Mechanical Behavior in Local Postweld Heat Treatment (Report III)†

- Criteria for heated band width based on through-thickness temperature distribution -

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Abstract

The heated band width is the most important processing parameter for local postweld heat treatment of tubes and pipes. A correct heated band width must be chosen so that the allowable maximum temperature difference in the soak band is maintained and a sufficient degree of stress relaxation is achieved. In this paper, the effects of the geometrical and the thermal parameters in the postweld heating treatment are investigated using axisymmetric FEM. The most severe condition in which the heat input and insulation are only applied to the outside surface of the pipe has been studied in detail. The effect of the geometrical and the thermal parameters on the through thickness temperature gradients is investigated. Through this study, it is found that the required heated band width is mainly influenced by the wall thickness and the heat transfer coefficient on the internal surface. The computed results show that the constant Hi number is inadequate for practical use under general conditions. A more general Hi number is proposed as a linear function of the thickness. Further, based on the computed results, the authors propose criteria for the heated band width which includes the effect of the geometrical and the thermal parameters.

KEY WORDS: (Postweld Heat Treatment)(Through-thickness Temperature Gradient)(Heated Band Width) (FEM)

1. Introduction

Local postweld heat treatment(PWHT) of pipes and tubes is very common in the field of fabrication and repair of pressure vessel components. When the local postweld heat treatment is performed, the weldment and the adjacent materials are locally heated to subcritical temperatures. For instance the temperature for carbon steel is 600 to 650°C. By this process, the welding residual stress is reduced and the mechanical properties of the weldment and the heat affected zone are improved. Unlike the uniform PWHT performed in the furnace, both temperature distributions along the axial direction and the thickness direction occur when a circumferential heating source is applied. In the practice of local postweld heat treatment, the temperature measuring point is fixed at the outer surface of the pipe, while no measurement is made on the inner surface. Thus, the temperature of the inner surface may not be within the permissible temperature range for the improvement of corrosion resistance or hardness reduction requirements. To ensure sufficient improvement of the toughness and reduction of residual stress, the process of the local PWHT is specified in some of the codes and standards as shown in **Table 1**. ASME Section III, B31.1, and Subsection NB do not provide specific guidance regarding the width of the PWHT heated band. Among codes which give recommendations, significant variation exists. For instance, BS2633 requires a minimum heated band width of 5 times pipe thickness. BS5500 and AS1210 also require a minimum PWHT heated band width of $5\sqrt{Rt}$ with its center at the connection, where R = inside radius and t = thickness. JIS Z3700 recommends the heated band width which covers all the area 3t from the edge in the axial direction, while 2t from the edge is recommended by JIS B8270. Special emphasis is placed on the temperature distribution along the circumferential direction in the case of horizontally oriented pipe in ANSI/AWS D10.10 and the requirement of the heated band width is given in the form of the Hi coefficient. The minimum heated band width, 2HB in **Table 1** is defined by the following equation.

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Table 1 Comparison of requirement for PWHT heated band width in various codes.

Code and Standard	Minimum Heated Band Width(mm)
B31.1	NA
B31.3	NA
ASME Section III Subsection NB	NA
BS2633	5t, either side of centerline
AS1210	$5\sqrt{Rt}$ center at the centerline
JIS Z3700	3t from the edge
JIS B8270	2t from the edge
ANSI/AWS D10.10	2HB

$$2HB=Hi[(D^2 - d^2)/2+d(SB)]/D \quad (1)$$

where D=outer diameter, d=inner diameter, SB=soak band width.

Hi is the ratio between heat input and heat loss coefficient and defined as follows.

$$Hi=Ac/(2Acs+Ai) \quad (2)$$

Ac=area covered with heating source,
Acs=sectional area of pipe,
Ai=soak band area at inner side of pipe.

