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RECOMMENDED PRACTICES FOR LOCAL POSTWELD HEAT TREATMENT

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Contents

ABSTRACT

The status of related code and other activities associated with local post weld heat treatment (PWHT) is briefly summarized. Terminology is proposed to facilitate specification of parameters for local circumferential PWHT. The terms soak band, heated band, gradient control band, axial temperature gradient, and control zone are defined. Considerations and recommendations are provided regarding specification of each of the parameters required for control of local circumferential PWHT. Various methods for performing local PWHT are reviewed. Detailed descriptions of low voltage electric resistance heaters and high velocity gas combustion burners are provided. Considerations for choosing the appropriate heating method(s) are discussed. The importance of, purposes for and methods to properly achieve temperature measurement are described.

KEYWORDS

local PWHT, soak band, heated band, gradient control band, axial temperature gradient, control zone, electric resistance, high velocity gas combustion

INTRODUCTION

Although post weld heat treatment (PWHT) of piping and pressure vessels may be performed in a furnace, weldment size and/or other issues may preclude such heating. In such cases, the weld and adjacent material may be locally heated by one of the methods discussed. Specifically, controlled heat may be applied to the weld metal, heat affected zone (HAZ) and a limited volume of base metal adjacent to the weld, as opposed to heating the complete weldment in a furnace or oven. Local heating is also very common during field fabrication and/or repair of components. The method used will often be determined by the availability of equipment, the accessibility of the area to be heated, constraints imposed by adjacent materials or components, and the type of heating operation to be performed.
The need for PWHT is driven by code requirements and/or concerns regarding the service environment. So called "code required" PWHT of ferritic steels is generally aimed at improving resistance to brittle fracture. To accomplish this, PWHT attempts to improve notch toughness and relax residual stress. When service requirements dictate the need for PWHT, additional objectives such as hardness reduction (for mitigation of wet H_2S cracking), stress relaxation aimed to be below a specific threshold level (for stress corrosion cracking), and other considerations become important, depending upon the environment. The strategy followed in providing recommendations for local, "code required" PWHT was to attempt to duplicate the outcome of furnace heating (i.e., heating the whole weldment) within a localized region, referred to as the soak band, surrounding the weld. While a similar strategy is applied to meet the additional objectives associated with service environments, the ability of furnace and/or local PWHT to meet these objectives must be carefully assessed for each environment.
Recommended practices are available for pressure vessels(l) and piping (2) which provide in-depth treatment of the various issues relating to local heating. These recommended practices also address bake-out, preheat/inter pass heating and post heating in addition to PWHT. The focus of the paper which follows relates to local, full circumferential PWHT. The reader is directed to the referenced recommended practices for information relating to other issues.

This paper does not attempt to address issues specific to the heat treatment of zirconium alloys. Such information is available elsewhere (3). However, it is important to note that three heat treatments are reported (3) to be commonly used: "stress relief anneal", "full recrystallization anneal" and "oxide thickening treatment". The stress relief anneal is performed in the temperature range 500 to 600°C (932 to 1,112°F) for the purpose of stress relaxation to: mitigate stress corrosion cracking, provide dimensional stability during machining operations and avoid delayed hydride cracking. The full recrystallization anneal is performed in the temperature range 600 to 750°C (1,112 to 1,382°F) for the purpose of altering grain boundary intermetallic phases to restore the corrosion resistance of welds intended for sulfuric acid service. The oxide thickening treatment is performed in the temperature range of 500 to 600°C (932 to 1,112°F) for times longer than those associated with stress relief anneal to form a thick adherent oxide surface. For situations where local PWHT is aimed at mitigating stress corrosion cracking (i.e., using a so-called stress relief anneal), the appropriateness of the stresses (magnitude and distribution) remaining after PWHT must be considered.

STATUS OF RELATED CODE & OTHER ACTIVITY

The American Welding Society (AWS) D10 Committee on Piping and Tubing is currently revising ANSI/AWS D 10.10-90[2] which provides recommended practices for local heating of welds in piping and tubing. Section VIII (4) of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Code has been considering revising some of the current requirements for local PWHT (paragraphs UW-40 and AF-410). As a result of this activity and a request from a joint industry project developing guidelines for PWHT of repairs to aging hydro processing reactors, a recommended practice for local heating of welds in pressure vessels(!) was prepared. This recommended practice for local heating of welds in pressure vessels is currently being reviewed by the Pressure Vessel Research Council (PVRC) for publication as a Welding Research Council (WRC) Bulletin. It is hoped that these two recommended practices will provide users with a comprehensive coverage of the various issues relating to local heating of welds in piping and pressure vessels. Both documents have sought to include both domestic and international viewpoints with regard to the issues. As a first step towards developing an internationally recognized consensus document relating to local heating of welds in piping and pressure vessels, it is currently planned to submit a document to Commission XI (Pressure vessels, boilers and pipelines) of the International Institute of Welding (IIW) at the Annual Assembly in 1998.

SPECIAL TERMINOLOGY FOR LOCAL HEATING

Due to the lack of standard terminology, the following terms are described and used: soak band, heated band, gradient control band, and axial temperature gradient. Figure 1 provides a schematic diagram which uses these terms to describe local circumferential heating. Although not included in Figure 1, the term control zone is also described and used in this paper.

The soak band (SB) is the volume of metal which must be heated to the minimum but not exceed the maximum required temperature. As a minimum, it should consist of the weld, HAZ, and a portion of the base metal adjacent to the weld being heated.

The heated band (HB) is the surface area over which the heat source is applied to achieve the required temperature in the soak band and limit induced stresses in the vicinity of the weldment. It should consist of the soak band plus any adjacent base metal necessary to both control the temperature and limit induced stress within the soak band.

The gradient control band (GCB) is the surface area over which insulation and/or supplementary heat source(s) are placed. It should encompass the soak band, heated band, and sufficient adjacent base metal such that the maximum permissible axial temperature gradient within the heated band is not exceeded.

The axial temperature gradient is the change in temperature (drop) moving away from the soak band in a direction parallel to the axis of the pipe or pressure vessel. It is frequently specified as a minimum distance, L, over which the temperature may drop to a percentage of that at the edge of the soak band.

