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Mechanical Behavior in Local Post Weld Heat Treatment (Report IV)†

- Influence of residual stress distribution in multi-pass welding -

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Abstract

Local post weld heat treatment (local PWHT) is usually performed for tempering and relaxation of residual stresses. The degree of stress reduction is influenced by the initial welding residual stress and the local PWHT applied. The residual stress distribution after the local PWHT for multi-pass welding joint of a pipe with heavy wall thickness is not very clearly understood yet. In this paper, the time history and the final distribution of the stress components under local PWHT, with different types of multi-pass welding process, have been studied. The local PWHT on the butt joint of a pipe is analyzed using an axisymmetric FEM model. Results show that the welding residual stresses change with the sequence and number of welding passes. The residual stress on the outer surface decreases slowly with the increase of the heated band width. On the contrary, the residual stress on the inner surface can be removed effectively with relatively small heated band width. Excessively wide heated band widths appear ineffective to further reduce the residual stress.

KEY WORDS: (Post Weld Heat Treatment) (Heated Band Width) (Multi-pass Welding) (FEM) (Creep) (Residual Stress Distribution)

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 industry for a number of years. In addition to the improvement of ductility of welds, local PWHT is performed to relieve the residual stresses when it is impractical to heat treat the whole vessel in a furnace. Many efforts have been addressed in published papers. F. M. Burdekin[1] took the hot yield strength of material at the local PWHT temperature as the target level of stress relief for the vicinity of weld and proposed a full heated band of $5\sqrt{Rt}$, where R and t are the inner radius and the thickness of the pipe. Varieties of criteria for the heated band width can be found in various codes and standards. An American National Standard (ANSI/AWS D10.10-9X)[2] suggests that size of the heated band width is determined by two considerations. One is the through-thickness temperature gradient, and the other is induced stresses and distortions. The minimum required heated band width determined considering the induced stress is SB plus $4\sqrt{Rt}$. Here SB is soak band. Recent studies show that the residual stress computed by creep analysis can give a direct criterion to assess the effect of stress relief[3,4,5].

The effects of welding residual stress on the heated band width necessary to achieve the expected level of stress relaxation have not been studied, especially for multi-pass welding. In this study, direct criteria for heated band width based on the residual stress computed by the FEM are employed to assess the effect of the welding residual stress on the local PWHT. Pipes with three types of welding residual stresses are analyzed under different conditions of PWHT. A series of computations using an axisymmetric model have been done to find the critical heated band widths.

2. Simulation Procedures and Model for Analysis

The pipe specimen with the following parameters is assumed to welded by multi-pass welding with different sequences. The specimen is cooled to room temperature by air cooling before the welding of subsequent layers. Welding speeds are selected between 500 and 600mm/min. The dimensions of the specimen are,

D=546mm, t=27.3 mm, L=1000 mm

The half groove width is 8mm. A specimen with idealized single pass welding is also analyzed for comparison. The welding parameters, such as the heat input Q and the cooling rate from 800℃ to 500℃

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$t_{800/500}$ are given in **Table 1**. The cooling rate is controlled to reflect the process in typical multi-pass welding.

Three types of welding model and PWHT model examined in this study are shown in **Figs. 1(a)** and **(b)**. Type-1 represents multi-pass welding starting from the inner surface as in the ordinary practice. Type-2 represents multi-pass welding in the reversed sequence. Type-3 is the idealized single pass welding. 2B represents the heated band width applied to PWHT process and W_{in} is thermal insulation width. Considering the geometry of circumferential butt welding, a simplified axisymmetric model based on the thermal-visco-elastic-plastic FEM is used. After the analysis of the welding residual stress, the creep analysis of the local PWHT is performed. The following conditions are considered in the numerical simulations.

(1) Heating rate is controlled as 220× 25/t (℃/hr).

(2) Material properties of the carbon steel shown in **Fig. 2** and the temperature dependent heat transfer coefficient given by the following equation are used.

$$\beta = E_c\left[(T+273)^2+(T_0+273)^2\right]\left[(T+273)+(T_0+273)\right]10^{-12} \quad (1)$$

where Ec=0.37 is coefficient assumed for surface where heat source is applied, Ec=4.31 is assumed for the surface subjected to air-cooling.

