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

-Determination of Critical Heated Band during Local PWHT-

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Abstract

Local post weld heat treatment (local PWHT) is usually performed for tempering and relaxation of residual stresses. The heated band width is the most important parameter controlling the effectiveness of local PWHT. However the determination rules of this parameter are very different in the different codes. In this study, a direct criteria for heated width was used according to the creep FEM analysis of stress relief during PWHT. This method clearly shows the whole history of stress relief during PWHT and a critical heated width can be obtained. The pipe with original welding residual stresses is analyzed under different conditions of PWHT. Numerical analysis shows that the maximum residual stress after PWHT decreases when the heated width increases. When the heated width becomes large enough, the residual stress after PWHT change very slowly and a critical heated width can be found which gives a residual stress close to the value obtained from the uniform PWHT. A series of different PWHT conditions are studied to find the critical heated widths by using this method. Compared with the heated widths based upon some applicable codes, it is found that a heated area of $2.5\sqrt{Rt}$ on either side of a branch connection seems more reasonable. The through thickness temperature gradient H_i criteria is also discussed in this study.

KEY WORDS: (Post Weld Heat Treatment) (Heated Band) (Residual Stress) (FEM)

1. Introduction

Stress corrosion cracking due to the combined effects of service environment and localized weld-induced stress has been recognized as a serious problem in the welding industry for a number of years. In order to improve the ductility of welds susceptible to cracking and relieve the residual stresses the local post weld heat treatment (local PWHT) is usually performed when it is impractical to heat treat the whole vessel in a furnace. The soak band, heated band and gradient control band are the main control parameters during local PWHT. The soak band consists of the through-thickness 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 metal, HAZ, and a portion of the base metal adjacent to the weld being heated. The heated band consists of 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 weld. The gradient control band consists of the surface area over which insulation and/or supplementary heat sources are placed.

The heated band width is the single most important parameter determining the effectiveness of local PWHT. However the determination criteria for the heated band widths are very different in the different codes. ASME Sections III, B31.1 and B31.3 do not provide specific guidance regarding the width of the PWHT heated band. BS 2633 provides a minimum recommended PWHT heated band width of five times pipe thickness (5t). However, in one figure it implies use of a heated area of $2.5\sqrt{Rt}$ on either side of a branch connection, where R = inside radius and t = thickness. BS5500[1] and AS 1210[2] also provides a minimum recommended PWHT heated band width of $5\sqrt{Rt}$ centered on the weld for circumferential welds and $2.5\sqrt{Rt}$ on either side of welds which connect nozzles or attachments to the shell. An

American National Standard (ANSI/AWS D10.10-9X)[3] suggests that the size of the heated band is determined by two considerations. One is the through-thickness temperature gradient, and the other is induced stresses and distortion. The minimum heated width is determined by the larger of the through-thickness temperature (with H_i = 5) or induced stress (SB plus $4\sqrt{Rt}$) criteria. H_i is an empirically derived ratio described as follows[4],

$$H_i = A_c/(2A_{cs}+A_i) \tag{1}$$

where, A_c = area of heat source on the outside surface,

$\quad A_{cs}$ = cross sectional area of pipe wall,

$\quad A_i$ = inside surface area of soak band (assumed 4t wide, centered on weld).

All of the above criteria are not clear enough to specify the stress relief in local PWHT. The best way we consider is to know the residual stresses after PWHT directly. In this study, a direct criteria for heated width was used according to the creep analysis of stress relief during PWHT[5]. This method is clear enough to show the real situations of stress relief in PWHT and a critical heated width can be obtained. The pipes with original welding residual stresses are analyzed under different conditions of PWHT. A series of computations have been done to find the critical heated widths using this method. Compared with the heated widths based upon some applicable codes, it is found that a heated area of $2.5\sqrt{Rt}$ on either side of a branch connection which seems more reasonable. The through thickness temperature gradient, H_i criterion are also discussed in this study.

