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THE INFLUENCE OF POST-WELD HEAT TREATMENT AND WELD PREHEAT ON BRITTLE FRACTURE

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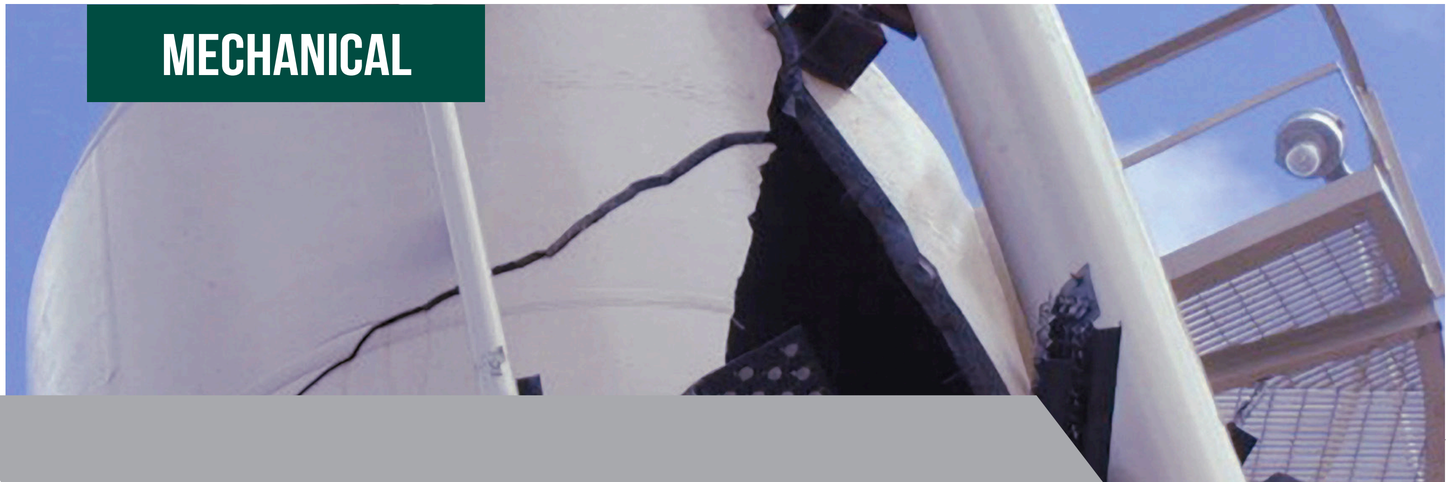

THE INFLUENCE OF POST-WELD HEAT TREATMENT AND WELD PREHEAT ON BRITTLE FRACTURE

BY: PHIL PRUETER, P.E.

INTRODUCTION

Post-weld heat treatment (PWHT) and weld preheat can have a significant influence on the risk for brittle fracture in welded components. This topic is particularly relevant given the recent changes in PWHT requirements for P-No. 1 carbon steel materials in the 2014 Edition of ASME B31.3, *Process Piping* [1]. Specifically, PWHT is no longer a mandatory requirement for any wall thickness, provided that multi-pass welding is employed for thicknesses greater than 3/16 of an inch and a minimum preheat of 200°F is implemented for thicknesses greater than 1 inch. Detailed fracture mechanics analyses have shown that the lack of a mandatory PWHT requirement for thicker carbon steel components may result in a significant increased risk for brittle fracture failures due to near-yield level weld residual stresses. Given the concern throughout industry regarding potential brittle fracture failures, this updated PWHT guidance is examined in this article, and commentary on the potential reduction in notch toughness due to PWHT is provided based on published data. This article provides an abbreviated summary of recently published Reference [2], wherein a rigorous approach to generate impact test exemption curves and to determine appropriate Charpy impact test temperatures by establishing separate as-welded and PWHT curves is provided.

These comparisons use the Fracture Toughness Master Curve (Master Curve), as documented in recently published Welding Research Council (WRC) Bulletin 562 [3]. The increased propensity for brittle fracture in as-welded components as opposed to PWHT components is clearly highlighted using this methodology. The Master Curve, in conjunction with the elastic-plastic fracture mechanics employed in API 579-1/ASME FFS-1, *Fitness-For-Service* (API 579) [4], provides a means to quantify the crack-driving force associated with weld residual stress and is anchored in state-of-the-art fracture mechanics. Lastly, commentary on the appropriateness of the current ASME B31.3 PWHT requirements is offered, and the effectiveness of using weld preheat in lieu of PWHT as permitted in the National Board Inspection Code (NBIC) [5] is examined using computational weld analysis.

PWHT FUNDAMENTALS

Weld residual stresses are a product of highly localized transient heat input that occurs during the welding process. As discussed in [6], weld residual stresses are the result of internal forces occurring without any external forces when the heating of the weld area relative to the surrounding material experiences restrained thermal expansion. Plastic strains then develop, and during the cooling process, tensile residual stresses are induced in areas adjacent to the weld deposit because of the restraint of the bordering (colder) base metal. These residual stresses increase the susceptibility for crack initiation and propagation and, depending on the process conditions and service environment, increase the risk of stress corrosion cracking, fatigue cracking, and ultimately, brittle fracture.