(3) The average values of the stress distributing on the inner and the outer surfaces in the weld and the HAZ are used to assess the effectiveness of the PWHT. Through thickness averag is also used as the third indicator.

(4) The holding temperature is 620℃ and the holding time is one hour.

(5) Power creep law ($\varepsilon^c = b\sigma^n$) with temperature dependent coefficients as shown in **Table 2** is used.

Table 1 Cases of welding and processing parameters.

Case	Layer	Q(J/mm²)	$t_{800/500}$(sec)
type-1	1	30	14.5
	2		16.8
	3		14.3
	4		11.3
	5		11.2
type-2	1	30	14.7
	2		15.6
	3		13.8
	4		10.2
	5		10.1
type-3	1	10	22.5

Table 2 Creep law used in computation.

T(℃)	450	500	600	625
b1	4.19×10^{-22}	1.67×10^{-18}	1.67×10^{-16}	6.67×10^{-16}
n1	5.0			
b2	2.64×10^{-21}	1.05×10^{-17}	1.05×10^{-15}	4.20×10^{-15}
n2	4.2			

3. Characteristics of Computed Welding Residual Stress

3.1 Residual stress distribution in the axial direction

Some of the existing codes recommend 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, but no recommendation on the distribution of the stress is given in any code or standard. Generally, welding produces high circumferential stress (σ_θ) and axial residual stress (σ_z). The axial distributions of the computed circumferential stresses on inner and outer surfaces are shown in **Figs. 3(a)** and **(b)**. The distributions on both inner and outer surfaces are generally the same regardless of the types of welding considered in this study. The maximum value appears in the heat affected zone (HAZ) adjacent to the weld and its value is roughly the level of yield stress. The minimum stress appears at the position 50 mm from the weld. This point corresponds to the edge of the region where the inherent strain (the plastic strain produced by the welding thermal cycle) exists. The residual stresses become negative or negligibly small when the distance from the weld is larger than 50 mm.

The axial distributions of the axial component of the stresses are shown in **Figs. 4(a)** and **(b)**. Unlike the circumferential component, the distributions on inner and outer surfaces are quite different. This arises from the fact that the axial stress away from the weld is caused by the bending of the pipe wall due to the circumferential shrinkage of the weld joint and the rotation of the groove. The magnitude of the bending stress is governed by the parameter $\sqrt{Rt}$. The rotation of the groove depends on the sequence of the welding.

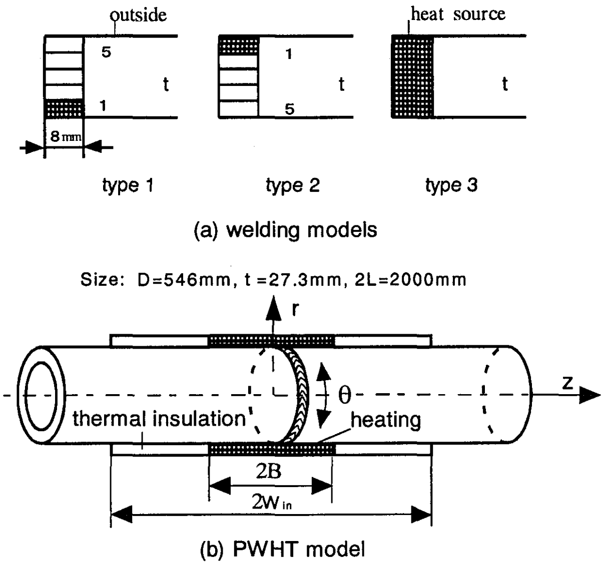

Fig. 1 Three types of welding and PWHT models.

Thus the rotations of the groove for type-1 and type-2 welding are opposite. The magnitude of the bending stress is the largest in type-1 because the circumferential shrinkage and the rotation of the groove act in the same direction. The magnitude is the smallest in type-2 because these factors act in opposite directions. It is also observed that the magnitude of the axial component of the stress in the normal sequence of multi-pass welding (type-1) is quite small compared with other types.