A control zone is a grouping of one or more heat sources which are controlled (turned on and oft) based upon input from a single temperature measuring device (typically a thermocouple). The thermocouple is placed at a particular location such that it represents the temperature of a volume of metal surrounding that location. One or more zones may be present in either or both the circumferential and axial directions.

Nomenclature

W = Widest width of weld.
HAZ = Heat affected zone.
SB = Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as **W** plus a multiple of t on each side of the weld).
L = Minimum distance over which the temperature may drop to a percentage of that at the edge of the soak band.
HB = Heated band (width of heat source).
GCB = Gradient control band (minimum width of insulation and/or gradient heat source).
T = Nominal thickness.
R = Inside radius.

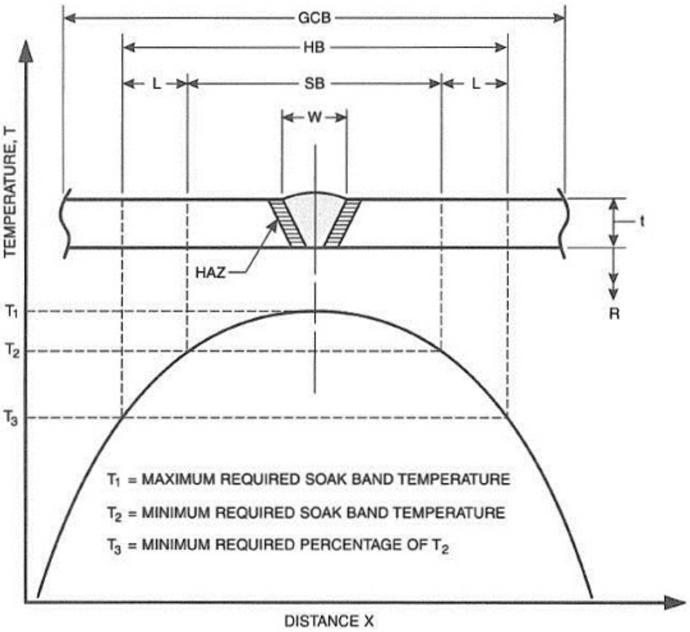


Figure 1. Schematic diagram for description of local circumferential heating.

CONSIDERATIONS & RECOMMENDATIONS FOR PARAMETERS

Fabrication codes generally specify requirements for local PWHT based upon the use of circumferential bands. The temperature around the circumference of these bands is aimed at being uniform. If local hot spots are created, these areas may become permanently distorted, contain high levels of induced stress, crack, or have their properties altered.

Fabrication codes may specify soak band width, heated band width and/or axial temperature gradients. However, non-specific terms such as "so that the temperature gradient is not harmful" are often used. Since local heating is typically from one side, radial (through-thickness) temperature gradients must be considered, but are not addressed by the fabrication codes.

The following sections provide detailed considerations regarding the soak band, heated band, gradient control band, and axial temperature gradients. Since requirements may differ between different codes and specifications, the applicable version of these documents should govern for each specific application.

Soak Band

The soak band is sized to insure that the required volume of metal achieves the temperature needed to produce the desired effect. In general, one must follow the requirements dictated by the applicable code. Approaches such as those used by ASME Section II1(5) (thickness of the weld or 2 inches [50.8 mm], whichever is less, on either side of the weld face at its greatest width) and B3l.3(6) (1 inch [25.4 mm] beyond the weldment on either side) for PWHT prevent the soak band from becoming unnec-essarily large as thickness increases.

Heated Band

The size of the heated band is important with regard to two considerations. Because of the inherent radial temperature gradient, the band must be large enough to insure that the minimum required temperature extends through the thickness in the soak band. In addition, local heating of a cylindrical segment can produce bending moments and shear stresses. These bending moments and shear stresses can cause distortion and/or induce residual stress in the weld region. The magnitude and location of these stresses are affected by the width of the heated band and axial temperature distribution.

Domestic codes generally do not provide specific guidance regarding the size of the PWHT heated band. Many interna-tional codes specify a minimum heated band size of 5 /IU centered on the weld, where R = inside radius and t = thickness.

Through-Thickness Temperature Gradient

Shiffrin reported(?) on experimental work performed on pipe from which it was concluded that through-thickness temperature gradients are proportional to the width of the heated band on the outside surface regardless of the thickness, diameter, or energy source. He further concluded that if the heated band size is at least 5t, where t = thickness, the temperature on the outside surface at an axial distance of "t" from the centerline of the weld will be approximately the same as that on the inner surface at the root of the weld.

In the decades since it was published, the Shiffrin work (or variations on it) has served as the basis for the majority of standard practices with regard to heated band sizing for local heating as it relates to the attainment of minimum temperature within the soak band. For example, an approach has been to size the heated band as the sum of the soak band width plus 2.5t on either side of the soak band. This type of approach is still widely used today. However, concerns have been expressed (8) that the 5t width is not sufficient, especially as the internal radius increases with no internal insulation.

Work has been reported (9) on the effect of the heated band size on the PWHT soak band temperature achieved at the 6:00 position on the inner surface for 6.625 in. (168 mm), 12 in. (305 mm), and 18 in. (457 mm) diameter pipes oriented horizontally. It was suggested that an empirically derived ratio be used to establish a relationship between the heat flow from the heat source and heat losses due to conduction through the wall and radiation and convection from the inner surface. Equation (1) describes this empirically derived ratio.

$$H_i = A_e/(2A_{cs} + A_i)$$

where:

A_e =Area of heat source on the outside surface

Acs = cross sectional area of pipe wall

Ai = inside surface area of soak band (assumed 4t wide, centered on weld)

The results of the work demonstrated that for a ratio of Hi = 1.19, two circumferential control zones, with control temperatures of approximately 1,150°F (621°C) at the 12:00 and 6:00 positions, on an 18-inch (0.46 m) diameter, 1-inch (25 mm) wall thickness pipe, a temperature difference of 120°F (67°C) could occur between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 position, 2t from the centerline of the weld). It was concluded that by sizing the heated band such that the ratio was at least 5, a temperature difference between the top outside and bottom inside of less than 45°F (25°C) would occur, thereby assuring achievement of the minimum temperature 1,100 °F (593°C) throughout the thickness. It was further demonstrated that the use of insulation on the inner surface reduced the temperature difference to 24°F (13°C).