2. Direct Criteria to Assess the Heated Band Width

The direct criteria based on the residual stress after local PWHT is to find a wide enough heated band width in local PWHT to produce an equivalent residual stress distribution to that a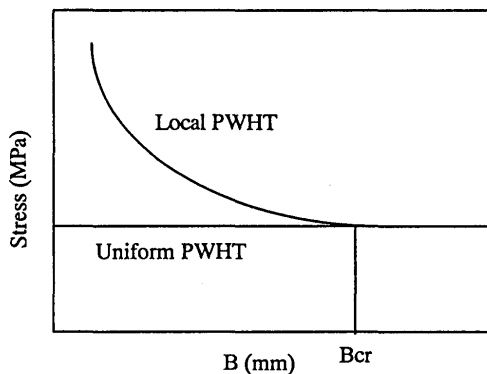rising from uniform PWHT. It is possible theoretically and has been verified by numerical analysis. The stress relief depends on the drop of yield point and the creep law of the material at high temperature. So the conditions to obtained equivalent residual stress involve keeping a uniform enough temperature in the soak zone so that no additional residual stress is induced by local PWHT. Very close results between local and uniform PWHT can be obtained. **Figure 1** shows the method to define the critical width of the heated band. As seen in **Fig.1**, the maximum residual stress after PWHT decreases when the heated width increases. When the heated band width becomes large enough, the residual stress after PWHT change very slowly so a critical heated width can be found which gives residual stresses very close to those obtained from a uniform PWHT. It is noted that the maximum temperature, heating rate and the hold time during uniform PWHT should be same as those in local PWHT.

3. Numerical Model and Series of Computation

An axisymmetric model based on the thermal-visco-elastic-plastic FEM is used. The following conditions were considered to improve the numerical model:

(1) to use the real material properties provided from JAPEIC as shown in **Fig.2**.

(2) to consider the convection heat transfer on the inside surface.

(3) to use an average stress in weld and HAZ (high stress zone) as an assessing value.

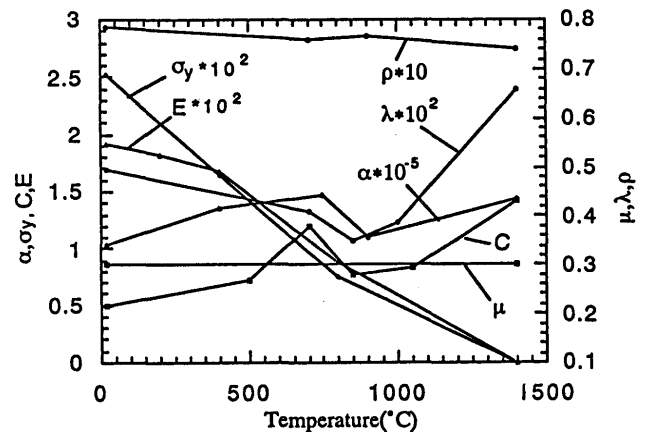(4) to consider welding residual stresses distribution occurring in through thickness welds.

Fig.1 Definition of the critical heated width

Fig.2 material properities

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Table 1   Series of computations

No.	D (mm)	t (mm)	L (mm)	V_H (°C/hr)	t_H (hr)	W_{in} (mm)	B (mm)
A1-A11	500	25	750	220	1.0	338	varied
B1-B10	250	25	750	220	1.0	238	varied
C1-C9	1000	25	1000	220	1.0	470	varied
D1-D9	500	50	1000	220	1.0	475	varied
E1-E9	500	50	1000	110	1.0	475	varied

At first the temperature distributions were analyzed and compared with the experimental results from JAPEIC[6]. The parameters in calculation: D=340mm, t=53 mm, L=900 mm, B=185, 285 mm, W_{in}=900 mm, V_H=104, 220 °C/hr. Heat transfer coefficients assumed: ß=0.0002 (insulation), 0.0033 (no insulation). Then a series of conditions for local PWHT were computed to assess their effects. **Table 1** shows the series of the computation.