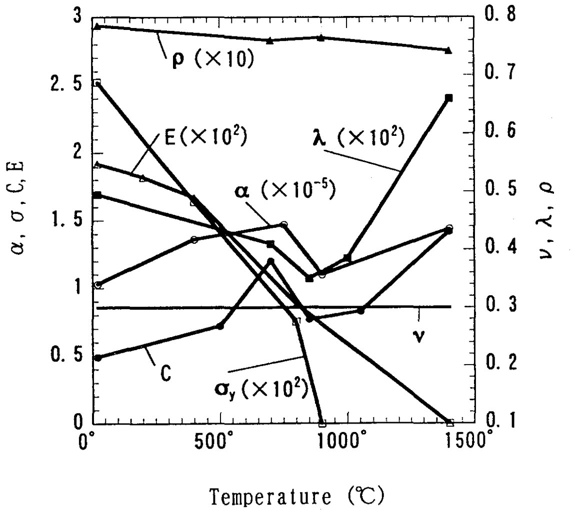

Fig. 2 Material properties of carbon steel.

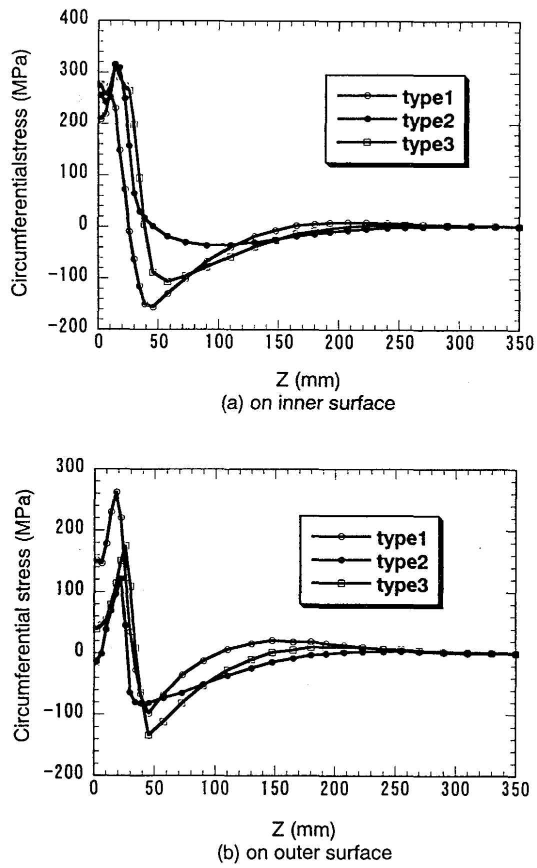

Fig. 3 Axial distribution of circumferential welding residual stress.

3.2 Through thickness welding residual stresses distributions

The through thickness distributions of welding residual stresses on the cross-section 10 mm away from the centerline of the weld which corresponds to the fusion line are shown in **Fig. 5**. It can be seen that the distributions of the stresses are quite different for three types of welds. In case of type-1, the through thickness distributions of the stresses are fairly uniform and the magnitudes are relatively small compared to the other two types. Comparing inner and outer surfaces, the stresses are generally larger on inner surfaces.

4. Residual Stresses after Local PWHT

4.1 Characteristics of residual stress

Figure 6 shows the history of the stress during the local PWHT in case of type-1 welding residual stress with a heated band width of 140 mm. The histories of the circumferential stress on inner surface, outer surface and through thickness average are shown. The stresses on both inner and outer surface are averaged value over the area 20 mm from the center of the weld. The through thickness average is taken the same width. As it is clearly seen, the circumferential stress on the inner surface is relaxed faster than that on the outer surface in the heating process. The effect of the heated band width on the stress relaxation of type-1 welding is shown in