It should be noted that the recommended ratio was empirically derived. As such, it is founded upon certain conditions inherent to the tests which lead to that recommendation, such as the number of control zones, the hold temperature, and the orientation of the pipe (i.e., horizontal versus vertical). For example, data is reported for one and two zone control on an 18-inch (0.46 m) diameter, 1-inch (25 mm) wall thickness pipe using a ratio of Hi = 4.81. For one zone of control, a temperature difference of 92°F (51°C) is reported between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 position, 2t from the centerline of the weld), while for two zones of control the difference was 70°F (39°C). It should also be

noted that for this size pipe, four circumferential control zones are sometimes used.

As the number of control zones is increased, lower empirical Hi ratios would be appropriate. With multiple control zones it is also possible to have different control temperatures for each zone. The use of different control temperatures for each zone would also affect the empirically derived Hi ratio. In addition, the empirically derived Hi ratio is based on a soak band size of 4t, which may be larger than that required by the applicable fabrication code. Therefore, Hi ratio of 5 may be conservative for situations in which a larger number of control zones are used and/or a smaller soak band size is required.

The empirically derived Hi ratio is also affected by the hold temperature. Temperature differences between the outside top (12:00 position, centered on the weld) and inside bottom (6:00 position, 2t from the centerline of the weld) are reported for hold temperatures between 500 to l,300°F (260 to 704°C) with a ratio of Hi = 2.28. The temperature difference varied from 21 to 64°F (12 to 36°C) as the hold temperature increased. This data suggests that a ratio of Hi = 2 may be appropriate for lower temperature heating processes such as bake-out, preheating and post heating when the temperature is below approximately 800°F (427°C).

The apparent conservatism in the empirically derived Hi ratio should be noted. As stated above, the ratio is based on test conditions that may be of lesser relevance to a particular set of circumstances (as in the case of a circumferential weld in a vertical pipe) or may be made less relevant by altering the methodology (as with added control zones). The importance of the work is that it highlights the need to size the heated band for through-thickness temperature gradient considerations based upon all of the factors which contribute to heat loss.

The above discussions are applicable to piping where it is generally not possible to place insulation on the surface opposite to that where heat is being applied. For pressure vessels in which insulation is applied to the surface opposite to that which heat

is being applied, the resultant through-thickness temperature gradient is greatly reduced as cited in the above example.

Induced Stresses and Distortion

Efforts to address the stresses resulting from local PWHT were first reported by Rose and Burdekin (10,11). This work was based upon establishing parameters which produced approximately the same degree of stress relaxation in the vicinity of the weld as would be achieved in a furnace. As an approximation, the hot yield strength (YS) of the material at PWHT temperature was used as the target level of stress relaxation. Having established the hot YS as an approximate target for stress relaxation, the Rose and Burdekin work then aimed at limiting the induced stress at the weld due to PWHT to something less than hot YS, thereby ensuring that the induced residual stress at the weld due to PWHT was no greater than the residual stress levels that would remain even if the PWHT were done in a furnace. As a result of this work, a heated band size of 5/Rt, where R = inside radius and t = thickness, centered on the weld was proposed. In addition, the axial temperature gradient was limited by the temperature at the edge of the heated band being no less than one-half of the peak soak band temperature. Many international pressure vessel1 and piping codes[2] have adopted this approach.

Concern has been expressed that a heated band size of 5./ru may be overly conservative. For example, a supplement to a German standard (12) explains the basis for changing the heated band sizing requirement from 5./Rt to 4./Rt. In swnmary, this supplement explains that the "run-out length" for stresses and moments induced by local heating according to the theory of shells is 2.83.JRi. It therefore concludes that a heated band size of 4 should provide an adequate margin of safety.

Detailed discussions(l,2) are available which are in agreement with the German standard and previous unpublished work(13). These discussions conclude that a total heated band size of soak band plus 4/Rt can be used to adequately control induced stresses in the soak band for "code required" PWHT. This recommendation differs from international codes and practices in that it specifies the "run-out-length" from the edge of the soak band instead of the weld centerline. This approach was used to insure adequate control of stresses throughout the soak band. However, the total size of the recommended heated band (soak band plus 4./1&) is of similar size to that used in international codes and practices (500) centered on the weld).

Recommended Approach for Sizing& the Heated Band

When attempting to size the heated band, one must, of course, insure that its width is adequate to achieve the minimum temperatures required in the soak band. Further consideration must then be made with regard to the effect of stresses induced by the local heating. Such consideration should include assessment of distortion and residual stresses.

The following recommendations are aimed at meeting the typical PWHT objectives found in fabrication codes (so-called "code required" PWHT). Additional consideration is necessary when concerns exist regarding the service environment.

For piping, it recommended to use the larger of the heated band size determined using either the induced stress (SB plus 4./ru) or through-thickness temperature gradient (with Hi = 5) criteria. The conservatism of each approach should again be noted. For the empirically derived through-thickness criteria (with Hi = 5), lower ratios and smaller resultant heated bands will be applicable as the number of control zones is increased (i.e. for large diameters) and for vertical pipe. For the induced stress criteria (SB plus 4. Ji«), more accurate modeling combined with refined acceptance criteria may result in a smaller multiplier and associated heated band size. While the outcome may be conservative, one can expect to meet both the through-thickness temperature and induced stress criteria. It should be noted that the resultant recommended heated band sizes are considerably larger than current domestic practices and greater than international practices for those cases where the empirically derived Hi ratio dominates.

For pressure vessels where insulation is used on the surface opposite to that which heat is being applied, it recommended to use the induced stress criteria (SB plus 4Ji«) to size the heated band.

Gradient Control Band

As the name implies, the primary function of this band is to control the axial temperature gradient. It also serves to minimize heat losses in the heated band (heat source). The characteristics of the insulation (both thickness and thermal proper- ties) directly affect the power requirements of the heat source. The size of the insulated area directly affects the axial temperature gradient. Domestic fabrication codes generally do not provide any guidance with regard to the size.