Here, D = outer diameter, t = thickness, L = half length of the pipe, V_H = heating rate, T_H = hold time, W_{in} = insulation width, B = heated width.

The power creep law ($\varepsilon^c = b\sigma^n$) was used (n=5.0, b = $1.0 \cdot 10^{-9} \cdot 0.1^{5.0}$).

## 4. Results of Computation

4.1 Comparison of temperature distribution

Figure 3 and **Fig. 4** show the comparisons of temperature distribution between FEM and experiment at the start and end of holding respectively.

The figures show that the measured temperature distribution can be simulated by the FEM model when a suitable heat transfer coefficient on inside surface is introduced. The heat transfer coefficient is assumed as a constant in this study and it is expected to be improved

as a temperature function in further investigations.

### 4.2 Through thickness temperature gradient related to H_i

Here it was defined that the through thickness temperature gradient DT is the temperature gradient from the exterior center of the pipe to the interior surface at a distance of two thickness from the weld centerline. Also the uniform heat widths (assumed ΔT=25°C) on outside surface SB_0 and inside surface SB_i are calculated at the start of the hold time. Series A-E in **Table 1** are computed with the consideration of convection heat transfer on the inside surface (ß=0.0017). **Figure 5** shows the relations between DT and H_i. **Figure 6** shows the relations between uniform heat widths and H_i for series A and D. From **Fig. 5** it can be seen that the effect of pipe diameter on through thickness temperature gradient is very small. However the thickness has an important effect on DT. In other words, even the values of H_i are the same if the through thickness temperature gradients are different and if the values of thickness are different. **Figure 6** shows that the uniform heat widths on outside surfaces SB_0 and inside surfaces SB_i are very different in thick pipe (50 mm of the thickness).
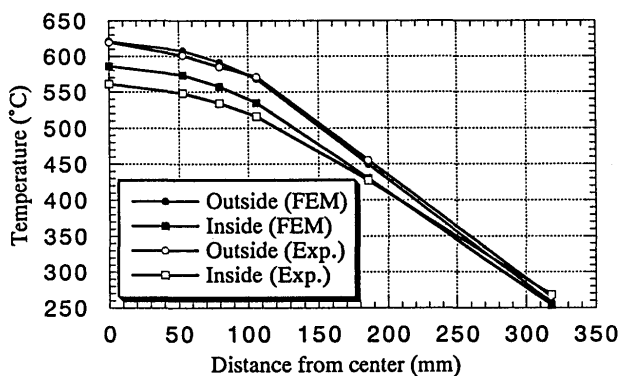
Fig.3   Temperature distribution (B185,V104,start of holding)
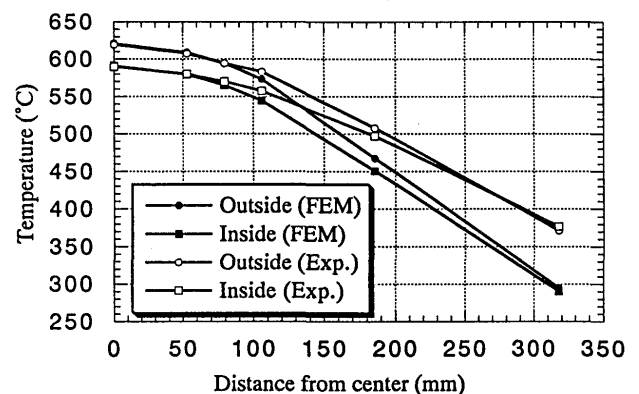
Fig.4   Temperature distribution (B185,V104,end of holding)
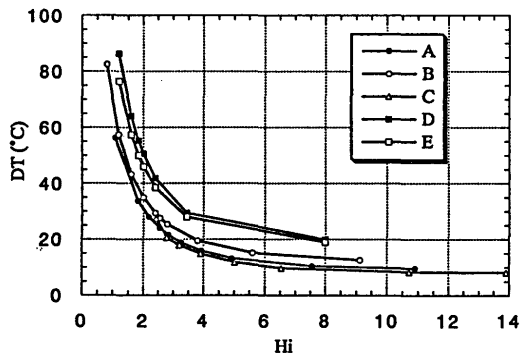
Fig.5 Relations between DT and H_i
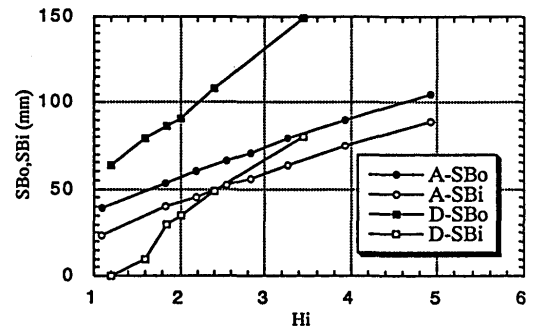
Fig.6 Relations between uniform heat widths and H_i

