Heated Band Width Criterion Based on Stress Relief in Local Post Weld Heat Treatment of Concurrent Tubular Joint †

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Abstract

A direct quantitative method has been proposed to assess the effectiveness of stress relief for tubular joint in local post weld heat treatment (PWHT). The 3-D welding residual stress and temperature fields in local PWHT are constructed. The characteristics of stress distribution in local PWHT for tubular joints have been studied using visco-elastic-plastic FEM. The welding stress distributions in single pass welding of different welding conditions are quite similar. The different welding sequences have little influence on the location of the peak value of stress. The degree of welding stress relief in hot spots of tubular joints under different conditions of local PWHT has been analyzed. The residual stress is greatly reduced with increase of the heated band width in local PWHT. The relations between heated band width and stress of circumferential and axial components are quite different. The optimum heated band widths for circumferential and axial components are $3.46\sqrt{Rt}$ *and* $4.8\sqrt{Rt}$. *Based on the computed results for serial computations with varying the parameters in local PWHT, a criterion of heated band width is recommended for the local PWHT of concurrent tubular joint in.*

KEY WORDS: (Local Post Weld Heat Treatment) (Tubular Joint) (Visco-Elastic-Plastic FEM) (Heated Band Width)

1. Introduction

Tubular joints are widely used in the field of pressure vessel manufacturing. The study of mechanical behavior of tubular joints in local post weld heat treatment (PWHT) and the criteria for stress relief are necessary to ensure the effectiveness of local PWHT. Many problems still exist in this area. Firstly, the geometry of the joint is complex. Secondly, it requires computation of both the welding residual stress and the stress relief by creep phenomena during local PWHT. Thirdly, there is a need to optimize the thermal parameters in a wide variety of heating conditions. Therefore the American Welding Society plans to issue recommendation on the practice of local heating of pipe[1), as also do the American Pressure Vessel Research Committee (PVRC) and the Japan Power Engineering and Inspection Cooperation (JAPEIC).

No comprehensive study of the mechanical behavior of tubular joints in local PWHT has been reported yet. In reference[2)], a method of using visco-elastic-plastic FEM has been proposed to study the stress variation in local PWHT of butt welded pipe. Computational results by an axisymmetric model show that at the initial heating stage, the welding residual stress decreases with increase of temperature due to the decrease of the yield stress. In the last stage of heating and the holding stage, the welding residual stress continues to decrease due to the creep deformation. In the cooling stage, the residual stress increases slightly by recovery of the Young's modulus. By analyzing the residual stress after the local PWHT with different geometrical and heating conditions such as the thickness and the heated band width, the effectiveness of stress relief of butt welded pipe was quantitatively assessed[3)]. The same method can also be applied to study the mechanical behavior of a tubular joint in local PWHT.

In this paper, the welding residual stress for single pass welding is generated by thermo-elasto-plastic FEM. Then the mechanical behavior of a tubular joint in local PWHT is analyzed using visco-elastic-plastic FEM. Based on these computations, the relation between residual stress and heated band width can be found and an optimum heated band width is recommended for

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Table 1 Computational conditions for tubular joint in welding.

Cases	Dimensions/mm						Welding conditions			
	Pipe			Nozzle			Welding speed	Heat input rate	Pass	Welding sequence
	D	t	2L	D_n	t_n	L_n	$v/(mm{\cdot}min^{-1})$	$Q/(kJ{\cdot}cm^{-1})$		
C-1							785	32	Single	A-B-C
C-2	500	25	1800	200	20	400	785	32	Single	C-B-A
C-3							393	32	Single	A-B-C
C-4	500	25	1800	160	20	400	393	32	Single	A-B-C

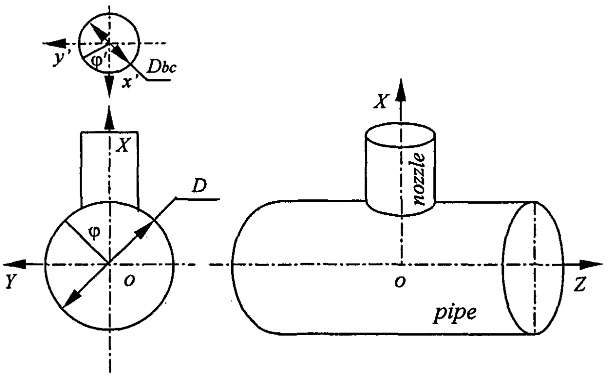

Fig.1 Coordinate system of tubular joint.