International pressure vessel codes generally recommend(IO) a IoiRt PWHT gradient control band centered on the weld. Accompanying this recommendation is the notation that such a size will generally insure achieving the maximum permissible axial temperature gradient (i.e., one-half temperature drop to the edge of the heated band). Common domestic industry practice is to use PWHT gradient control band sizes between two and three times that of the heated band, while international practice is
to use the 1 of i size. Detailed discussions are provided elsewhere (l ,2) regarding considerations for sizing the

gradient control
band. These discussions conclude that sizing the gradient control band to 2./Rt on either side of the heated band will reasonably limit the thermally induced stress. Obviously, such a gradient control band sizing recommendation must be based upon assumed insulation characteristics. A discussion of the assumed insulation characteristics upon which the gradient control band sizing requirements are based is included at the end of this section.

Two different methods for sizing the gradient control band have been considered. One is based upon 2./Rt on either side of the heated band (where the width of the heated band equals SB plus 4.Jlu). This results in a total gradient control band width of
soak band plus 8./ru: . This approach is similar to that used by international codes and practices, except it is -I/Rt smaller depending upon the size of the soak band. The second is a recently proposed method (9) based upon through-thickness temperature issues. This second method recommends one pipe diameter on either side of the heated band. This approach results in a total gradient control band size of 2 pipe outside diameters (2D) plus the width of the heated band. The heated band plus 2D
generally ranges from 2 to 3 times larger than the heated band plus 4/Rt . Based upon the justification discussed elsewhere (1,2)
and successful international experience, sizing the gradient control band based upon the heated band plus 4/Ri is recommended.
If concerns exist regarding the need to further reduce the axial temperature gradient or achieving temperature in the soak band, consideration could be given to increasing the size, with heated band plus 2D being an upper limit.

It is also important to note that if wall thickness changes, attachments are present within the gradient control band, or pipe is being welded to flanges, valves, etc., the use of supplemental heat source(s) may be required.

The gradient control band size recommended above is based upon minimum typical insulating (or R) values of 2 to 4 °F-ft^{2}- hr/BTU (0.35 to 0.70 °C-m^{2}/W). R value is simply the inverse of the conductance of an insulating layer (i.e., R = insulation thickness/k: value). For example, at a PWHT temperature ofl,200°F (649°C), a 2 inch (50.8 mm) thick layer of 6 lb/ft:3 (96.1kg/ m^{3}) density refractory ceramic fiber having a conductivity of0.53 BTU-in/hr-ft2-°F (76.4 W-mm/m^{2}-^{0}C) at 600°F (316°C) mean temperature gives an R value of 3.8 °F-ft2-hr/BTU (0.67 °C-m^{2}/W) at that mean temperature. Insulation types and thicknessescan be combined as required to achieve R values within this range.

Axial Temperature Gradient

The axial temperature distribution plays an important role in limiting the previously discussed induced stresses during PWHT. Although it is the second derivative of the axial temperature distribution (the rate of change in the axial temperature gradient) which affects induced stress, the axial temperature gradient is the parameter which is generally specified.

Domestic codes either have no requirement or use the undefined term "gradually diminishing". International codes frequently provide a more specific requirement. They typically require that material at a distance of 2.5Jit on either side of the weld centerline be at a temperature greater than one-half of the heat treatment temperature (i.e., soak band temperature). Such an approach is common in various international piping and pressure vessel codes. It should be noted that a different minimum temperature results depending on the temperature scale being used. Using the Fahrenheit scale and an assumed soak band temperature of 1,100°F (593°C), the minimum temperature allowed at the edge of the heated band would be 550°F (288°C). Using the Celsius scale and an assumed soak band temperature of 593°C (l,100°F), the minimum temperature allowed at the edge of the heated band would be 297°C (567°F). Based upon the magnitude of the difference, this is not expected to be significant.

The Dutch pressure vessel code(l4) limits the temperature drop at two locations: one-half the distance to the edge of the heated band and at the edge of the heated band. The minimum temperature required at one-half the distance to the edge of the heated band is 80%, while that at the edge of the heated band is 50%. Such a requirement provides greater assurance of a uniform axial temperature gradient.

Discussions provided elsewhere(l,2) consider the effect of controlling the axial temperature gradient in the heated band by limiting the maximum temperature drop at its edge. These discussions demonstrate that by limiting the maximum temperature drop to one-half of the temperature at the edge of the soak bank, stresses are adequately controlled within the soak band for common piping and pressure vessel materials.

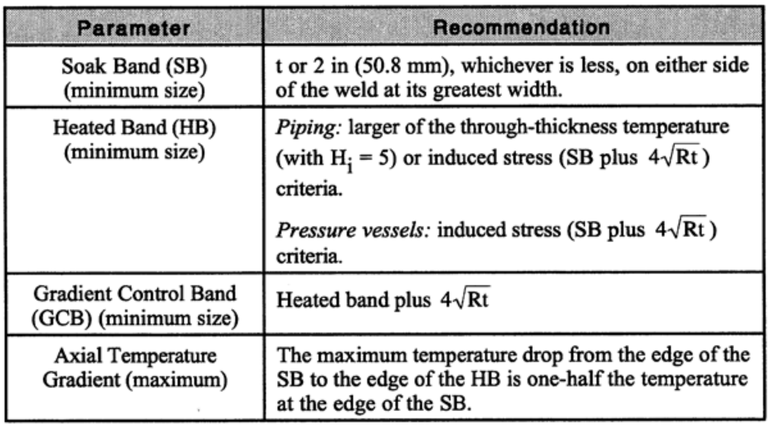
The one-half temperature drop approach is recommended based upon the referenced discussions (l ,2), its widespread use in international practice, ease of use and ability to account for varying pipe flexibility (since the distance over which the drop may occur is based upon a function of. Jiu). In contrast, an approach based upon a fixed maximum axial temperature gradient for all diameter/thickness combinations can be overly conservative in some cases and non-conservative in others. The one-half temperature drop approach also avoids a concern which may arise when using a fixed maximum axial temperature gradient. In such situations, the maximum gradient may be applied to inappropriately short intervals of length and result in unnecessary rejections.

It is therefore recommended that the axial temperature gradient during PWHT be controlled such that the temperature at the edge of the heated band be no less than one-half the temperature at the edge of the soak band during heating, hold and cooling.