To diminish the likelihood of these failure modes in pressure-retaining equipment, PWHT is often employed as a means of stress relief for carbon and low-alloy steels. The WRC Book, *Weldability of Steels* [7], describes the PWHT as being accomplished by heating a welded structure to a temperature range high enough to reduce the yield strength of the steel to a small fraction of its magnitude at ambient temperature. Since the material can no longer sustain the weld residual stress level, it undergoes plastic deformation until the stresses are relaxed to the soak temperature yield strength (with some amount of additional relaxation due to creep occurring if post-heating is continued for longer hold times). Figure 1 shows the substantial relaxation of residual stress in carbon steels as a function of temperature for three different hold times.

As discussed in WRC Bulletin 452 [8], PWHT of carbon and low-alloy steels is typically performed below the lower critical transformation temperature and is referred to as sub-critical. The lower and upper critical transformation temperatures designate where the crystal structure of steel begins and finally completes a change from body-centered cubic to face-centered cubic upon heating, as well as the reverse effect upon cooling. Furthermore, PWHT can have both beneficial and detrimental effects for pressure vessel and piping components. Three primary benefits of PWHT are recognized: tempering, relaxation of residual stresses, and hydrogen removal. Resulting benefits such as avoidance of hydrogen-induced cracking, dimensional stability, and improved ductility, toughness, and corrosion resistance in some materials also result from the main benefits. However, PWHT is known to degrade toughness in some steels. As highlighted in, the effect of PWHT on notch toughness of weld metals varies widely according to material composition, strength level, flux, heat input, and the target temperature and hold time of PWHT. Contradictions also occur in published toughness data due to different experimental parameters and the general scatter in measured data.

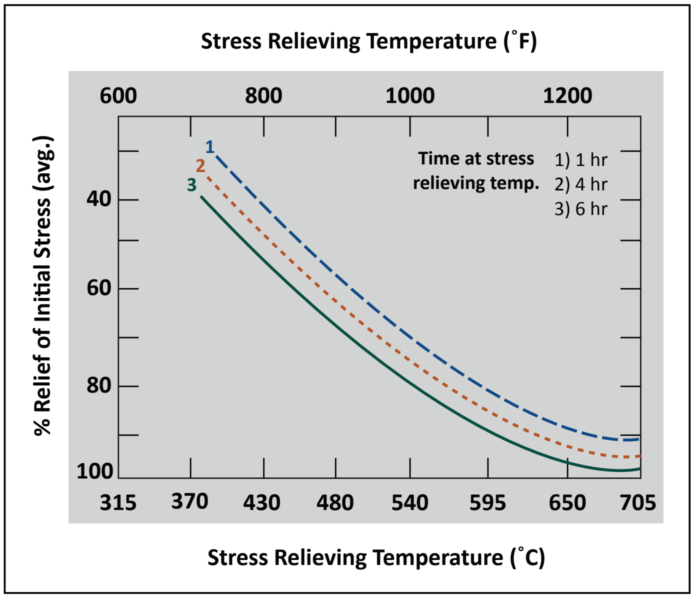

Figure 1 - Stress relaxation in carbon steel as a function of PWHT temperature [7].

THE EFFECT OF PWHT ON MATERIAL PROPERTIES

Several publications examine the effects of PWHT on material properties. WRC Bulletin 59 [9] is an early publication that discusses the potential degradation of notch toughness in weldments due to stress relief. Additionally, WRC Bulletin 302 [10] indicates that carbon steels can experience a progressive loss of notch toughness for longer PWHT hold times and higher temperatures. WRC Bulletin 481 [11] offers an in-depth study into the effect of PWHT on material properties and notch toughness on A516 carbon steel. Figure 2 shows the effect of PWHT on Charpy-V Notch (CVN) energy for SA-516-70 as a function of temperature for different stress relief conditions. This figure highlights how toughness degradation is anticipated for longer hold times and higher PWHT temperatures. ASME B31.3 PWHT guidance requires a hold temperature of 1100°F-1200°F for carbon steels and a hold time of 1 hour/inch of thickness (for wall thickness up to 2 inches).

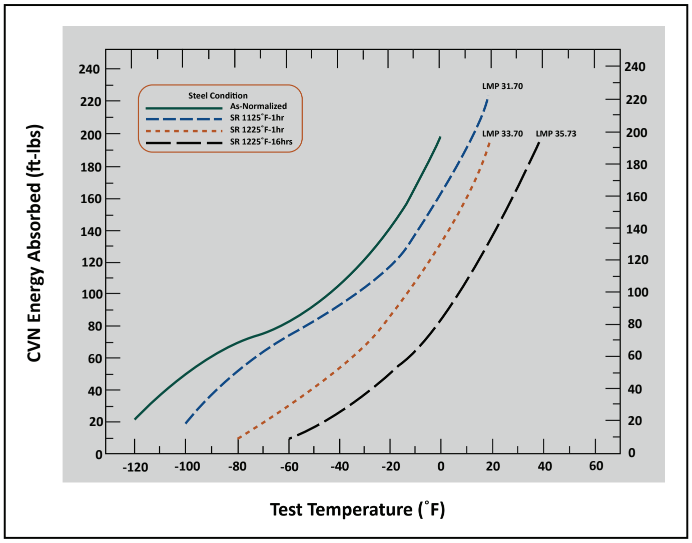

Figure 2 - The effect of PWHT on CVN energy for SA-516-70 as a function of temperature for different stress relief conditions [11].