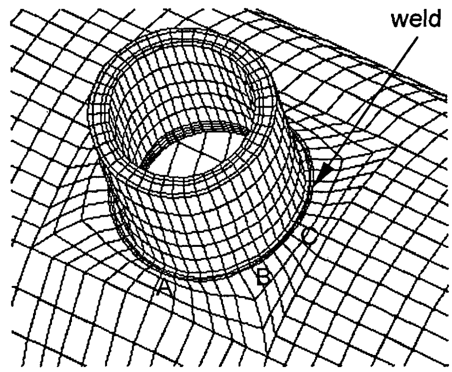

Fig.2 Mesh division and welding sequence.

practical use.

2. Equation of Intersection line

To describe the intersection line formed by pipe (chord) and nozzle, an equation of the intersection line must first be constructed. As to the equation of the intersection line, much work has been done in reference[4]. Some important results of concurrent tubular joint reasoned to set a base for mesh division in FEM analysis. The tubular joint consisted of pipe and nozzle needs transformation between two coordinate systems. The definition of coordinate system is shown in **Fig.1**. One is the coordinate system of *o-XYZ* assumed for the pipe. The origin of the coordinate system for the pipe is located at center of the pipe. The X axis is in the axial direction, while the Z axis is in the direction of vertical upward. φ is the circumferential angle of an arbitrary point on the pipe surface. Another is the coordinate system of o'-$x'y'z'$ for the nozzle. φ' is circumferential angle of a point on the nozzle surface, which is used to describe the starting point of the welding and the welding direction. The transformation matrix between the pipe coordinate system and the nozzle coordinate system is given as follows.

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{Bmatrix} x' \\ y' \\ z' \end{Bmatrix} \qquad (1)$$

From the relationship $X^2 + Y^2 = R_c^2$, the equation of the intersection line in the nozzle coordinate system is given as,

$$z' = \sqrt{R_c^{\,2} - (R_n \sin\varphi')^2}\ . \qquad (2)$$

Then, the intersection line in the nozzle coordinate system can be expressed as,

$$\begin{cases} Z = R_n \cos\varphi' \\ \varphi = \tan^{-1} \dfrac{R_n \sin\varphi'}{z'} \end{cases} . \qquad (3)$$

By using Eq.(3), the FEM mesh at intersection line between the pipe and the nozzle can be generated. As it is shown in **Fig.2**, the section of weld at any point along the intersection line can be modeled smoothly. The tubular joint used in computation is a concurrent tubular joint and no enforcement is a given in the vicinity of intersection line.

3. Model and Method for Analysis

3.1 Welding model

The welding stress is generated by thermo-elasto-plastic FEM. Heat input moving with constant speed is applied along the welding line which is the intersection line between the pipe and the nozzle. The section of weld is "I" type. The welding condition is shown in **Table 1.** The welding sequence assumed in computation is shown in Fig.2. Considering the symmetry of the concurrent tubular joint, one-fourth of the tubular joint is selected for mesh division. All the points on the symmetric surface in the center of the pipe are fixed as to mechanical boundary condition while only one point of the pipe is fixed in the vertical upward direction.

Table 2 Creep parameters used in computation.

T/°C	450	500	600	625
b	2.64×10^{-21}	1.05×10^{-17}	1.05×10^{-15}	4.20×10^{-15}
n		4.2		

Table 3 Computational conditions of tubular joint in local PWHT.

Cases	Heating speed v_H/(°C·h^{-1})	Holding temperature T/°C	Holding time t_H/h	Cooling speed v_C/(°C·h^{-1})	Insulation Band/mm		Heated band Width/mm	
					$2W_{in}$	W_n	2B	B_n
case1	220	620	1,2	220	600	150	varied	100
case2,case3							350	
case4	220	620	1	220	560		280	

3.2 Construction of temperature in local PWHT

The temperature difference in the soak band which consists of the weld and its vicinity must satisfy the requirement of the local PWHT process. The temperature field for a tubular joint is quite different to that of circumferential heating of a pipe. Application of a single-point temperature control model will result great temperature difference in the soak band because the intersection line of the tubular joint doesn't locate in one vertical surface. When the temperature control point is applied at the lowest point of the intersection line, the temperature at the highest point of the intersection line is about 150 °C below the requirement of holding temperature. On the contrary, it is the same when the temperature control point is applied at the highest point of the intersection line. The temperature field generated by such control methods is meaningless for further study. Therefore, the temperature field of the tubular joint in local PWHT is controlled in the following manner in the computation. The surface heat source is applied on the outer surface of the elements within the heated band width of 2B as shown in **Fig.3**. The heat input at each element is controlled so that the temperature at the element follows the programmed PWHT temperature cycle. In this way, the temperature in the soak band along the intersection line is maintained in the range of 30 °C. The above assumption corresponds to the local PWHT with multi-control commonly employed in real practice.