Summary of Recommendations for SB, HB, GCB & Axial Temperature Gradient

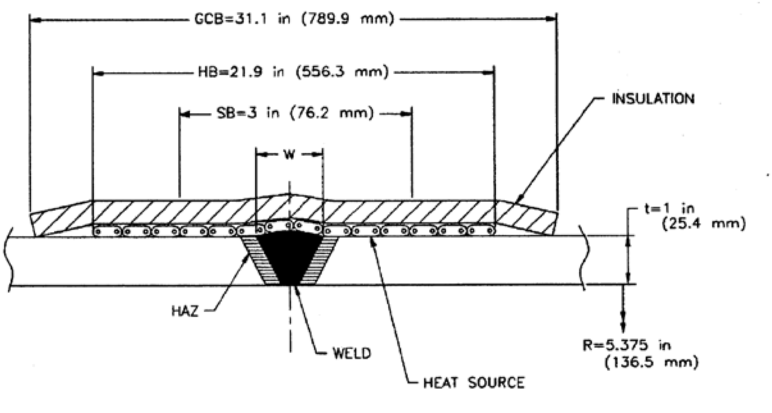
In all cases, one should follow the requirements provided in the applicable code or specification. In most cases, especially for domestic codes, this will be limited to the soak band for PWHT. As previously discussed, the recommendations for PWHT which follow are applicable for "code required" situations. Additional consideration is necessary when concerns exist regarding the service environment. Table I provides a summary of the recommendations. Note that these recommendations should only These recommendations are for "code required" PWHT. Larger heated band and gradient control band sizes may be required when concerns exist regarding the service environment.

Table I. Summary of Recommendaions for SB, HB, GCB and Axial Temeperature Gradient



Parameter	Recommendation
Soak Band (SB) (minimum size)	t or 2 in (50.8 mm), whichever is less, on either side of the weld at its greatest width.
Heated Band (HB) (minimum size)	*Piping:* larger of the through-thickness temperature (with $H_i = 5$) or induced stress (SB plus $4\sqrt{Rt}$) criteria. *Pressure vessels:* induced stress (SB plus $4\sqrt{Rt}$) criteria.
Gradient Control Band (GCB) (minimum size)	Heated band plus $4\sqrt{Rt}$
Axial Temperature Gradient (maximum)	The maximum temperature drop from the edge of the SB to the edge of the HB is one-half the temperature at the edge of the SB.

Figure 2. Example of parameters for local circumferential PWHT of a butt weld in a 12 NPS, 1-in (25.4 mm) wall thickness pipe in accordance with B31.3 soak band requirements. (SB, HB, and GCB sizes shown are minimum recommended.)



An example of the parameters recommended in Table I is provided in Figure 2. The example shown in this figure is based upon heating a butt weld in a 12 inch NPS, 1-in (25.4 mm) wall thickness pipe. The soak band sizing is based upon the assumption that the weld is 1t wide (1 in [25.4 mm]) and used the B31.3 soak band size requirement of 1-in (25.4 mm) beyond the weldment on either side.

METHODS FOR LOCAL HEATING

Various methods can be used to accomplish local heating of welds. Possible heat sources include: low or high voltage electric resistance heaters (contact pads or radiation elements sup- ported on a structure); combustion burners (high velocity gas, luminescent flame, and infrared burners); induction coils, and quartz lamps. For piping, low voltage electric resistance is most common domestically, while internationally low and high voltage electric resistance and induction coils are common. For pressure vessels, low voltage electric resistance and high velocity gas combustion are common domestically, while these two methods and high voltage electric resistance are common internationally.

Width of SB based upon assumption that W = 1-in (25.4 mm).

Assuming temperature at the edge of the SB = 1,100°F (593°C), minimum temperature at the edge of the HB must be 550°F (288°C).

Low voltage electric resistance heating pads are used in contact with the weldment for conduction heat transfer. High velocity gas combustion is generally used in conjunction with a temporary furnace. An entire vessel can become its own furnace by simply covering its exterior surface with thermal insulation and using the turbulent heated air of a combustion heating system to convectively heat the vessel shell from the inside. In a similar fashion, sections of a vessel can be heated by employing insulated bulkheads internally to create an isolated heat chamber. Alternatively, a temporary furnace can be constructed around a vessel.

High voltage electric resistance heaters offer similar advantages to combustion heating of large vessel sections. They can be placed a fixed distance from the weldment surface, as in a temporary furnace constructed within or on the outside of a pressure vessel, for radiant and convective heat transfer. These elements are usually connected in star (wye) formation to take advantage of the increased voltage with this type of connection with 3-phase electric power. A neutral connection at the star point of each circuit allows individual control of each element in the star. However, it is not common domestically to run a neutral with a 3-phase supply. As such, the use of internally bulk headed electric resistance temporary furnaces is more common outside of the United States. Wider utilization in the United States appears to be limited due not only to the inability to achieve individual element control, but also to safety concerns relating to the use of high voltage. In addition, installation and equipment requirements are greater for high voltage heaters compared to internally fired high velocity gas combustion.

However, high voltage electric resistance does offer many benefits when compared to low voltage electric resistance heating. Specifically, avoiding the use of transformers results in lower secondary amperage for the same energy output, and hence lower rated contactors and other components. In addition, the number of heating elements may be reduced for the same energy output because of the higher voltage. 'typically, the elements used for high voltage electric resistance heating are more robust than those used for low voltage.

A detailed discussion of the various heat sources typically used for local heating of piping is provided elsewhere (2). The following sections briefly describe local heating using low voltage electric resistance heaters and high velocity gas combustion burners. While this discussion is primarily aimed at pressure vessels, some of the information is also applicable to piping.

Additional information regarding electric resistance and gas-fired techniques has been reported (15,16) elsewhere.

Electric Resistance

Electric resistance heating can be performed using elements placed either externally or internally. When performing external heating, the use of low voltage flexible ceramic pad (FCP) type heaters, placed in contact with the outer surface is most common. When internal electric resistance heating is used, elements are normally mounted on bulkheads or other structural support. High voltage heaters are frequently used for such internal bulkhead heating.