Another concept introduced in WRC Bulletin 481 is required impact test temperature multipliers based on PWHT temperature and hold time. Figure 3 shows recommended impact test requirement multipliers for normalized carbon steel (for test temperatures below -40°F). Essentially, this matrix implies that required impact test energy should be multiplied by a constant based on PWHT temperature and hold time, with multipliers increasing for higher temperatures and longer hold times. For typical PWHT temperature and hold times for piping components, the factor could be as low as 1.25. As discussed, these multipliers are considered to be conservative.

	PWHT Time (hrs)							
Temp. (˚F)	1	2	3	4	5	6	7	8
1125	1.25	1.25	1.25	1.25	1.33	1.42	1.42	1.66
1150	1.25	1.25	1.33	1.33	1.66	2	2.5	2.5
1175	1.25	1.33	2	2.5	2.5	2.5	4	4
1200	1.33	2.5	3.3	4	5	5	5	5
1225	2.5	4	5	5	5	5	5	5
1250	4	5	5	5	10	10	10	10

Figure 3 - Impact test requirement multiplier for normalized carbon steel (test temperatures below -40°F) [11].

WRC Bulletin 371 [12] also investigates the effects of PWHT on the mechanical properties of thermo-mechanical control process (TMCP) steels. This study shows that, for lower carbon equivalences, PWHT does not generally degrade notch toughness; this generally holds true for quenched and tempered materials. In fact, Reference [7] indicates that, for carbon and low-alloy steels, the toughness of the heat-affected zone (HAZ) following PWHT is slightly increased for 0.15% carbon and considerably toughened for 0.25% carbon.

An ASME STP document by Spaeder et al. [13] states *"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."* This document goes on to suggest that the removal of mandatory PWHT should also apply for steels used in lethal service, or Category M components in ASME B31.3, (including vessels containing combustible substances where a leak could produce a vapor cloud type of safety issue). This document also references an EPRI report [14] that suggests a reduction in PWHT requirements for P-No. 1 steels, based on a limited set of impact test data for base, weld, and HAZ test specimens up to 1.5 inches in thickness. These documents are referenced as background in the ballot to revise PWHT requirements in the 2014 edition of ASME B31.3. Notably, References [13, 14] do not include fracture mechanics calculations to evaluate the effect of weld residual stress on crack-driving force, and ultimately brittle fracture, for as-welded construction vs. PWHT materials.

Lastly, work by Smith et al. [15] discusses the effects of extended PWHT on the microstructure and material properties of welded joints. Aforementioned WRC Bulletin 452 [8] offers a comprehensive overview of the historical work used to develop current PWHT guidance and effectively highlights the evolution of technology pertaining to local PWHT over the years. Reference [16] provides documentation of potential detrimental effects of excessive PWHT on pressure vessel steels. This study indicates no detrimental effect from PWHT on notch toughness of SA-516 grade 70 carbon steel, quenched and tempered, and indicates marginal scatter for normalized material of the same grade. Reference [17] shows experimental data that suggest higher-than-typical PWHT temperatures for SA-542M grade steels (Cr-Mo material used for heavy-walled pressure vessel components) have only limited effect on the microstructure and do not degrade fracture toughness.

FRACTURE MECHANICS APPROACH

The use of the Master Curve in conjunction with the elastic-plastic fracture mechanics methodology described in API 579 provides a way to generate modern impact test exemption curves anchored in state-of-the-art fracture mechanics. This approach utilizes the Failure Assessment Diagram (FAD) for the evaluation of crack-like flaws in components. The FAD approach (summarized in Figure 4) was adopted in API 579 because it provides a convenient, technically-based method to determine the acceptability of a component with a crack-like flaw. The driving force for failure is measured by two distinct criteria: unstable fracture and limit load. Linear-elastic fracture typically controls failure in cracked components fabricated from a brittle material, and plastic collapse at a limit load typically controls failure if the component is fabricated from a material with high toughness (high ductility). Elastic-plastic fracture occurs between these two extremes. In the analysis of crack-like flaws, the results from a stress analysis, stress intensity factor, limit load solutions, material strength, and fracture toughness are combined to calculate a toughness ratio (K_r) and a load ratio (L_r). These two quantities represent the coordinates of a point that is plotted on a two-dimensional FAD to determine acceptability. If the assessment point is on or below the FAD curve, continued operation is acceptable.