4.3 Axial temperature gradient

Some codes recommended controlling the axial temperature gradient by limiting the temperature drop at the edge of the heated band to one-half of the temperature at the edge of the soak band. Here are some computed results about this problem. Series A in **Table 1** are computed with the consideration of convection heat transfer on the inside surface (β=0.0017). The temperature at the edge of the soak band is 600 °C.

Table 2 Axial temperature gradients

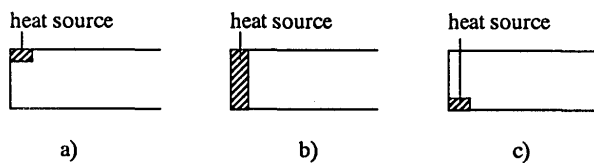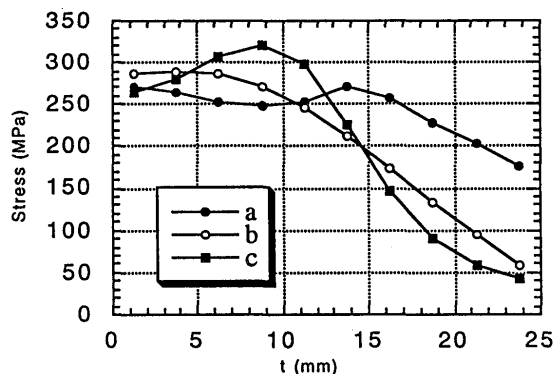| Heated width (mm)	75	125	150	175	195	225	270	338
T_{HB} (°C)	530	483	462	442	427	406	374	319
Temp. drop (°C)	70	117	138	158	173	194	226	281

Fig.7 Three types of welds

Fig.8 Distribution of welding residual stresses through the thickness

Table 2 shows the temperature at the edge of the heated band T_{HB} and the temperature drop between these two edges related to the heated widths at the start of the holding. From **Table 2** it can be seen that the temperature drop increases when the heated width increases and all are within the limit of one-half of the temperature at the edge of the soak band. However the temperature drop should be divided by the distance between above two edges to show the axial temperature gradient which decreases with the increases of the heated width.