A heated band can be created by using flexible ceramic pad (FCP) heaters, with each heater typically developing 3.6 kW of thermal power when connected to an 80 Volt, alternating current circuit of a power source. Because of conductive heat losses into the adjacent unheated shell sections and convective and radiate heat losses from the heated weldment assembly, the actual heated band must be wider than the required soak band.

The heated band may be comprised of one or more bands of FCP heaters with multiple control zones (circuits), depending on the diameter and thickness of a given weldment assembly. Typically, an 80 volt FCP has a surface area of approximately 120 in^2 (0.077 m^2), producing approximately 30 W/in^2 (46.8 kW/m^2) and is available in a variety of combinations of length and width. In addition, 60 and 40 volt FCP heaters are available with similar power density, and special configuration heaters can be fabricated. Heater selection is made to minimize circumferential gaps between heaters, and thus optimize surface coverage, in order to create a uniform heated band width sufficient to maintain temperature uniformity across the soak band. Typically, heater spacing up to the wall thickness or 1in (25.4 mm), whichever is less, can be accommodated without detrimental heat loss.

High Velocity Gas Combustion

Heating of pressure vessels by direct internal firing, with high velocity gas burners offers many advantages. Good temperature uniformity is obtained due to the forced convective mode of heat transfer. High velocity heated air is amenable to the use of distribution tubes to direct flow into regions of stagnant air, to enhance turbulent convective heat transfer. Where suitable external insulation exists on a pressure vessel, the installation time for an internal combustion heating system is much less than required for the attachment of heaters and insulation to the vessel's outer surface. The heating system consists of at least one burner and high volume air blower, supported by at least one control console, or gas train, with its essential piping, valving, and electronic instrumentation, for safety and precise control of temperature and heating and cooling rates, etc.

Direct internal firing can be used to heat the whole pressure vessel or sections, depending upon local heating needs. When sections are to be heated, insulated bulkheads are erected to limit the area being heated. As previously discussed, the decision to heat a larger section than the required local area can be driven by several factors. It may be easier and less expensive to bulkhead a section and use direct internal firing as opposed to external heating with electric resistance heaters. It is common for nozzles or other attachments not requiring PWHT to intersect the region to be heated. The resultant need to heat an even larger section to insure an acceptable gradient across these attachments further enhances the advantages of cost and time savings from direct internal firing. There are cases when it is necessary to heat an entire vessel in situ. In each of these instances, the vessel is insulated externally and heated internally, thus turning the vessel into its own furnace.

The use of bulkheads to isolate sections of a vessel for heating a weldment or repair is particularly appropriate in cases where the area to be heated is sufficiently large (e.g., a cluster of several nozzles, etc.) to preclude the less cost-effective use of FCP heaters. In those instances, bulkheads are typically erected beyond each edge of the required soak band at a distance based upon the heated band width requirements as previously discussed. The resultant volume between bulkheads creates an internal furnace, or heat chamber. Insulation is installed on the hot face of each bulkhead and on the external surface of the pressure vessel shell opposite the heat chamber, typically extending past the bulkheads a distance based upon gradient control band requirements as previously discussed. The volume between the bulkheads can be heated with a high velocity combustion system in the same manner as with complete vessel heating.

Burner(s) are directed into appropriate openings, such as manway(s), etc. It may be necessary to attach a special distribution tube to each burner to direct heated air flow to areas which would otherwise be difficult to heat using burners alone. Generally, each distribution tube is custom-designed using materials suitable for operation at the required temperature. Certain applications require a distribution tube that incorporates a discharge tee to force heated air in opposing directions. Often the tee will be fitted with compressed air tubing for analog control of heated air flow rates, in an effort to achieve temperature uniformity throughout a vessel with limited access openings.

The gas flow into the system can be controlled manually or automatically by the gas train’s microprocessor. Gas flow input, air input and exhaust dampers are adjusted to achieve precise control of heating and cooling rates and temperature distribution throughout the system. Burners are typically available in sizes from 1/2 MBtu/hr (0.15 MW) to 10 MBtu/hr (2.9 MW). The output of some burners can be adjusted to as little as 1% of their maximum rated power. Each burner is fitted with a spark ignition device and the flame is monitored by an ultraviolet flame sensor coupled to an automatic gas safety shut off valve, to provide a fail-safe process. In addition, each burner is coupled to an adjustable high volume air blower via flexible ducting, to provide a discharge velocity of up to 450 ft/s (137.2 mis). This establishes a turbulent flow of heated air within the vessel, and thereby enhances convective heat transfer and temperature uniformity.

The combustion system's heated air is exhausted through a dedicated opening(s), such as an existing nozzle, and may be modulated with a damper plate. The temperatures of sections or attachments with thicknesses which significantly differ from the bulk of the shell should be monitored to ensure conformity with the vessel shell at all times. In fact, supplemental electric heating should be used on nozzles, skirt welds, and other attachments of relatively large thickness, in order to achieve heating in concert with the rest of the vessel, and thereby prevent harmful temperature gradients.

One of the biggest obstacles preventing more widespread use of direct internal firing is a lack of understanding of the process. In many cases, safety concerns are raised regarding the use of a combustion heating technique, especially in a refinery or petrochemical plant environment. While it is critical to insure the safe operation of combustion heating systems in such environments, it should also be realized that electric resistance heating equipment must also be carefully controlled since it typically utilizes contactors which create sparks when opening and closing.

Considerations for Choosing the Appropriate Heating Method

Obviously, the first issue to consider when choosing which of several available heating methods to use is the ability to meet the technical requirements. Low voltage electric resistance and high velocity gas combustion can generally provide satisfactory results if correctly applied with an understanding of their limitations. For example, electric resistance heating is better suited to heat small local areas, especially where achievement of adequate gas flow might be difficult. Therefore, it is common to use both methods together: supplemental electric heaters on heavy wall attachments in conjunction with gas firing of a large section.

The need for non-uniform temperature heating provides an important example where the combined use of electric and gas firing techniques is well suited. In this situation, electric resistance heaters can be used to achieve the soak band temperature, while high velocity gas is used to heat a circumferential band of adjacent shell metal to a percentage of the soak band temperature. This provides a means to balance thermal expansion, while limiting the net section strength loss at elevated temperature. This is frequently an important consideration when heating sections of vertical vessels in which buckling or distortion due to wind, dead weight or other loads is a possibility.