The material used for computation is S25C. The temperature dependent material properties provided by JAPEIC[5] are used. As for the creep, the power creep law ($\dot{\varepsilon} = b\sigma^n$) is employed in the visco-elastic-plastic FEM. The parameters of the creep law are shown in **Table 2.**

3.3 Local PWHT model of tubular joint

The definition of the geometrical parameters of tubular joint model for local PWHT is shown in Fig.3. The diameter of pipe is defined as D/mm, the thickness

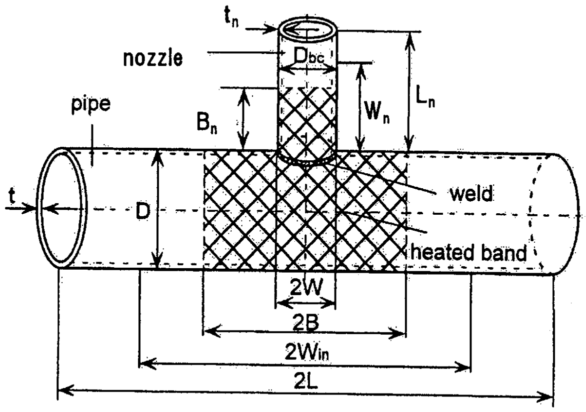

Fig.3 Definition of parameters for local PWHT of tubular joint.

of pipe is t/mm, and the length of pipe is 2L/mm. The diameter of nozzle is defined as D_{bc}/mm, the thickness of pipe is t_n/mm, and the length of the nozzle is L_n/mm, respectively. The insulation bands (W_{in}, W_n) meet the requirement of $5\sqrt{Rt}$, where R is the inner radius of the pipe or the nozzle and t is the thickness of the pipe or nozzle. The heated band width for the tubular joint is plotted in shaded area, where the heated band width of 2B centers on the pipe and B_n is assumed for the nozzle in the vertical upward direction. The details of local heating parameters are shown in **Table 3**. A one-fourth model is selected for the computation of mechanical behavior in local PWHT. The mechanical boundary condition assumed for the local PWHT is the same as that for welding. The heat transfer coefficient at the area where the heat source or the insulation is placed is assumed as β = 0.0002 W·cm^{-2}·°C^{-1}. The rest of the area facing the static air is assumed to be β = 0.0033 W·cm^{-2} ·°C^{-1}.

3.4 Definition of optimum heated band width

The relation between residual stress in the soak band and the heated band width can be obtained by visco-elastic-plastic FEM. The residual stress decreases with

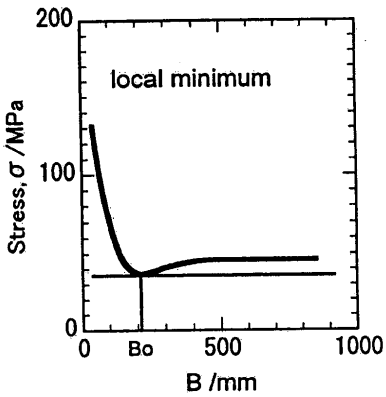

Fig.4 Definition of optimum heated band width for local PWHT.

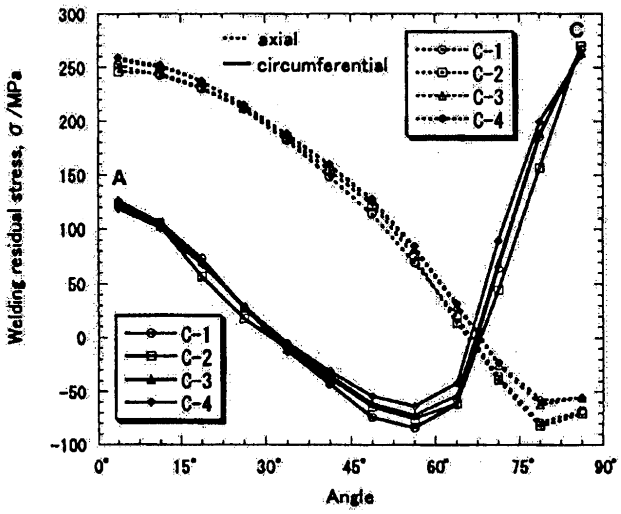

Fig.5 Influence of welding condition on distribution of residual stress.

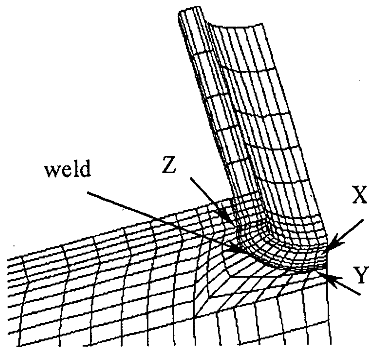

Fig.6 Locations of stress evaluation points.