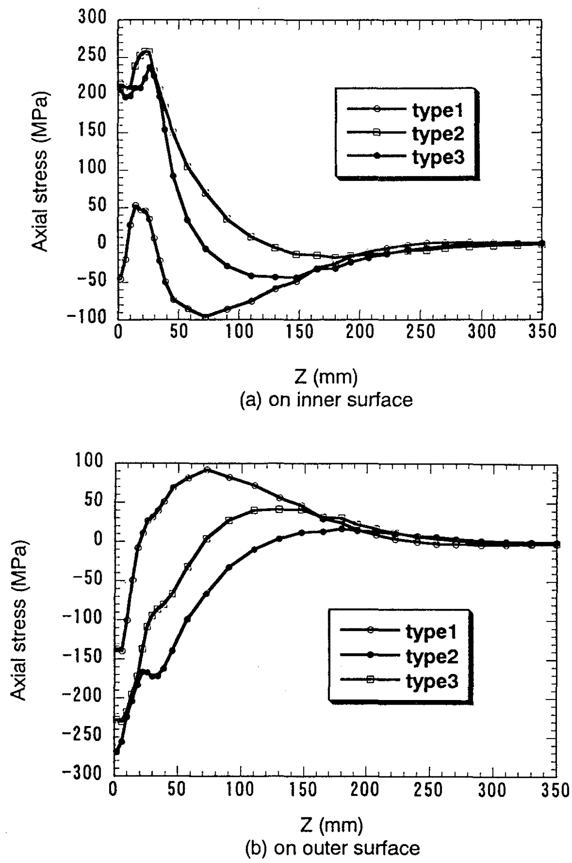

Fig. 4 Axial distribution of axial welding residual stress.

Figs. 7(a) and **(b)**. The stress histories under the uniform PWHT are also shown for comparison. The stresses shown here are the average over the area 20 mm from the center of the weld. When the heated band width is larger than 140 mm, the welding residual stress, especially the circumferential stress on the inner surface, is reduced to the level of uniform PWHT. The axial distributions of the stresses are shown in **Figs. 8**. The shape of stress distributions is almost maintained during the local PWHT, except for the circumferential stress on outer surface.

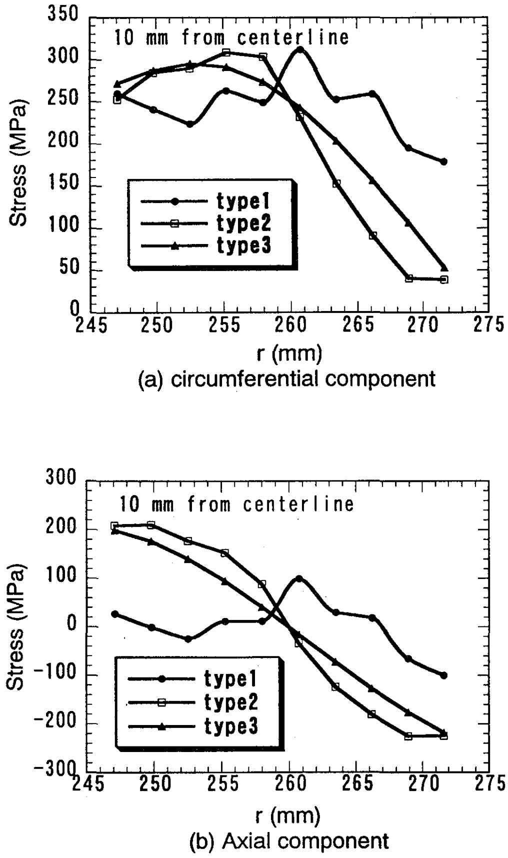

Fig. 5 Through thickness distribution of welding residual stress.

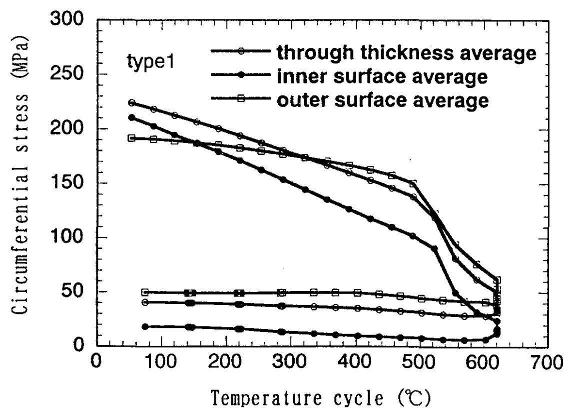

Fig. 6 Stress history in thermal cycle during local PWHT.