The variations in the existing codes comes from two facts. One is that many factors such as the thickness, the radius, soak temperature, soak band width, insulation, etc., are influencing the size of the heated band width. The second reason is that the requirement for the heated band width changes with the purposes of PWHT. Two are proposed for PWHT. One is material improvement by keeping the soak band width in the required temperature range. Another is the relaxation of the residual stress. In this work, the critical heated band width from the aspect of the temperature gradient is investigated using FEM. Through serial computations, the effects of various parameters on the critical heated band width and the meaning of the existing criteria are clarified. Further, regression equations are proposed which give the critical heated band width, as functions of the wall thickness and the heat transfer coefficient on the internal surface.

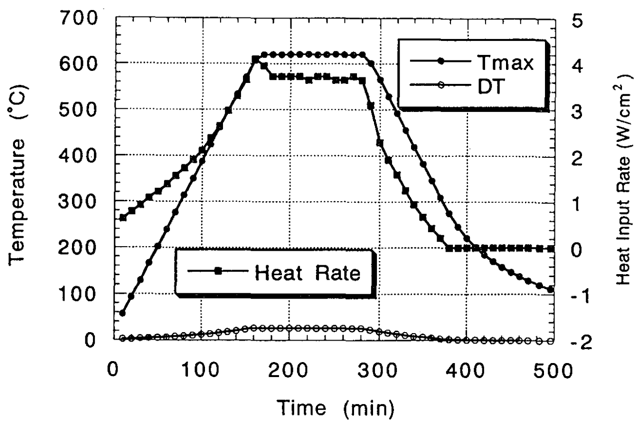

Fig. 1 Process of local PWHT and through thickness temperature gradient.

2. Local PWHT and Simulation Method

2.1 Procedure of local PWHT

In real practice of local PWHT, the heat input rate is controlled so that the temperature at the monitoring point follows a specified history which is given in terms of the heating rate, the hold temperature and hold time. The heat input is controlled in the FEM analysis as in real practice using the PID method. **Figure 1** shows the temperature history at the monitoring point which is located at the center of the heated band on the outer surface, and also, the heating rate and the temperature difference DT in the soak band. As is seen from **Fig. 1**, the temperature difference has a maximum value during the hold time. The required heat input rate also increases with the temperature during the heating process.

2.2 Simulating method

The heated band width in the local PWHT necessary for sufficient stress relaxation and material improvement is influenced by various parameters. These parameters can be classified into geometrical parameters, material parameters, thermal parameters, etc.. The geometrical parameters are the diameter D and the thickness t of the pipe. The parameters dependent on the material are soak temperature, allowable temperature variation in soak area and hold time. The heated band width, the insulation width, heating and cooling rates are the thermal parameters. Thus, depending on the size and the material parameters of the pipe to be treated, the thermal parameters, such as the heated band width, soak temperature, heating and cooling rates must be properly chosen.

To clarify the effect of geometrical parameters on the minimum required heated band width, the axisymmetric visco-elastic-plastic FEM is employed. Serial computations are performed with the following conditions.

(1) The heating rate V_H is controlled at 220*25/t °C/hr.
(2) The insulation band W_{in} is $10\sqrt{Rt}$ when the heated band 2HB<W_{in}.
(3) The hold temperature is 620°C.
(4) The soak band width SB is 3t.
(5) The temperatur gradient DT is measured at the beginning of the hold time.

Table 2 Material properties used in computation.

Temperature(°C)	20	200	500	700
Heat conductivity(W/cm°C)	0.495			0.41
Thermal capacity(J/g°C)	0.49		0.72	1.20
Density(g/cm^3)	7.85			7.60
Heat transfer coefficient(W/ cm^2 °C)	0.0033(no insulation), 0.0002(insulation)			

Table 3 Effect of insulation width.

t(cm)	R(cm)	B(cm)	Half insulation length(cm)	Temperature difference(°C)
2.73	27.3	20.5	41.0	25.42
2.73	27.3	20.5	85.0	25.45
5.46	27.3	27.3	54.0	50.37
5.46	27.3	27.3	85.0	50.02

(6) The material properties used in the computation are given in **Table 2**.

3. Effects of Specific Parameters on Through-thickness Temperature Gradients

3.1 Relationship between temperature gradient and half heated band width

When local PWHT is applied, temperature gradients occur in the soak band. With an increase of heated band width, temperature gradients(DT) are reduced as seen from **Fig. 2**. The value of DT is almost the same when the wall thickness is the same, while the outer radius R has only a small influence.