The Master Curve approach works best in the ductile-brittle transition region. This is the region of design for pressure vessels and piping constructed to the ASME Codes. Furthermore, a fracture toughness-to-Charpy impact energy is not required. The Master Curve provides a way to directly index into a fracture toughness model described by a 3-parameter Weibull distribution by using a reference transition temperature; thus, probability is incorporated into the fracture toughness calculation. Additionally, the reference transition temperature can be correlated to the ASME reference temperature. This permits the use of the existing ASME material categorization by exemption curve designation (i.e., A, B, C and D). Lastly, the Master Curve can be used to account for the loss in fracture toughness of a material due to the service environment, and

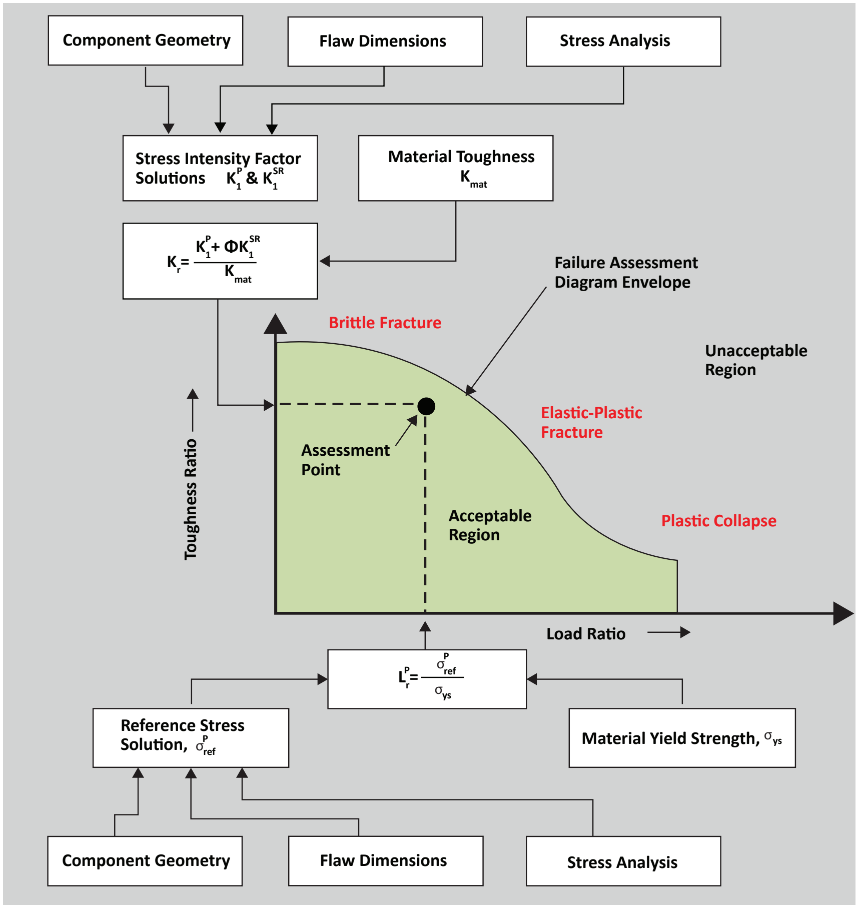

Figure 4 - Failure Assessment Diagram (FAD) consistent with API 579 [4].

is supported by ASTM Standard E1921 [18]. The technical background has also been fully documented by Wallin [19]. Additional details on the FAD-based fracture mechanics approach (including commentary on the Master Curve and limitations associated with the current ASME exemption curves) are offered in References [2-4].

THE INFLUENCE OF PWHT ON BRITTLE FRACTURE

The weld residual stress guidance in the 2016 edition of API 579 indicates that, with weld residual stress perpendicular to the weld seam, an 80% relaxation residual stress is predicted due to PWHT. Similarly, for residual stress parallel to the weld seam, a 70% relaxation in residual stress is predicted due to PWHT.

To highlight the influence of weld residual stress on the propensity for brittle fracture, a set of impact test exemption curves is generated for t/4 and t/8 (1/4 and 1/8 of component wall thickness, respectively), reference flaws for different ASME material categories (A, B, C, and D designations), with and without PWHT. These curves reflect the fracture mechanics approach described above in conjunction with the Master Curve. Figure 5 compares exemption curves (as-welded vs. PWHT) for a t/4 reference flaw, and Figure 6 compares exemption curves for a t/8 reference flaw.

A 5% probability of failure is assumed in all cases, and primary stress is assumed to be 2/3 of material yield strength (this corresponds to a typical design stress from internal pressure), where the yield strength equals 40 ksi.

The reference flaw is assumed to be ID surface-breaking (semi-elliptical with a length-to-depth ratio of 6:1) and oriented