4.2 Relationship between residual stress and heated band width

The relation between the heated band width and the residual stress after the local PWHT is summarized in **Fig.9**. Since the circumferentail stress is dominant, its values on both inner and outer surfaces are plotted in Fig.9 (a) and (b), respectively. In general, the residual stresses after PWHT becomes small when the heated band width is large. If the curves are closely examined, they are divided into two types as shown in **Fig. 10**, namely the local minimum type and the monotonic type.

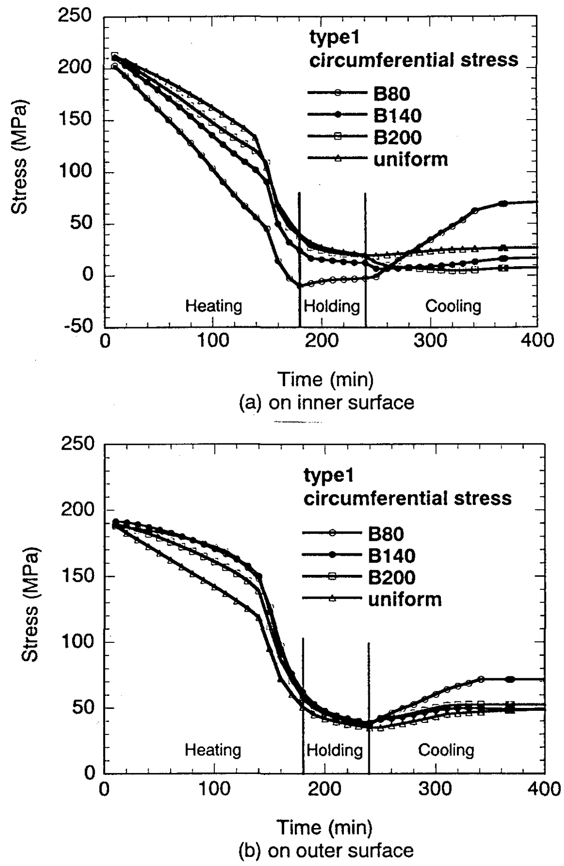

Fig. 7 Effect of heated band width on stress relaxation by local PWHT.

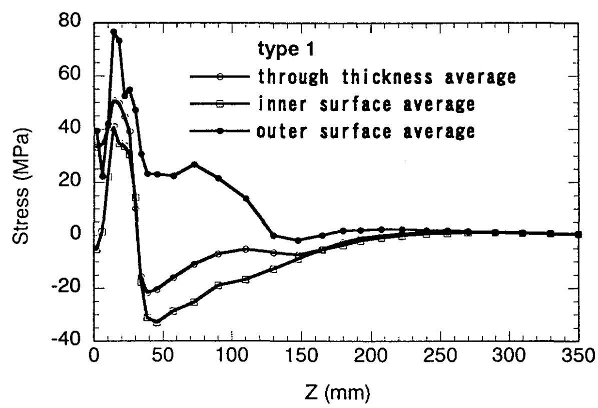

Fig. 8 Circumferential stress distribution after local PWHT.

The stress on the inner surface for type-2 and type-3 and that on outer surface for type-3 decreases monotonically with the increase of the heated band width. On the other hand, stresses for type-1 welding have a minimum value at certain value of heated band width.

Comparison with the uniform PWHT tells us that the residual stress becomes smaller than that for uniform PWHT when the heated band is wide enough except for the stress on outer surface for type-2 and type-3 welding.