3.2 Effects of wall thickness and pipe diameter

The effect of the wall thickness upon the critical heated band width is examined by FEM analysis. Two series of computations with different allowable temperature differences, namely DT=25 and DT=40°C were performed. The soak band was assumed to be 3t in these computations. As seen from **Fig. 3**, the critical heated band width decreases with the thickness of the pipe. It also becomes small when DT is large. This means that when the temperature difference allowable in the soak band for the material to be treated is small, the heated band width becomes large.

The effect of the outer radius on the critical heated band width is examined in the same manner. Two series of pipes with t=5.46cm and t=2.73cmm were examined. Two values of allowable temperature differences, namely DT=25°C, and DT=40°C were assumed. As it is seen from **Fig. 4**, the influence of the radius is negligible when the radius is larger than certain limit. Its effect

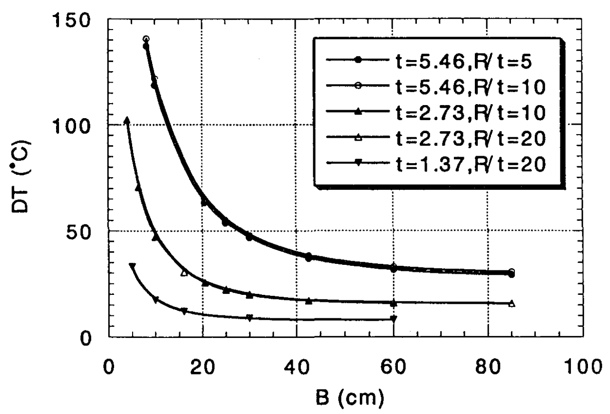

Fig. 2 Relationship between B and DT.

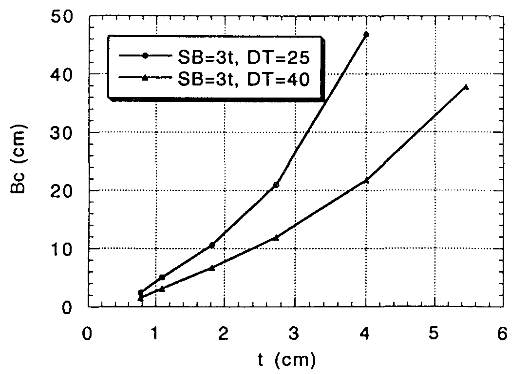

Fig. 3 Critical half heated band Bc for DT=25 and DT=40°C.

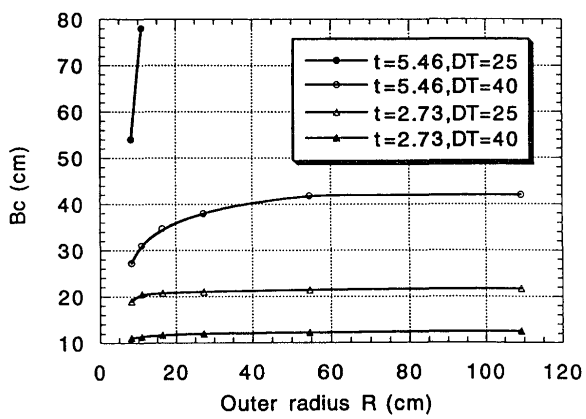

Fig. 4 Effect of radius on critical heated band width.

becomes significant when R/t becomes small. Thus, for the pipes with small R/t which are frequently used in nuclear power plants, the effect of radius can't be neglected. The critical heated band width Bc for pipes with small R/t value decreases significantly compared to those with large R/t.

3.3 Effect of insulation width

In real practice, the insulation width is greater than the heated band width, and wider insulation width is generally preferable. The influence of the insulation width W_{in} was examined using two pipes with t=2.73cm and t=5.46cm as examples. As is shown in **Table 3**, the influence of increasing the insulation width is small. When the insulation length is greater than $5\sqrt{Rt}$, the difference in DT is negligible.

