excellent toughness in the as welded condition at extremely low temperatures. Many failures of shovel parts had occurred in this service prior to the use of "T-1."

In 1951, the ASME Boiler and Pressure Vessel Code Committee first recognized the use of quenched and tempered high strength steel by adopting Code Case 1134. This Code Case permitted the construction of small seamless vessels. The Code Case required a streamline vessel and prohibited welding.

In 1954 and 1955, Chicago Bridge and Iron Co. together with U.S. Steel undertook a test program to be used as a basis to seek ASME Code recognition of quenched and tempered high strength steel for welded applications. The test program was a follow-up to U.S. Steel's development of "T-1" steel. Their results of the test program were described in three papers, "Design of Welding Pressure Vessels Using Quenched and Tempered Steel" by Zick [32], "Suitability of Quenched and Tempered Steels for Pressure-Vessel Construction" by Bibber [33], and "Properties and Characteristics of a Quenched and Tempered Steel for Pressure Vessels" by Doty [34].

The Bibber paper [33] described the results of burst tests and drop impact tests on pressure vessels. Burst tests were conducted on five pressure vessels, two of which were in the as-welded condition, and three of which were in the PWHT condition. Drop weight tests were also conducted on four pressure vessels; two of which were in the as-welded condition and two which were in the PWHT condition. The vessels were cylindrical in shape with a tangent length of 16 feet, a diameter of 4 feet, a wall thickness of ½ inch, and hemispherical heads.

E12015 low-hydrogen electrodes (Ni-Mo-V) were used to fabricate the as-welded vessels whereas E9015 low hydrogen (Mn-Ni) electrodes were used to fabricate the PWHT vessels. The electrode selection reflected the excellent properties of Ni-Mo-V weld metal in the as-welded condition, but it is drastically embrittled by a PWHT. The vessels were tested at temperatures in the range -22 to -50F using a calcium-chloride brine.

For the burst tests, the vessels were mounted in a horizontal position on a test stand, and tested at temperatures in the range -42 to -50F. For the drop impact tests, the vessels were mounted in a horizontal position and rested on rockers 14 feet apart and below a 149 foot guide tower for a tup made from a 26,700 pound ingot. The tup was dropped from various heights, the greatest being 122 feet. The pressure in the vessel at the time of impact was in the range 1800 to 1880 psi and the temperature in the range -22 to -41F.

In all cases, failure in both the burst and drop-impact tests was characterized by 45-degree shear fractures indicating that ductile failure occurred at all the test temperatures investigated. The Bibber paper concluded that there were no significant differences in the performance between the vessels tested in the as-welded condition and the vessels tested in the PWHT condition. This confirmed the belief that if a material has sufficient toughness at the operating temperature, a PWHT is not necessary.

The Doty paper [34] presents the results of a test program designed to determine tensile properties, notch toughness, metallurgical characteristics, welding characteristics, and cutting characteristics of the ½ inch plate used for the vessel tests reported in the Bibber paper.

In 1955, the ASME Boiler and Pressure Vessel Code Committee recognized by Code Case No. 1204 the acceptance of the quenched and tempered "T-1" steel (subsequently ASTM A517 Grade F) for welded construction, but mandated PWHT for welded construction for product greater than ⅝-inch thick. Presumably, it was difficult to accept that the steel could be welded and have good notch toughness and not require a PWHT for restoration of toughness, which was the experience with commonly used C and C-Mn steels. ASME subsequently recognized other quenched and tempered steels such as NAXTRA 100 by Code Case 1297 (subsequently Grade A of ASTM A517) and SSS 100 by Code Case 1298 (subsequently ASTM Grade E of ASTM 517). These Code Cases had the same ⅝-inch thickness limitations as Code Case 1204.

A paper in 1965 by Doty [35] described the results of explosion bulge tests of butt-welded specimens of ½ and 1-inch thick "T-1" plates (ASTM A517 Grade F) and butt-welded specimens of ½ and 1-inch thick "T-1" type A plates (ASTM A517 Grade B) and a paper in 1968 [36] describes the results of additional explosion-bulge tests of butt-welded ½, 1 and 2-inch thick "T-1" plates. Shielded metal-arc welded plates in the as-welded condition, showed fracture-transition-elastic (FTE) temperatures in the range -30 to -40F and submerged-arc-welded plates in the as-welded condition, with or without weld reinforcement, showed FTE temperatures in the range -10 to -60F. PWHT had a negligible effect on the FTE temperature of welded plates with the weld reinforcement removed but significantly raised the FTE temperatures of welded plates with the weld reinforcement in place.

Beginning in 1957, welding fabricators of alloy steel quenched and tempered structural and pressure vessel application reported to steel producers and users that base-metal coarse-grained HAZ of welds were crack free in the as-welded condition, but cracks were present after PWHT.

Such cracking had not been observed in the studies described in References [32], [33] an [34]. In 1957, a fabricator described such cracking at the toes and roots of fillet welds in an "egg crate" structure made entirely of ¼-inch "T-1" steel plate and fillet welds.

Studies by U.S. Steel revealed that such stress-rupture cracks developed in highly-restrained weld assemblies of high yield strength steels usually containing Cr and Mo as major alloy elements. The "Gleeble" device for duplication and testing of weld-heat-affected zone susceptibility was very useful to U.S. Steel in evaluating the effect of steel composition and stress rupture cracking. It became apparent that no composition range, within the compositions listed in A517, was completely immune to PWHT cracking. This observation reflects the complex nature of the competing effects of microstructural changes and stress relaxation.