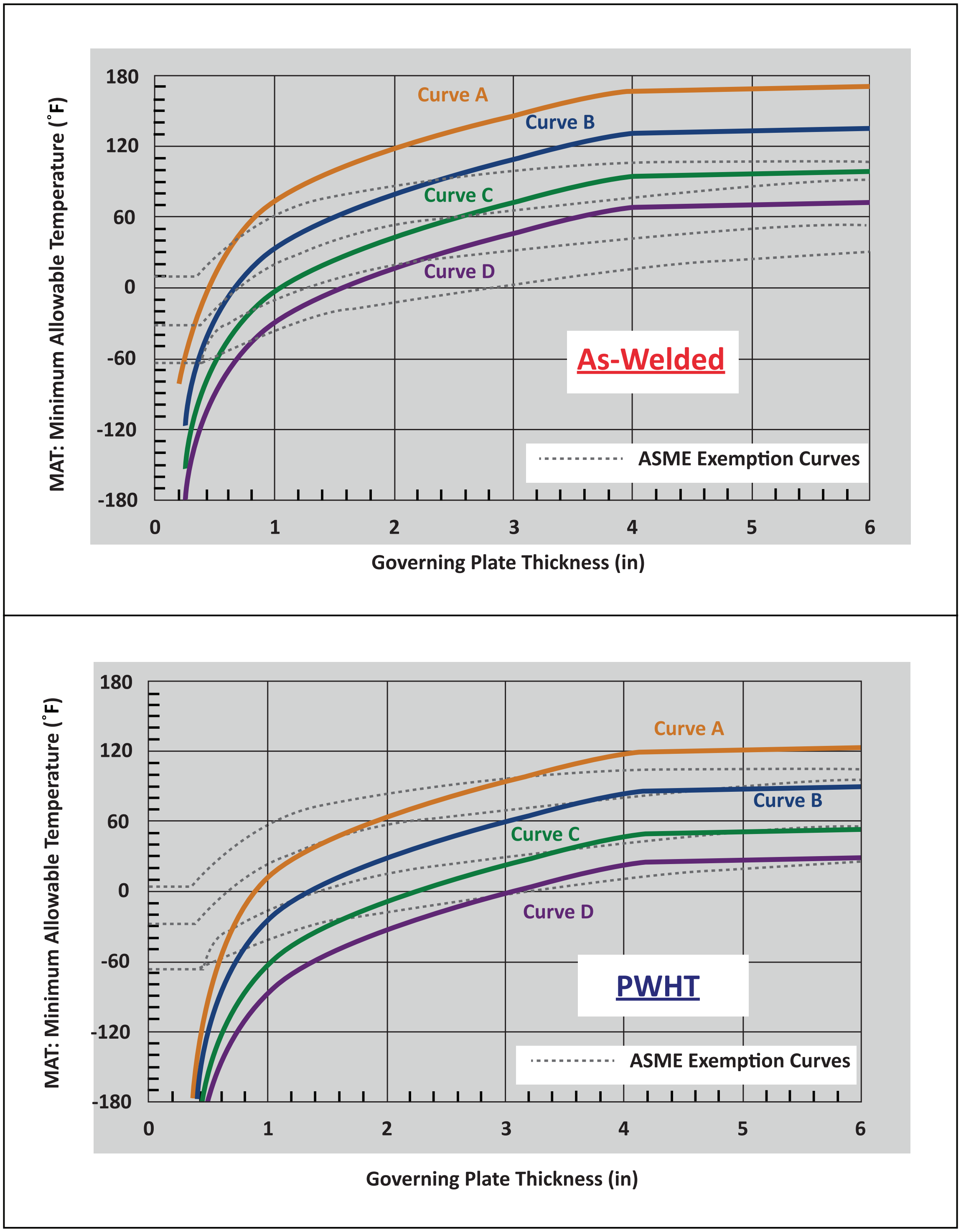

Figure 5 - Exemption curves for a t/4 reference flaw generated using the Master Curve.