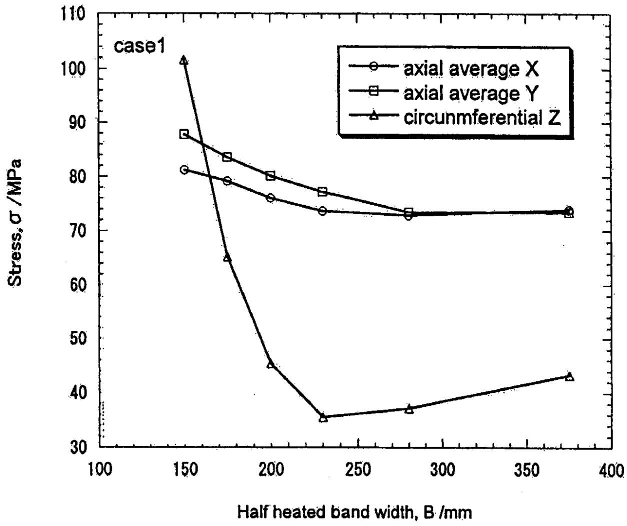

Fig.7 Relation between stress and heated band width in local PWHT.

increase of heated band width as shown in **Fig.4**. The residual stress changes very slowly if the heated band width is large enough. It is also observed that the value of the residual stress shows the local minimum at B_0. The heated band width for such a local minimum is defined as the optimum heated band width.

4. Stress Distribution and Optimum Heated Band Width

4.1 Characteristics of welding stress distribution

The distributions of the residual stress computed for the different welding conditions are shown in **Fig.5**. It can be seen that the distributions resemble each other regardless of the welding condition. The influence of welding sequence on stress distribution is very small in single pass welding. The peak value of the stress appears in the same position. The welding distribution along the intersection line under different welding condition is shown in Fig.5. In this figure, $\varphi' = 0°$ is the lowest point of the intersection line, while $\varphi' = 90°$ is the highest point of the intersection line. The peak value appears in the vicinity of the heat affected zone. The radial stress is about half of the yield stress. The axial stress component of the pipe is very large. The peak value, which appears at $\varphi' = 30°$ in the nozzle coordinate system, exceeds the yield stress. It becomes smaller with increase of φ', and becomes compressive at the position of $\varphi' = 90°$. The circumferential stress component distributes in the opposite way. The peak value appears in the position of $\varphi' = 90°$. Since the distribution of the welding residual stress is almost independent on the welding condition, it is reasonable to select the welding residual stress shown in Fig.5 as the initial stress for the computation of stress relief by local PWHT.

4.2 Relation between residual stress and heated band width

The peak value of the stress at different points (X, Y and Z) in the vicinity of the weld are chosen to evaluate the effectiveness of stress relief as shown in **Fig.6**. The relation between stress after local PWHT and heated band width is shown in **Fig.7**. With increase of heated band width, the stress after local PWHT decreases significantly. The relation between the circumferential stress component and heated band width behaves a little differently from the relation between the axial stress component and the heated band width. Considering the diameter of the nozzle is D_n = 200 mm, the optimum heated band width based on circumferential stress and axial stress are $3.46\sqrt{Rt}$ and $4.8\sqrt{Rt}$ respectively. A half heated band of B = 3t recommended by JIS is not sufficient to achieve local minimum stress. The stress of tubular joint after local PWHT is found to be larger than that in the case of circumferential local PWHT of a pipe. The stresses after local PWHT redistribute and the peak value of stress after local PWHT is over 140 MPa.

4.3 Heated band width criterion of tubular joint

The optimum heated band width is obtained based on the serial computations of local PWHT with different heat treatment conditions. The heated band width for a concurrent tubular joint is recommended as follow.

$$2B_o = 2W + 4.8\sqrt{Rt}$$

where, $2W$/mm is the length of weld on pipe,
R/mm is inner radius of pipe,
t/mm is thickness of pipe.

5. Conclusion

(1) The mechanical behavior during the local PWHT of tubular joint was investigated using visco-elastic-plastic FEM and criteria for the heated band width were proposed.

(2) The peak value of axial stress component appears at the lowest point of the intersection line while the peak value of circumferential stress component locates at the highest point of the intersection line.

(3) For effective stress relaxation, a heated band width of $2B_o = 2W + 4.8\sqrt{Rt}$ is recommended for the local PWHT of tubular joints.

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