4.3 Definition of critical heated band width

The critical heated band width is defined as the half width of the heated band which is large enough to relax the welding residual stress to the same degree as in the case of the uniform PWHT. It can be obtained as the heated band width B at the intersection of curves for the local and the uniform PWHT in Fig. 9. According to this definition, the critical heated band width can be determined except for the stress on the outer surface with type2 and type-3 welding. Since type-2 and type-3 welding are exceptional as welding procedures, this definition can be applied to the most cases of practical welding. Using this definition, the critical heated band widths for type-1 welding determined based on stresses on inner and outer surfaces are 140 mm and 100 mm, respectively. Noting that $\sqrt{Rt}$ =81.9, these values of heated band are about 1.2~1.7$\sqrt{Rt}$.

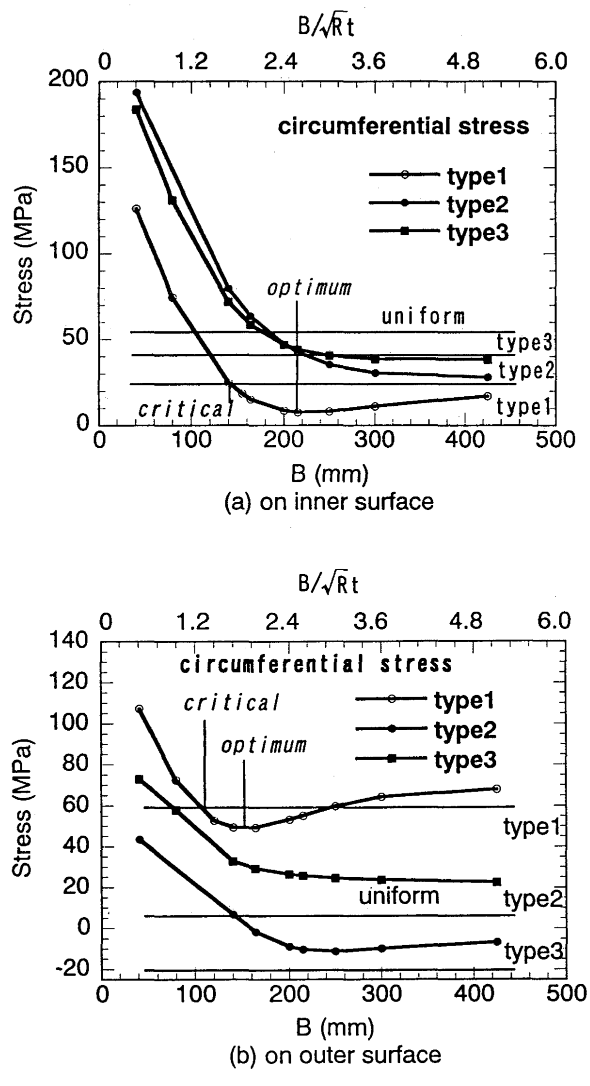

Fig. 9 Relation between heated band width and residual stresses after PWHT.

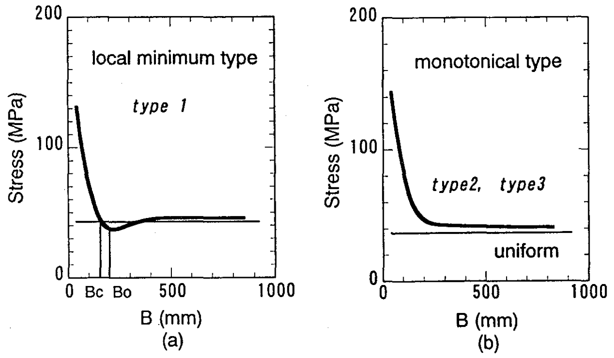

Fig. 10 Definition of critical and optimum heated band widths (a)local minimum type(b)monotonic type.