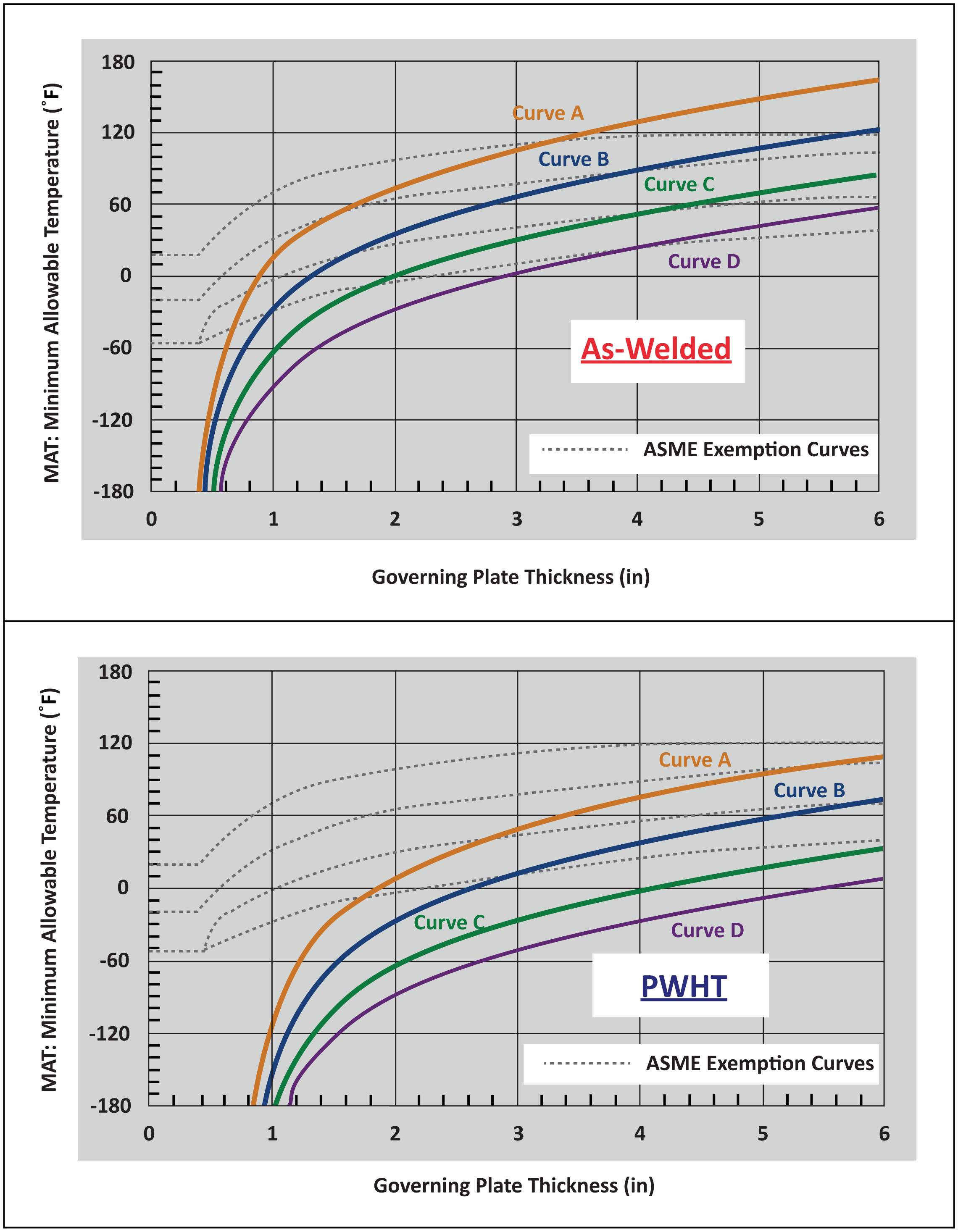

Figure 6 - Exemption curves for a t/8 reference flaw generated using the Master Curve.

longitudinally in a cylindrical shell weld, remote from structural discontinuities. Appropriate weld residual stress for full-penetration welded locations in accordance with Annex 9.D of API 579 is considered. The ASME Section VIII Division 1 [20] exemption curves are shown in these figures for reference (dotted lines in the background).

These figures highlight the significant effect of weld residual stress (and PWHT) on minimum allowable temperature (MAT) to provide protection against brittle fracture for different component thicknesses. To offer some perspective on the effect of PWHT for a 1.5-inch thick, Curve B component with a flaw depth of 1/4 the wall thickness, the difference in MAT for as-welded vs. PWHT is approximately +55°F. The same comparison for a flaw depth of 1/8 means that the wall thickness is approximately +75°F. Additional exemption curves corresponding to different material properties are provided in WRC Bulletin 562.

These comparisons show that weld residual stress is a significant contributor to brittle fracture and represents a crack-driving force that cannot be overlooked. While PWHT in general may cause a reduction in fracture toughness for some carbon and low-alloy steels, the reduction in toughness would generally have to be significant in order to outweigh the beneficial effect that PWHT has on relaxation of weld residual stresses (and resulting increased resistance to brittle fracture and other damage mechanisms such as stress corrosion cracking). Based on the carbon steel fracture toughness data summarized in this article, and even referring to the conservative required impact energy multipliers highlighted in Figure 3 for typical piping PWHT parameters, it is unlikely that a marginal decrease in fracture toughness from PWHT would justify the omission of stress relief for carbon steels (based on modern fracture-mechanics methodologies).

Given the concern throughout industry for potential brittle fracture failures in pressure vessels and piping, and in contrast to the current ASME B31.3 guidance, the Engineering Equipment and Materials Users Association (EEMUA) is currently funding the development of new impact test exemption curves and Charpy impact test temperature guidance that uses the modern fracture mechanics methodology described in this article. The EEMUA intends to incorporate these updated exemption curves and impact test procedures into a new publication for establishing minimum design metal temperature (MDMT) as a function of component thickness for both as-welded and PWHT construction. E^2G is currently leading this ongoing effort.

THE EFFECT OF WELD PREHEAT

An explicit weld simulation case study of a 4-pass weld is provided herein to evaluate the effects of weld preheat on projected weld residual stress. NBIC permits the use of preheat in lieu of PWHT for P-No. 1 (groups 1, 2, and 3) and P-No. 3 (groups 1 and 2), and states that "competent technical advice shall be obtained from the manufacturer of the pressure-retaining item or from another qualified source, such advice being especially necessary if the alternative is to be used in highly stressed areas, if service conditions are conducive to stress corrosion cracking, if hydrogen embrittlement is possible, if the component operates in the creep regime, or if the alternative is being considered for on-stream repairs or hot tapping on piping systems." This alternative approach recommends that the weld area be preheated and maintained at a minimum temperature of 300°F; however, for P-No. 1 materials, the preheat temperature may be reduced to 175°F. Additionally, this alternative approach is limited to SMAW, GMAW, FCAW, or GTAW welds, and carbon equivalence must be less than 0.40. The goal of the finite element analysis (FEA) weld simulation summarized in this article is to quantify the relaxation in calculated weld residual stress due to a permissible NBIC weld preheat.