4.4 Influence of welding residual stresses distributions

Three kinds of welds are analyzed by FEM for comparison. The heat sources are near the outside, near the inside and through thickness respectively as shown in **Fig.7 a), b)** and **c)**. The distribution of welding residual stresses (circle stress) along the thickness direction is shown in **Fig.8**. It can be seen that the locations of maximum stress in three kinds of welds and the stress level in outside parts of the pipe are very different. These may have an influence on stress relief during local PWHT. Computation results show that residual stresses of type(a) can be reduced by local PWHT even less than by uniform PWHT when the heated width is large enough. However it is difficult to get same result for type(c). The type(b) is in the middle situation. **Figure 9** shows the characteristics of stress relief related to heated width under three types of weld conditions. These phenomena may be explained by the interaction between welding residual stresses and thermal stresses induced by local PWHT. The bending stresses induced by local PWHT are positive on outside surfaces and negative on inside surfaces and may reduce the welding residual stresses of type(a).
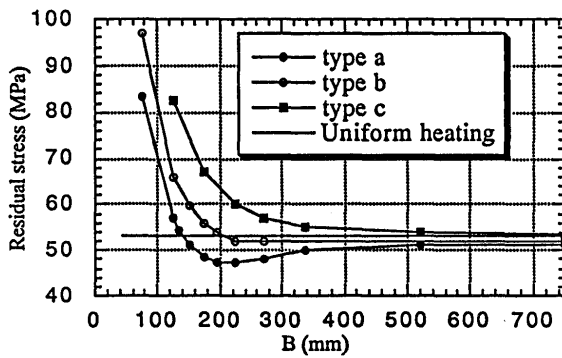
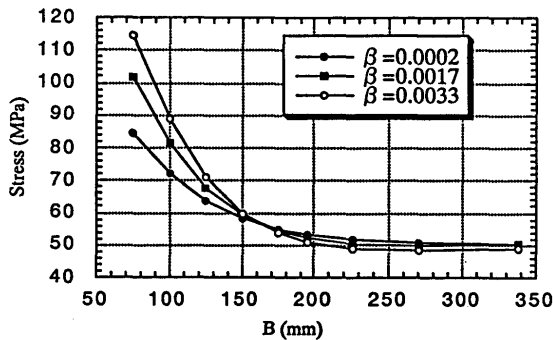**Fig.9** Residual stresses related to heated width under three types of welds

Fig. 11 The relation between residual stresses and heated width for series A,B,C

Fig.10 Residual stresses under different heat transfer conditions
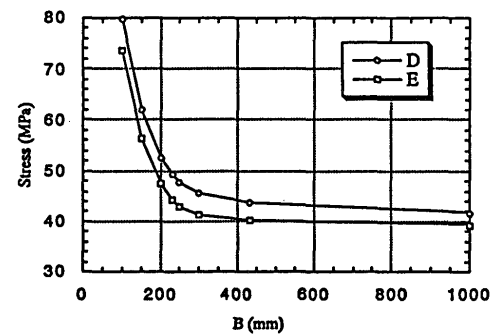
Fig. 12 The relation between residual stresses and heated width for series D,E

4.5 Influence of the convection heat transfer on the inside surface.

Figure 10 shows the relation between residual stress and heated width of series A with different convection heat transfer on the inside surface. It can be noted that the residual stress increases with an increase of convection heat transfer coefficient only in the case of narrow heated widths. When the heated width is large enough, the residual stresses are very close and the critical heated widths are similar under different conditions of convection heat transfer. Of course it is necessary to increase the heating power when convection heat transfer increases. This phenomenon is important to show that it is impossible to reduce the residual stresses by unnecessarily increasing the heated width.
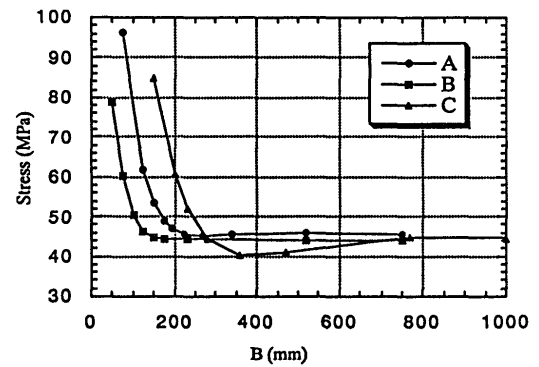
4.6 Residual stresses after stress relief of PWHT

The residual stresses after stress relief in local PWHT under different conditions in **Table 1** are computed by FEM creep analysis. The through thickness heat source was used to determine the welding residual stresses (type b). The convection heat transfer on the inside surface was assumed ß=0.0017.