Because of the ability to utilize individual zones of control, electric resistance heaters are also better suited to provide gradient heating. However, as the number of electric resistance heaters increases, the number of control zones, power/control consoles and total power requirements can become excessively large. A minimum diameter of approximately 4 ft (1.2 m) is generally required for proper application of high velocity gas combustion to prevent direct flame impingement, unless distribution tubes are used. This minimum diameter also appears to coincide with the size where high velocity gas combustion begins to gain a cost advantage, depending on the length of the heated region.

The advantages of one method over the other emerge as specific dimensions and requirements are considered. In general, as the size of pressure vessel and/or area to be heated increases, it becomes more likely that high velocity gas combustion will be more advantageous. Therefore, when not constrained by other issues, it is desirable to evaluate the cost and time requirements of each approach to insure efficient use of resources.

The following example highlights a situation where high velocity gas combustion was more advantageous than electric resistance. PWHT was required for six nozzles being attached to a DEA-absorber column. The electric resistance method required five separate heat cycles over 6 ten-hour shifts in which two nozzles were heat treated together and the others separately. Direct internal firing of bulk headed sections required only three separate heat cycles over 4.5 ten-hour shifts in which groups of three, two and one nozzle were heated at a time. As a result, the price of the high velocity gas combustion approach was approximately 40% of the electric resistance approach. Since this price difference does not reflect the impact on the plant's schedule, inclusion of down-time costs would further increase the advantage of high velocity gas combustion.

TEMPERATURE MEASUREMENT

Temperature-indicating crayons and paints, thermocouples, resistance temperature devices (RTDs), infrared instruments, bi-metallic switches, expansion bulbs, or other temperature sensitive devices may be selected to measure the temperature, depending upon the application and required accuracy. Although temperature can be measured using these various methods, thermocouples are most common for local PWHT. A detailed discussion regarding the use of thermocouples during local heating is provided in the piping and pressure vessel recommended practices{l,2). The following sections highlight several important issues relating to temperature measurement when using thermocouples.

Thermocouple Installation

Any recording or controlling instrument reads the temperature at the junction (short) between the thermocouple wires closest to the instrument. Therefore, the wires must "touch each other" or be made common only where the temperature is to be measured. At all other locations, the wires must be electrically insulated from each other and from the component being heated.

The hot junction must be at the same temperature as the surface whose temperature is being measured. Large errors can arise if there is not intimate contact or the wires contact each other outside the hot junction. This requires that:

(1) the hot junction be insulated from external radiant heat (this may require application of insulating putty);
(2) the thermocouple wire be kept under insulation for approximately 8 in. (200 mm) to prevent heat conduction along the wire (expected to be minor for thin gauge wire);
(3) the thermocouple be protected from corrosive media; and
(4) the hot junction must be in intimate contact with the surface whose temperature is being measured.

temperature differences. When using mechanically attached thermocouples (such as sheathed, twisted wire end, welded end, with or without insulation}, the measurement accuracy depends on heat transfer from the work piece to the bead junction. For such mechanically attached thermocouples, the temperature at the junction may not represent the temperature of the metal surface due to the configuration of the attachment and the proximity of the heat source. With thermocouples directly attached by capacitor dis- charge welding, the hot junction is integral to the work piece, and as such, heat transfer is generally not a concern. Temperatures of mechanically attached thermocouples which were -130°F greater than that of a thermocouple attached by capacitor discharge welding and reading 1,292°F have been reported (15). Another source reports (9) that "stainless steel sheathed thermocouples secured to the pipe wall with a welded clip consistently reported temperature values 30 - 40°F (16 - 22°C} above the temperature reported by thermocouple junctions welded to the pipe wall by capacitance discharge." The data reported (9) for these stainless steel sheathed thermocouples were taken during PWHT in the temperature range of 1,100 to l,200°F (593 to 649°C).

Fabrication codes frequently provide a special allowance for attachment of thermocouples by low energy (usually limited to 125 W-sec.) capacitor discharge welding without requiring either welding procedure or welder performance qualification testing. Such low energy attachment results in a small HAZ which is easily removed by light grinding.

After capacitor discharge welding, the thermocouple welds should be carefully inspected for proper attachment before insulation is applied to the junction. Slight pulling on the attached thermocouple wires is an effective way to insure that they are secure. In addition, it is also good practice to secure the thermocouple to the work piece so as to minimize stress on the point of thermocouple attachment (hot junction).

The above discussion has highlighted the desirability of using thermocouples which are directly attached to the component by capacitor discharge welding. It is recognized that such an installation approach may not be desirable on zirconium alloys. For components where zirconium alloy cladding on steel is being utilized, thermocouples could be directly attached by capacitor discharge welding to the steel. For cases where the temperature on a zirconium alloy surface must be measured, a mechanical attachment technique must be carefully selected so as to minimize potential temperature differences between the thermocouple junction and the zirconium alloy surface.

Installation of a spare thermocouple at each location offers a means to address thermocouple failures which may occur during the heating cycle. Therefore, use of a spare thermocouple is recommended in all cases. Duplex thermocouple wire/ extension wire is available and can be used such that two thermocouples are installed at each location and connections brought back to the control/recording equipment. While only one would be connected at any given time, the spare will be readily available in case of a problem.

Accuracy of Thermocouple Temperature Measurements

A number of factors determine the overall accuracy of a thermocouple temperature measuring system. They include sensor, system connections, and instrumentation error contributions. Using a capacitor discharge welded type K thermocouple, the overall accuracy of the system (including sensor, system connections, and instrument error contributions) is estimated to be ±5°F (±2.78°C) if proper calibration and installation techniques are used. This correlates well with recently reported (9) work in which the accuracy was reported to be ±4.5°F (±2.5°C).

Location of Thermocouples

Regardless of other considerations, the ability of thermocouples or any other method to adequately reflect temperature is dependent upon measurement at appropriate locations. There are two purposes for locating thermocouples: control or monitoring.

The location of control thermocouples must be based upon the nature of the heat source, location(s) of heat source(s), and the component being heated. The objective of control thermocouples is to assure that appropriate heat is supplied to regions (control zones) to achieve the temperatures required in these regions. For example, for a circumferential band of electric resistance heaters centered on the weld, control thermocouples would most likely be placed along the centerline of the weld.