As discussed in Reference [21], due to the range of temperatures involved in welding, many materials experience solid state phase transformations, most notably, carbon and low-alloy steels. However, in materials such as austenitic stainless steels and nickel alloys, solid state phase transformations tend to have a negligible effect with respect to welding simulations and may generally be ignored. Published literature suggests (Reference [21]) that it is reasonable to assume that neglecting solid state phase transformations in carbon and low-alloy steels will give conservative through-wall stress predictions. This is a valuable simplification because stainless steel material properties are generally available to significantly higher temperatures with less overall scatter. In this case, a 4-pass nozzle-to-head weld is simulated using an advanced cyclic plasticity material model (outlined in Reference [22]) with elevated temperature physical properties corresponding to stainless steel; that is, solid state phase transformation is not explicitly considered. Thermal-mechanical axisymmetric FEA is employed for this set-in nozzle with a shell R/t ratio of 50 and a nozzle R/t ratio of 10. An advanced subroutine that lays each weld pass down sequentially is utilized. A case with no preheat (weld region initial conditions correspond to ambient temperature) and a case with a 300°F preheat (consistent with NBIC [5] guidance) are investigated. Figure 7 shows the simulated weld fusion boundary (gray region), as well as each pass that is added sequentially into the non-linear FEA model.

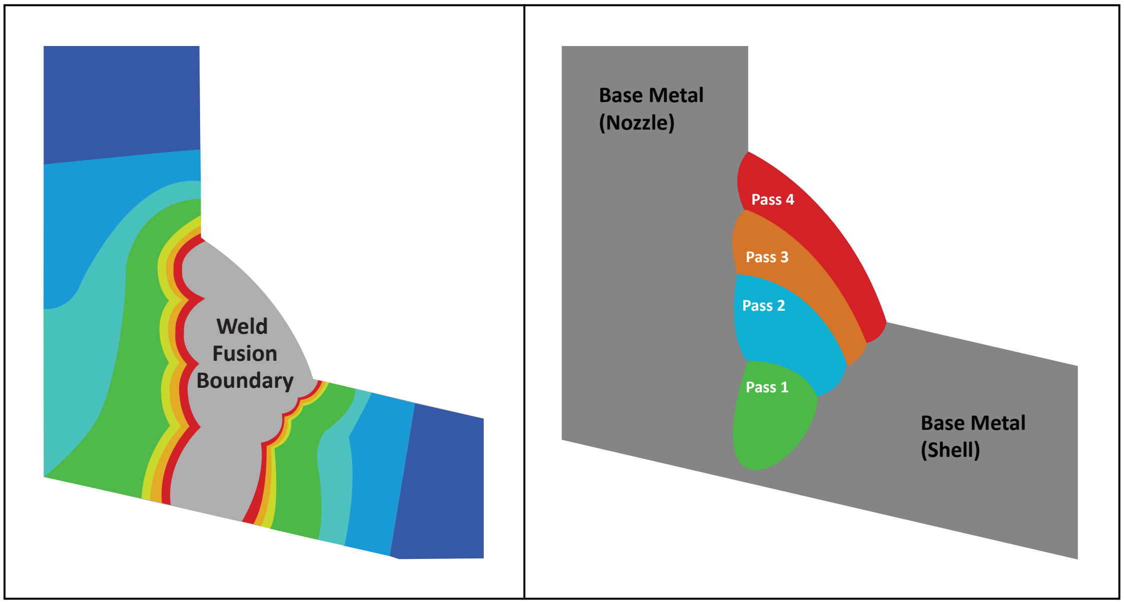

Figure 7 - 4-Pass computational weld simulation fusion boundary and weld passes.