Figure 11 and Fig. 12 show the relation between residual stresses and heated width for series A-E respectively. Here, the average circle stress in weld and HAZ (high stress zone) was used as an assessing value since it is more stable than the maximum stress. The critical heated width is defined as that width which

Table 3 Critical heated widths and some computed results

No.	D (mm)	t (mm)	DT (°C)	SBo (mm)	SBi (mm)	Sr (MPa)	Bcr (mm)	Bcr/t	Bcr/$\sqrt{Rt}$	H$_i$
A	500	25	23	67	53	48.5	180	7.2	2.4	2.62
B	250	25	35	51	40	46.4	125	5	2.5	2.0
C	1000	25	16	92	74	47.5	260	10.4	2.5	3.62
D	500	50	51	91	35	47.8	250	5	2.5	2.0
E	500	50	46	93	49	44.3	230	4.6	2.3	1.84

Fig.13 Stress histories during PWHT under different heated widths

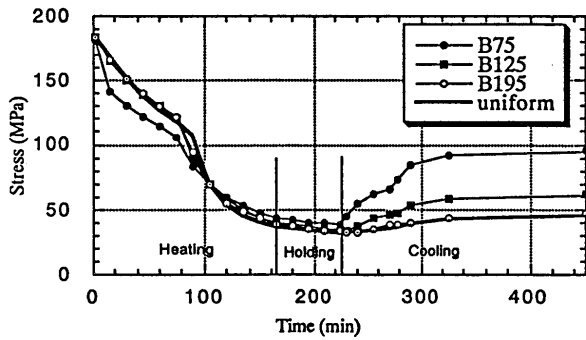Fig.14 Residual stress distributions under different heated widths

reaches the residual stress after PWHT and changes very slowly close to the value obtained from the uniform PWHT.

Figure 13 and **Fig. 14** show the stress histories during local PWHT and the residual stress distributions for series A respectively.

Table 3 shows critical heated widths and some computed results. Sr are the residual stresses after stress relief by local PWHT for these critical heated width.

5. Discussions

5.1 About criteria for sizing heated band width

This study shows that direct criteria based on the residual stress after local PWHT are very useful tools for sizing heated band widths. This is clearly shown by the results comparing those analyzed using the thermal stress or residual stress induced only by local PWHT. It is found that the diameter and the thickness of the pipe have a large influence on the residual stresses after local PWHT. As seen in **Table 3**, the criterion of five times pipe thickness (5t) seems not suitable. A heated area of $2.5\sqrt{Rt}$ on either side of a branch connection, and SB plus $4\sqrt{Rt}$ (centered on weld, SB=3t), are two criteria that seem reasonable compared with this study. The H_i=5 criterion is too large from the view of residual stress even under the case of convection heat transfer on inside surface. It is necessary to make the H_i concept clearer by further investigations.

5.2 About H_i=5 criteria

This criterion is based on the concept of through thickness temperature gradients determined by experiments. The H_i number should have a value of at least 5 to maintain a maximum temperature gradient of no more than 25°C. However through our computations

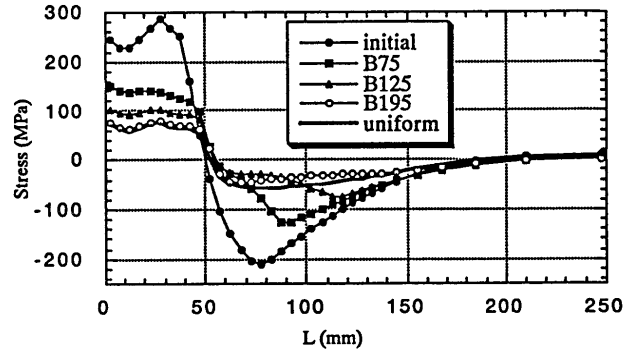we found that the relations between DT and H_i are very much influenced by the thickness as shown in **Fig.5**. Here an axisymmetric model was used with a consideration of the convection heat transfer on the inside surface. It is expected that DT will increase if the temperature differences between the 6:00 and 12:00 position are considered. This phenomenon means that even when the values of H_i are the same, the through thickness temperature gradients are different if the values of thickness are different. H_i=5 criterion may be too large for small thickness and may not be large enough for large thickness. It seems that the experiments from reference[4] were with 1-in (25 mm) thicknesses only and there are no data for 2-in (50 mm) thicknesses.