Monitoring thermocouples should be placed to insure that all of the parameters specified to control the local heating operation are being achieved. Thermocouples should be placed to measure the maximum and minimum anticipated metal temperatures and to delineate the axial temperature gradient. To achieve this, thermocouples should be placed at planes coinciding with the centerline of the weld, the edge of the soak band and at the edge of the heated band. The number of thermocouples in each of the planes would depend upon the specific component size, configuration and geometry. It is always a good practice, if possible, to locate thermocouples on the surface opposite to that of the heat source for one sided heating, to insure that the required temperatures are achieved throughout the thickness.

The use of monitoring thermocouples represents a cost effective means to assure that specified parameters for local heating are achieved. Therefore, the use of more than the recommended minimum number of monitoring thermocouples should be considered, especially when unusual circumstances or uncertainties are present. In addition to the monitoring thermocouples, controlling thermocouples would be required, with the number and location dependent upon the number of control zones and heating method as discussed above. Figure 3 provides an example of recommended monitoring and control thermocouple locations for PWHT of a horizontal pipe butt weld for pipe size greater than 12NPS but less than or equal to 24 NPS.

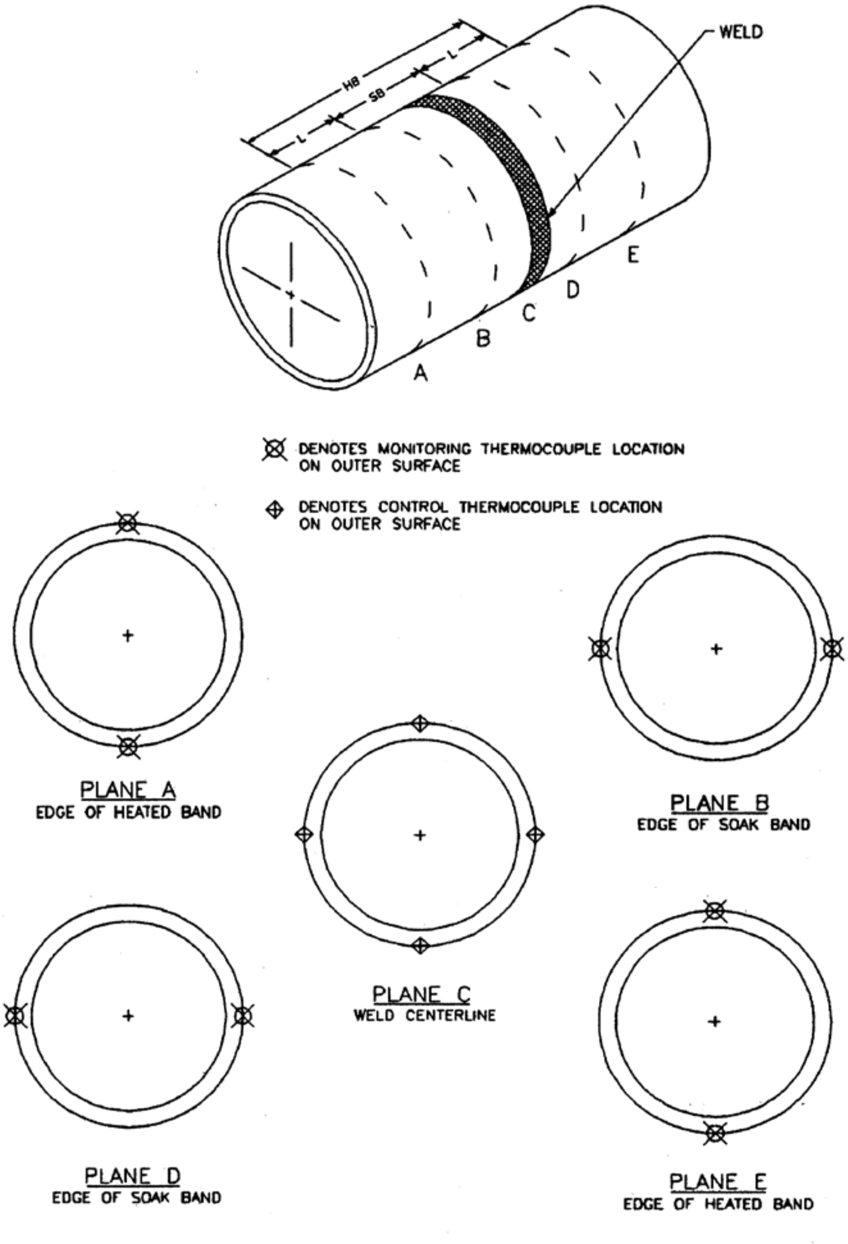
SUMMARY AND CONCLUSIONS

This paper has attempted to address some of the issues associated with local full circumferential PWHT of welds in piping and pressure vessels. The reader has been directed to recommended practices(l,2) for piping and pressure vessels for a more complete treatment of local heating issues. Use of special terminology (soak band, heated band, gradient control band, axial temperature gradient, and control zones) has been recommended to improve the ability to specify local heating procedures. Considerations and recommendations were provided regarding specification of each of these parameters. Various methods for performing local PWHT were reviewed and considerations for choosing the appropriate method(s) discussed.

Heating using high velocity gas combustion burners offers significant cost and time savings. The use of this process is often excluded due to lack of understanding. It is strongly recommended that when appropriate, the use of this process be considered.

Adequate measurement of temperature during local PWHT represents the most cost effective means for assessing whether the desired outcome was achieved. Use of thermocouples directly attached by capacitor discharge welding provides a desirable method to measure temperature. When it is necessary to measure the temperature on zirconium alloy surfaces, careful selection of mechanical attachment methods must be made to minimize temperature differences between the thermocouple and the metal surface. Recommendations were provided for location of thermocouples at the weld centerline, edge of the soakband, edge of the heated band and on the side opposite to that of the heat source (where possible).

Figure 3 . Minimum number of thermocouples (monitoring & control) recommended for circumferential PWHT of a horizontal pipe butt weld for pipe greater than 12 NPS but less than or equal to 24 NPS (4 zones of control).



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