3.4 Critical through thickness temperature gradients

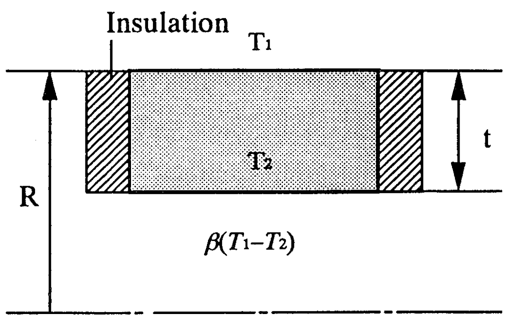

Fig. 5 Simple model of heat transfer.

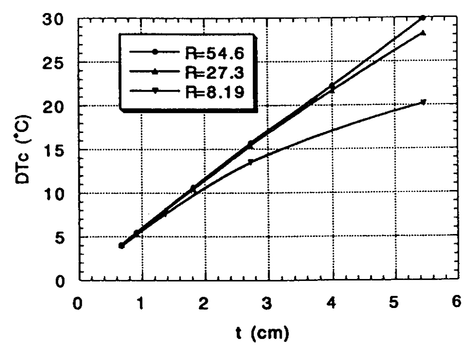

Fig. 6 Critical DT for different wall thickness.

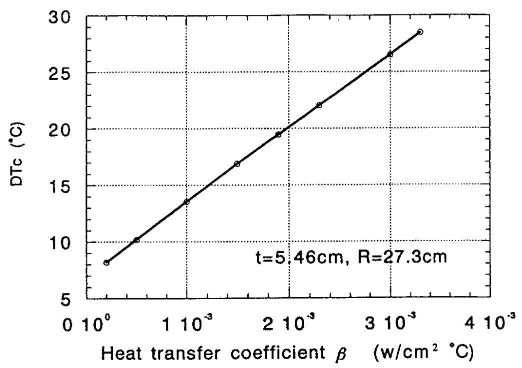

Fig. 7 Effects of heat transfer coefficient.

As long as heat flow is allowed in the form of heat transfer on the surface, a through thickness temperature gradient is unavoidable. The most severe condition is when the insulation is only applied on the outside surface of the pipe and the internal surface is not insulated. The through thickness temperature gradient in this situation can be estimated using a simple model as shown in **Fig. 5**. The model is the section of pipe with unit length. Both sides of the section are insulated. This corresponds to a heated band width of infinite length. The temperature on the outer surface of the pipe is held at the soak temperature and heat transfer is assumed on the inner surface. Since no insulation exists, the heat transfer is assumed to be 0.0033 w/cm^2°C. The computed critical through thickness temperature gradient DTc is plotted against the thickness in **Fig. 6**. As it is clearly seen, the critical through thickness temperature gradient exceeds 25°C, when the radius is 54.6cm and the thickness is greater than 4.5cm. This means that the through thickness temperature gradient can't be kept within the allowable limit no matter how large the heated band width is. In such situation, insulation on the internal surface is effective. The relation between the critical heated band width Bc and the heat transfer coefficient β for the pipe with t=5.46cm is shown in **Fig. 7** as an example. As already mentioned, the through thickness temperature requirement is not achieved without insulation(β=0.0033 w/cm^2°C). By applying insulation(β=0.0002w/cm^2°C), the requirement can be achieved with Bc=29.7cm which is practically reasonable.

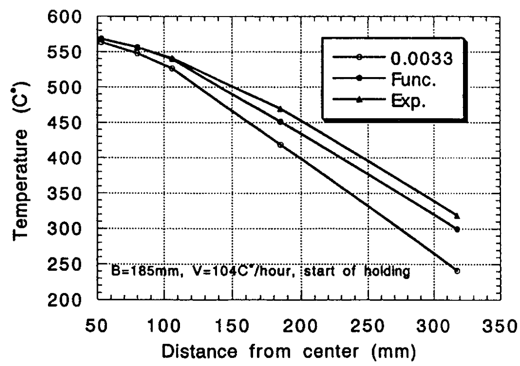

Fig. 8 Temperature distribution on inner surface.