On the other hand, residual stresses are influenced by two factors. One is temperature distribution, the other is the constraint of the structure. The H_i criterion considers the temperature distribution, but does not consider the constraint, especially the influence of the diameter of the pipe which affects residual stresses.

5.3 About soak band

When using the $2.5\sqrt{Rt}$ criterion of the heated width from the point of view of stress relief, the other important problem is to ensure the soak band which contains a through-thickness volume of metal since there are two main purposes for PWHT. One is to improve the properties such as the hardness of the welding joint, the other is to relieve the residual stresses. The through-thickness temperature gradient of the soak band is more related to the improvement of the properties. However it is difficult to define a constant temperature gradient such as 25 °C for any cases. The important problem is to ensure the soak band is heated to the minimum but does not exceed the maximum required temperature and these factors depend on types of the material. Two required considerations for heated band width can be suggested.

One is from the point of view of stress relief and it has already been dealt with successfully in this study. The other is from the point of view of property improvement and it involves ensuring that the through-thickness temperature gradient in the soak band. The heated band width can therefore be obtained by the choice of the larger one from both considerations. Because of the imperfectious of the H_i criteria mentioned above it is also possible to develop instead a new through-thickness temperature criterion. Through series of computations and experimental results, the optimum heated band width can be obtained by considering the allowable through-thickness temperature gradient DT and the effect of size of the vessel (such as thickness t and radius R). Based upon these results it is possible to find a new through-thickness temperature criterion which can be used during local PWHT of pressure vessels.

The $H_i=5$ criterion considered the temperature differences between the 6:00 and 12:00 positions on horizontal pipe due to convection heat transfer. However, increasing the heated width to solve this problem is not the only way and may not be best from the economic view. Several ways can be suggested such as multiple control zones, coil induce heating, interior surface insulation, non-uniform heated width etc. and some of them have already been used in Japan.

5.4 Heating and cooling rates, hold time

According to the creep law the degree of stress relief is primarily related to the hold temperature. The creep strain rate at 650 °C is much greater than that at 600 °C. Stress decreases slowly when the hold time increases, so too a long hold time is not necessary. The additional residual stress may be caused by creep strains occurring under the condition of insufficient heated band widths. When the heated band is wide enough it's very small and can be neglected. The heating and cooling rates have some influence on residual stress and it's better to give a limit value.

6. Conclusions

(1) The measured temperature distribution can be simulated by an FEM model when a suitable heat transfer coefficient on the inside surface is introduced. The heat transfer coefficient was assumed as a constant in this study and it is expected to be improved as a temperature function in further investigations.

(2) Three kinds of welding residual stress distributions are used to show the effects on stress relief during local PWHT. The through thickness weld is closer to real situations and is used in this study.

(3) The residual stress increases with an increase of the convection heat transfer coefficient only in the cases of narrow heated widths. When the heated width is large enough, the residual stresses are very close and the critical heated widths are similar under different conditions of convection heat transfer.

(4) From the point of view of stress relief, the criterion of five times pipe thickness (5t) seems not suitable. A heated area of 2.5 $\sqrt{Rt}$ on either side of a branch connection, and SB plus 4 $\sqrt{Rt}$ (centered on weld, SB=3t), seem more reasonable on the basis of this study.

(5) The relations between the through thickness temperature gradient DT and H_i are influenced by the thickness. The H_i concept may not be suitable for heavy wall thickness pressure vessels.

(6) Property improvement and stress relief are the two main considerations for sizing the heated band width. It is possible to develop a new through thickness temperature criterion instead of H_i by this method in further investigations.

(7) The temperature differences between the 6:00 and 12:00 position on horizontal pipe can be found due to convection heat transfer. Several ways can be suggested such as multiple control zones, coil induce heating, interior surface insulation, non-uniform heated width etc.

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