Many technical papers have been published on the subject of stress-relief cracking susceptibility in the base-metal HAZ of welded steels or in the weld metal when subjected to PWHT. References [37], [38], [39], [40] and [41] are some of these papers. In 1974, Doty described [42] such cracking in some representative steels. In 2000, the British concluded after much study, that the famous John Thompson, forged and welded Cr-Mo-V steel vessel, which had been post-weld heat treated, failed on hydro test as a result of reheat cracking [43].

Beginning in 1958, U.S. Steel warned users of “T-1” steel that a PWHT could result in reheat cracking. The brochure, “How To Weld T-1,” was used to convey information on cracking.

In closure, recognition should be given to the significant differences in the notch-toughness of carbon or carbon-manganese steels and the notch-toughness of relatively low-carbon quenched and tempered high strength alloy steels. In the case of carbon and carbon-manganese steels, there is usually a loss of toughness as a result of welding, whereas in the low-carbon quenched and tempered alloy steels, toughness after welding is still good, even to much lower service temperatures than those for carbon and carbon-manganese steels. Thus, plastic deformation can occur at points of stress concentration during a required hydro test and in the presence of residual stresses from welding. A reduction in residual stresses by PWHT is not necessary for plastic deformation. In addition, the risk of stress-relief cracking is also eliminated by omitting a mandatory PWHT. This view should be considered for eliminating the PWHT requirements in Part UHT, Table UHT-56 in ASME Section VIII, Division 1 for SA 517 and SA592 steels.

APPENDIX B

Excerpt from USX Brochure on Welding "T-1" Steel [44]

Rule 4

Use Caution in Applying Postweld Heat Treatment

Postweld heat treatment as used in this book means any heat treatment subsequent to welding provided the heat treatment temperature exceeds 700°F but does not exceed that used by the steel manufacturer to temper the steel. Generally, welded structures of ISG Plate "T-1" Steels should not be given a postweld heat treatment. Loss of weld-metal and heat-affected-zone toughness and stress-rupture cracking may occur as a result of such a treatment. Many modern steels for welded construction, such as the "T-1" Steels, are designed to be used in the as-welded condition. Unlike some carbon steels, the postweld heat treatment process can have an adverse effect on such alloy steels. Those alloying elements that contribute most significantly to the attainment of high strength and notch toughness in alloy steels and in weld metal joining these steels are usually the alloy elements that have an adverse effect when weldments of such steels are postweld heat treated.

The decision to use a postweld heat treatment with the "T-1" Steels, as for other steels, should only be made when the user of the steel can be sure that the anticipated benefits from the heat treatment are needed and will be realized and that possible harmful effects can be tolerated. Postweld heat treatment is necessary for some applications in which the steel used has inadequate notch toughness after cold forming or welding, for some applications in which the steel after cold forming or welding must retain close dimensional stability during machining, or for some applications in which high residual stresses from cold forming or welding might lead to stress corrosion cracking. When the application is one of these, careful consideration should be given to whether or not the "T-1" Steels are appropriate steels to use, and whether the possible harmful effects of postweld heat treatment can be tolerated. Furthermore, careful consideration should be given to whether or not the particular design, fabrication and inspection should be proven by testing one or more prototypes in the as-welded and postweld heat treated conditions.

The results of notch-toughness tests have shown that postweld heat treatment in the temperature range 950 to 1200°F may impair weld metal and heat-affected-zone toughness; the extent of impairment depends on chemical composition, treatment temperature and time at temperature, and is greater with slow cooling as in stress relieving. Furthermore, when welds in the "T-1" Steels, as with many other alloy steels, are given a postweld heat treatment above about 950°F, intergranular cracking may occur in the grain-coarsened region of the heat-affected zone of the base metal. The intergranular cracking occurs by stress rupture, usually in the early stage of the postweld heat treatment. Susceptibility to this cracking increases with increasing weld restraint and with increasing severity of zones of stress concentration. In addition, chromium, molybdenum and vanadium are major contributors to this crack susceptibility, but other carbide-forming elements assist. The precipitation of carbides during the elevated-temperature stress relaxation alters the delicate balance between resistance to grain boundary sliding and resistance to deformation within the coarsened grains of the heat-affected zone. The cracking is variously known as "stress-rupture cracking", "stress-relief cracking," and "reheat cracking."

Some procedures and techniques that have been used individually or in combination to minimize such cracking are as follows:

1. Choose weld joint design, weld location and the sequence of assembly of members by welding that will minimize weld restraint.

2. Choose the weld joint design and contour the weld finish to minimize zones of stress concentration. Butt welds are preferable to fillet welds. Remove backing strips if used, and then back weld.

3. Use weld metal having elevated-temperature strength significantly lower than that of the heat-affected zone of the steel during the postweld heat treatment.

4. Surface or butter in the toe area of fillet welds. One or more adjacent stringer beads are deposited in the anticipated toe area for the desired fillet weld. These surfacing or buttering welds should be made with low-strength weld metal. The desired fillet weld should then be made such that at least half a bead width of the surfacing welds remains exposed as described in the discussion on *Weld Restraint*.

5. Air hammer peen the welds as previously described in the discussion on *Weld Restraint*.

CAUTION: None of these procedures or techniques can be guaranteed either individually or in combination to eliminate the possibility of stress-relief cracking in any particular application.

If postweld heat treatment must be performed, the temperature should not exceed that used by the steel manufacturer for tempering the steel. A postweld heat treatment at about 50°F lower than the tempering temperature is desirable to avoid lowering the strength of the steel.

It is also recommended that the weldments be non-destructive tested (NDT) both prior to and after the postweld heat treatment to establish if any cracking is present. The NDT may include liquid penetrant, magnetic particle, x-ray and ultrasonic testing.

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