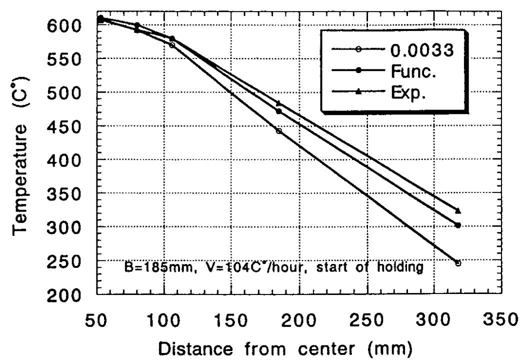

Fig. 9 Temperature distribution on outer surface.

3.5 Effect of temperature dependence of heat transfer coefficient

In a strict sense, the heat transfer coefficient on the internal surface of the pipe changes with the temperature. The function which describes the temperature dependent heat transfer coefficient is assumed to be given by Eq.(3).

$$\beta(T) = E_c * 10^{-12}\left[(T+273)^2 + (T_0+273)^2\right]\left[(T+273) + (T_0+273)\right] \quad (3)$$

The constant Ec in the function is determined to be 4.31 by comparison with measurements obtained for test models. The dimensions of the model and the processing parameters of PWHT are listed as follows.

outer radius: R=17.0cm
thickness: t=5.3cm
half heated band width: HB=18.5cm
insulation width: Win=39.5cm
heating rate: V_H =104°C/hr
heat transfer coefficient on the insulated surface:
β =0.0002 w/cm^2°C

Figures 8 and 9 show the axial distribution of temperature on the outer surface and the inner surface, respectively. The measured and two computed temperatures are compared. In one computation, constant heat transfer coefficient β =0.0033 is assumed on the inner surface. In the other computation, the temperature dependent coefficient defined by Eq.(3) is assumed. As seen in **Fig. 8** and **Fig. 9**, the agreement between the computation and the experiment is improved by use of the temperature dependent heat transfer coefficient.

The effect of the temperature dependency of the heat transfer coefficient on the temperature difference in the soak band DT, is also examined. Pipes with two different wall thicknesses, namely t=5.46cm and t=2.73cm, with the same outer radius R=27.3cm are selected as examples. The relationship between heated band width and the temperature difference DT is shown in **Fig. 10**. The effect of the temperature dependency of the heat transfer coefficient is generally small.

4. Criteria Based on Hi

The criteria based on the Hi number was proposed by C. Bloch, J.Hill and et al.[4]. It is concluded that Hi = 5 is necessary to ensure the temperature gradient in the soak band is less than 25°C. This criterion is derived using the idealized heat balance model described in **Fig.11** and assuming that the soak band width is 4t and the allowable temperature difference is 25°C.

The equation for the heat balance is given by,

$$Qc=Qa+Qcr \quad (4)$$

where, Qc is the heat flux into the pipe, while Qa and Qcr are heat fluxes out through the end sections of the pipe and the heat flux out through the heat transfer on the internal surface of the pipe, respectively. These are defined by the following equations.

$$Q_c = -K_c A_c (dT/dx)_c \quad (5)$$

$$Q_a = -K_a A_a (dT/dx)_a \quad (6)$$

$$Q_{cr} = (H_c + H_r) A_i \Delta T \quad (7)$$

where, Ac, Aa and Ai are the areas of heated surface, the cross-sectional area of the pipe and inner surface area of the soak band. Kc, Ka are constants describing heat conductivity and Hc, Hr are constants for the radiation and the convection heat transfer. (dT/dx)c and (dT/dx)a are the temperature gradients in the radial and axial directions, respectively. Following some simplification, which is discussed later, the Hi number defined by the following equation is derived[4].

$$Hi=Ac/(Aa+Ai)=Ac/(2Acs+Ai) \quad (8)$$

The procedure to derive the above equation is the following. By substituting Eqs.(5)-(7) into Eq.(4), it is found that,

$$-KcAc(dT/dx)c=-KaAa(dT/dx)a+(Hc+Hr)Ai\Delta T \quad (9)$$

At this point the following two simplifications are introduced.