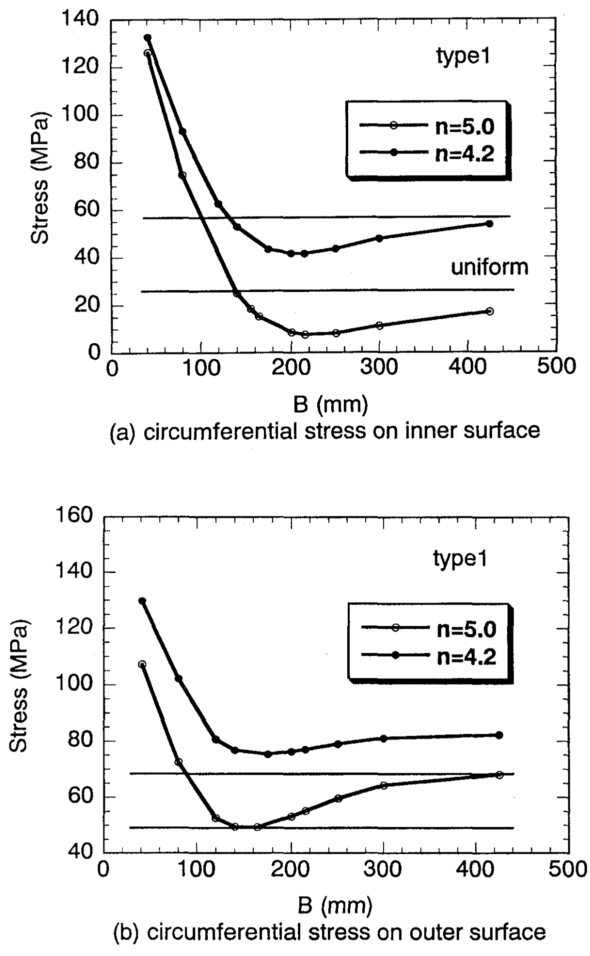

Fig. 11 Effect of exponent in creep law on residual stress.

In addition to the critical heated band width, an optimum heated band width can be defined. When the curve representing the relation between the heated band width and the residual stress is the local minimum type, the optimum heated band width is obtained as the band width which gives the minimum stress. In case of type-1 residual stress, the optimum half heated band widths based on stresses on inner and outer surfaces are 230 mm ($2.8\sqrt{Rt}$) and 150 mm ($1.8\sqrt{Rt}$), respectively (see Figs 10(a), (b)). Comparing these values with 2.5t, which is recommended by BS2633[6] and 68 mm in this case, the requirement of 5t may be less conservative compared to $2.5\sqrt{Rt}$ recommended by AS1210[7].

4.4 Effect of exponent of creep law

Figure 11 shows the effect of the exponent of creep law on the stress relaxation during the local PWHT. The relation between heated band width and the circumferential stress by the local PWHT with B=140 mm is shown. When the exponent is 5.0, the magnitude of the stress is about 30 % less compared to the case of 4.2. This implies that the creep property must be carefully chosen so that reliable prediction on residual stress can be made. However the value of the optimum heated band width is not significantly influenced by the exponent of creep law.

5. Conclusions

(1) Three types of welding residual stress distributions are used to show the effects of initial stress distribution on the stress relief during local PWHT. The welding residual stresses distribution, especially that of the axial component, is quite different compared with the residual stresses formed by idealized single pass welding. The peak values of welding residual stresses generally appear in the HAZ adjacent to the weld on both inner and outer surfaces and they reach almost the yield stress.

(2) The residual stress is relaxed through the combined actions of the thermal stress and the initial stress itself. In addition to that, a difference of constraint may cause a difference in the degree of relaxation of each stress component. The computed results show that the distribution form of the stress components after the PWHT remain roughly the same as those of the initial welding residual stresses, except for the circumferential stress on outer surface. Thus, the magnitude of the stress at a point, or an average over the high stress area, can be used as a measure to determine the critical heated band width.

(3) Comparing the types of welding residual stress, the degree of residual stress relaxation on the inner surface is the largest for type-1 and the smallest for type-3. The curves describing the relation between the heated band width and the residual stress can be divided into the local minimum and the monotonic types. Type-1 welding, which is corresponds to normal welding procedure, belongs to the local minimum type. For type-1 welding, both the critical heated band width and the optimum heated band width can be defined.

(4) From the point of view of stress relief, the criterion of 2.5t may not be sufficient and the criterion of $2.5\sqrt{Rt}$ gives more reasonable criterion on heated band width.

Acknowledgement

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