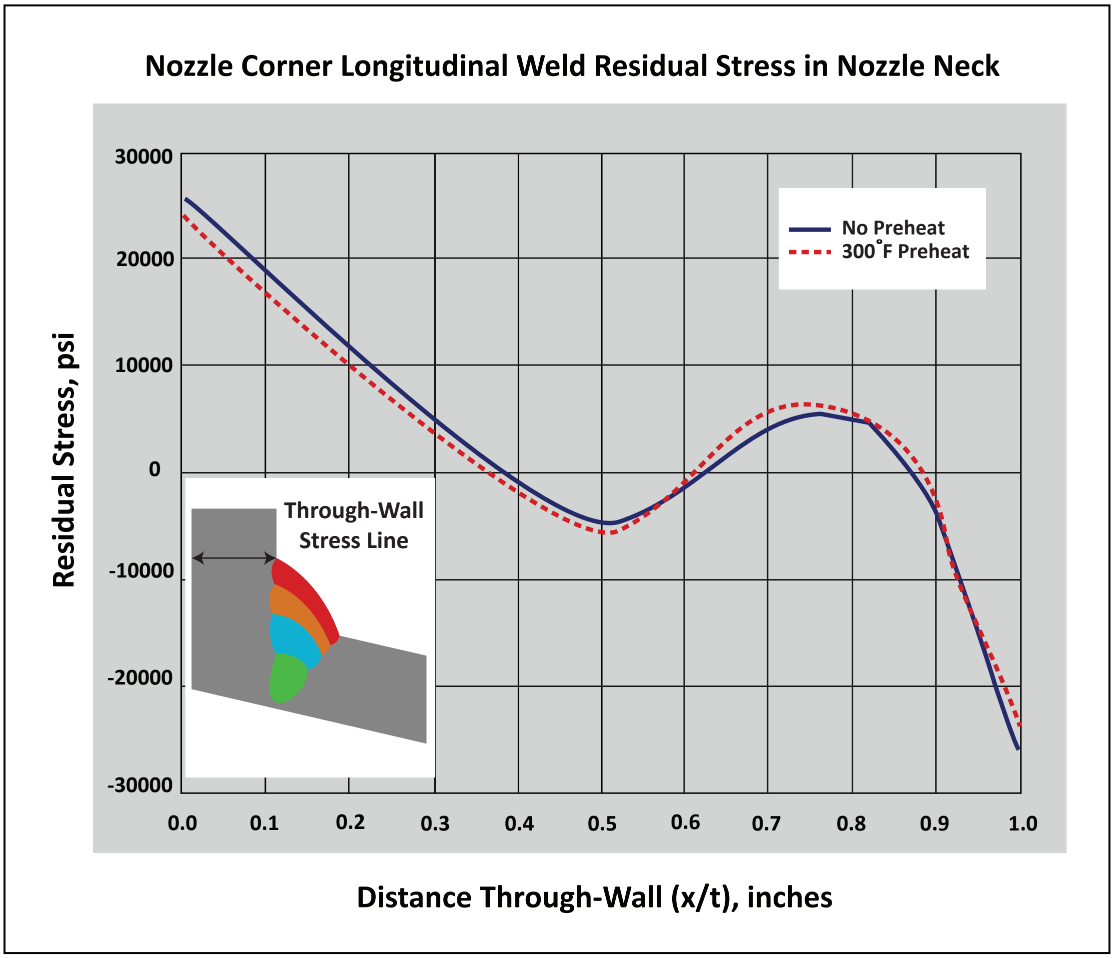

Figure 8 - Through-wall longitudinal stress distributions from FEA (ID to OD) in the nozzle neck with and without preheat.

Figure 8 shows through-wall longitudinal stress profile (psi) in the nozzle neck adjacent to the weld deposit for the model with no preheat and the model with a 300°F preheat. The through-thickness dimension is normalized. This comparison indicates that a 300°F preheat has very minimal effect on through-wall residual stress profiles, with essentially negligible difference in the nozzle neck (a roughly 5-10% difference is observed in the head adjacent to the weld deposit). For additional comparisons of this model, refer to Reference [2].

These comparisons affirm the theory that performing preheat is not comparable to PWHT in terms of stress relaxation behavior and overall remaining weld residual stresses (even though a tempering effect may still be achieved). Therefore, it is important to note that simply conforming to NBIC guidance and implementing preheat in lieu of PWHT is not generally recommended, particularly for thicker walled components, equipment in low-temperature service that may be prone to brittle fracture, or for pressure vessels or piping in aggressive service environments that may be prone to damage mechanisms such as fatigue or stress corrosion cracking.

SUMMARY AND CONCLUSIONS

Based on the literature review and the modern fracture mechanics methods discussed in this article, the recent removal of a mandatory PWHT requirement for P No. 1 carbon steels (of any thickness) in ASME B31.3 could potentially increase the likelihood of brittle fracture. Based on state-of-the-art fracture mechanics, weld residual stresses reflect a significant crack driving force (and a meaningful contributor to brittle fracture). As described in WRC Bulletin 562, impact test exemption curves generated using the Fracture Toughness Master Curve in conjunction with the elastic-plastic fracture mechanics methods of API 579 show that MAT magnitudes to provide protection against brittle fracture, for components with and without PWHT, are significantly different. For an assumed reference flaw, MAT values for as-welded components can be markedly higher relative to an equivalent component that received PWHT.

Additionally, any reduction in fracture toughness due to stress relief would have to be significant in order to outweigh the beneficial effect that PWHT has on the relaxation of weld residual stresses. Material chemistry can be controlled (for example, regulating carbon equivalence) to minimize the potential for notch toughness degradation during PWHT in carbon steels. Also, PWHT provides increased resistance to brittle fracture and other damage mechanisms such as fatigue cracking or stress corrosion cracking due to this residual stress relaxation. To this end, omitting the PWHT requirement for thicker carbon steel components is not generally recommended, unless flaw tolerance is well understood (based on fracture mechanics calculations) for as-welded construction and more detailed inspection is carried out at fabrication and throughout the life-cycle of a given component in order to rule out the presence of flaws at or near critical locations.

Lastly, the results of a 4-pass, computational weld simulation at a nozzle junction are summarized in this article. The intent of this case study is to highlight the effect that a 300°F preheat has on weld residual stresses compared to that of a weld with no preheat. NBIC permits the use of this type of preheat in lieu of PWHT. The simulation discussed herein shows that preheat has a very minimal effect on calculated residual stresses (even though it may provide some tempering effect). Based on this analysis, using preheat in lieu of PWHT is not generally recommended following component alterations or repairs due to increased susceptibility to brittle fracture or other damage mechanisms that are intensified by the presence of high residual stresses. In conclusion, weld preheat as specified in NBIC does not represent a substitute for PWHT from a weld residual stress relaxation perspective.

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