(1) Assume that the contributions from Qa and Qcr are roughly the same, i.e..

$$-Ka(dT/dx)a \approx (Hc+Hr)\Delta T \quad (10)$$

(2)The order of the temperature gradient is DT/t.

$$(dT/dx)c,\ (dT/dx)a \approx DT/t \quad (11)$$

then equation(9) is reduced to,

$$KcAcDT/t \approx (Hc+Hr)\Delta T(Aa+Ai) \quad (12)$$

by rearranging equation(12), it is found that,

$$DT \approx \frac{t(Hc+Hr)\Delta T}{Kc}\frac{(Aa+Ai)}{Ac} = \frac{t(Hc+Hr)\Delta T}{Kc}\frac{1}{Hi} \quad (13)$$

The above equation suggests that the heated band width can be related to Hi. Bloch et al. demonstrated such relations based on serial experiments and proposed Hi=5 for the cases with DT=25°C. However, as seen from Eq.(13), DT is also a function of thickness t. In other word, the critical value of Hi is not a constant. It must be a function of t.

$$Hi = \frac{(Hc+Hr)\Delta T}{Kc}\frac{t}{DT} \quad (14)$$

To clarify this point, serial computations were made, and the relation between the Hi and the wall thickness were examined. In these serial computations, the two situations in which the soak band widths are 3t and 4t were examined. Noting that:

$$Ac=2\pi R*2HB$$
$$Acs=\pi\left\{R^2-(R-t)^2\right\}$$
$$Ai=2\pi(R-t)*4t \text{ or } 2\pi(R-t)*3t$$

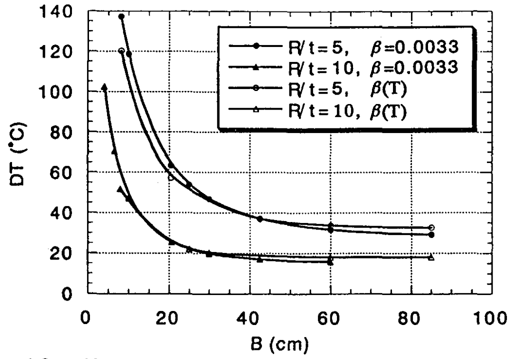

Fig. 10 Effects of temperature dependent heat transfer coefficient.

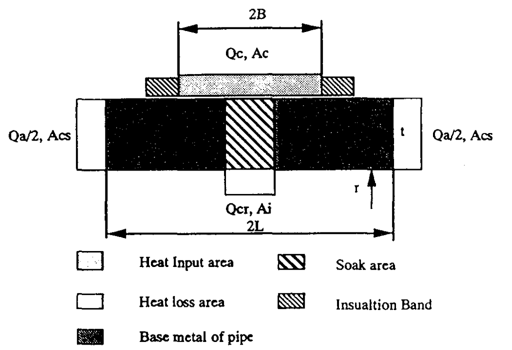

Fig. 11 A simplified heat input and heat loss model.

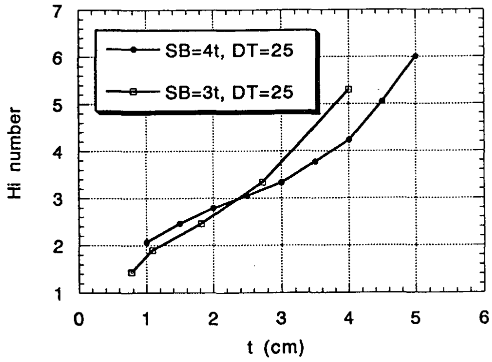

Fig. 12 Effect of wall thickness on Hi number.

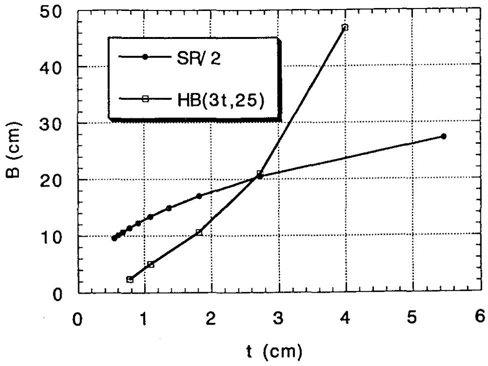

Fig. 13 Optimum critical half heated band width.

2HB=Hi*t*(6-5t/R) (for SB=4t) (15)

2HB=Hi*t*(5-4t/R) (for SB=3t) (16)

Since the critical heated band width is available from the computation, the Hi number for the given t and R can be obtained using the above relations. Figure 12 shows the relation between the wall thickness and the computed Hi number. It is seen that Hi=5 is unreasonable when the soak band width is 4t and DT is 25°C, however, it is too large for thinner pipes and too small for the thicker pipes. The influence of soak band width is slight. The effect of the radius R is expected to be small. Since the relation between Hi and t is fairly linear and this agrees with Eq. (14), a more general Hi number can be proposed as a linear function of t for the case in which DT=25°C, i.e..

Hi=1.2t (cm)

5. Proposed Criteria for Heated Band Width

5.1 Two criteria for the heated band width

As discussed earlier, both sufficient degree of stress relaxation and improvement of material properties must be achieved by the local PWHT. The criteria for the heated band width must be determined from these aspects. Figure 13 shows the critical heated band width based on the stress criterion and that based on the through thickness temperature criterion. The curves for the two criteria insect at t=27mm. Since the heated band width must be large enough to fulfill both of them, the critical heated band width is determined by the stress criterion when the thickness of pipe is less than 27mm. On the other hand, it is determined by the through thickness temperature criterion when the thickness is greater than 27mm.

5.2 Criteria for heated band width based on through thickness temperature gradient

As discussed in section three, the heated band width necessary to maintain the temperature variation in the soak band is influenced by various parameters. Among these parameters, the thickness of the pipe and the heat transfer coefficient on the inner surface of the pipe have significant influences. Thus regression curves are generated as functions of the thickness t(cm) and the heat transfer coefficient β_c (w/cm^2°C) using the results from serial computations. When the allowable temperature difference is 25°C , the critical heated band width is given by following equation.

$$Bc = (1.52 * 10^2 * \beta_c + 0.50)(2.68 * t^{2.04} + 2.10) \quad (cm) \quad (17)$$

The above equation can be applied to pipes in the thickness range of $0.7 \le t \le 4.5$ cm. The applicable upper limit is given by the critical through thickness temperature gradient as shown in **Fig. 6**. According to **Fig. 6**, the requirement of DT=25°C can't be satisfied if the thickness is greater than 4.5cm.

In the same manner, a regression curve is generated for DT=40°C and it is described by the following equation.

$$Bc = (1.52 * 10^2 * \beta_c + 0.50)(3.0 * t^{1.5}) \quad (cm) \quad (18)$$

6. Conclusion

Through the present study on criteria for the heated band width based on the through thickness temperature gradient, the following conclusion are drawn.

(1) The heated band width is mainly determined by the wall thickness of the pipe, allowable temperature variation and the heat transfer coefficient on the inner surface. The influence of the radius is observed only when the radius is very small compared to the thickness.

(2) The temperature dependent heat transfer coefficient improves the agreement between experiment and the computation, although its effect on the critical heated band width is small. Similarly, the effect of insulation width is small, if it is sufficiently large.

(3) There is a limit to the minimum temperature variation, the achievable by the local PWHT. Such critical through temperature gradients increase with the thickness. Further reduction of temperature gradient is possible by introducing insulation.

(4) The constant Hi=5 is insufficient to meet the requirement of through wall thickness temperature gradients. Results of serial computations and an equation derived using a simple heat balance model suggest that the Hi number is roughly proportional to the thickness. Thus, Hi=1.2t is proposed as a more general form of Hi number.

(5) The critical heated band width is determined by criteria based on residual stress and through thickness temperature gradient. The critical heated band width is determined by the stress criterion when the thickness of the pipe is less 27mm. It is determined by the through thickness temperature gradient when the thickness is greater than 27mm.

(6) Based on the computed results, a formula which gives the critical heated band width is proposed as a function of both the thickness and the heat transfer coefficient on the inner surface.

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