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

-Visco-Elastic-Plastic FEM Analysis of Local PWHT-

Jianhua WANG*, Hao LU** and Hidekazu MURAKAWA***

Abstract

Local post weld heat treatment (local PWHT) is usually performed when it is impractical to heat treat the whole vessel in a furnace. Many factors have an influence on PWHT procedures, such as size of the pipe, heated widths, insulation conditions, heating rates, soak temperatures and hold times, material composition etc. However up to now the influences these factors have on PWHT are not very clearly understood and different criteria for sizing the parameters can be found in different codes . This study provides a direct method to assess the effectiveness of local PWHT. An axisymmetric model was used based on the thermal-visco-elastic-plastic Finite Element Method with the consideration of creep phenomena. Investigations show that the thermal stresses induced by local PWHT are much affected by creep behavior and the changes of Young's Modulus very much. The stress relief history during whole local PWHT was studied using the present method. The results show that the stresses decrease quickly in the heating stage, they decrease slowly according to creep law in the holding stage and then suddenly increase when the cooling stage starts. The study shows the possibility that through a series of computations the effects of many factors can be assessed and the optimum parameters can be found by using this model.

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

1. Introduction

PWHT is performed after welding generally at a higher temperature. Local PWHT is usually performed when it is impractical to heat treat the whole vessel in a furnace. PWHT can have both beneficial and detrimental effects. Two primary benefits of PWHT are recognized. These are tempering and relaxation of residual stresses. Consequential benefits such as improved ductility, toughness and corrosion resistance result from the primary benefits. It is important that PWHT conditions be determined based upon the desired objectives. For PWHT to be successful it must be based upon engineering assessment and optimization of parameters to meet the desired objectives. Many factors influence PWHT procedures such as size of the pipe, heated widths, insulation conditions, heating rates, soak temperatures and hold times, material composition etc. However up to now the influences these factors have on PWHT are not very clearly understood and different criteria for sizing the parameters, such as the heated band, in different codes can be found. The width of the heated band is a typical and important problem which is recently examined by JAPEIC (Japan Power Engineering and Inspection Corporation) and the authors of this paper are also involved in this research probject[1].

This study provides a direct method to assess the effectiveness of local PWHT. An axisymmetric model was used based on the thermal-visco-elastic-plastic Finite Element Method and the consideration of creep phenomena. By using this model both temperature and stress distributions can be obtained during whole local PWHT history. Investigations show that the thermal stresses induced by local PWHT are much affected by creep behavior and the changes of Young's Modulus. The study of stress relief history shows that the stresses decrease quickly in the heating stage, then decrease slowly according to creep law in the holding stage and then suddenly increase when the cooling stage starts. The study shows the possibility that through a series of

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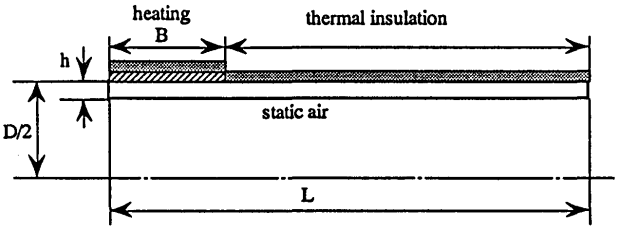

Fig.1 Axisymmetrical model of Analysis

computations the effects of many factors can be assessed and the optimum parameters can be found by using this model. This method is also studied by an author who is just preparing an American National Standard "Recommended Practices for Local Heating of Welds in Piping and Tubing" (1998 Edition of AWS D10.10) and some ideas and results obtained from this study are also referred in the annex of this code[2].

2. Axisymmetrical Thermal Analysis by FEM

The thermal analysis of local PWHT is the essential prerequisite before stress analysis, therefore ensuring the high accuracy of the thermal analysis is the first important step. An axisymmetrical thermal analysis by FEM is used with the consideration of the temperature dependency of the materials properties. Some techniques to improve the accuracy are introduced in the program of thermal analysis which has been developed by authors. Half of the pipe was analyzed using the axisymmetrical model as shown in **Fig.1**. The mesh division was formed by rectangular elements. Heating and cooling rates, holding temperatures and times can be easily satisfied by the automatic changes of heat input in this program.

3. Methods of Creep Analysis

3.1 Creep law, creep strain rate and increment of creep strain

In this study, the power creep law is used as follows[3],

$$\dot{\varepsilon}^c = b\sigma^n \quad (1)$$

here, σ=axial stress, $\dot{\varepsilon}^c$=creep strain rate, b,n=constants of the creep properties dependent on temperature.

In three dimensional problems, the component of the creep rate can be written as

$$\{\dot{\varepsilon}^c\} = 1.5\dot{\bar{\varepsilon}}^c\{\sigma'\}/\bar{\sigma} \quad (2)$$

here, $\dot{\bar{\varepsilon}}^c$ =equivalent creep strain rate. $\bar{\sigma}$=equivalent stress, $\{\sigma'\}$= deviatric stress.

Taking account of the effect of variation in the stress state and creep properties, the creep strain increment $\{d\varepsilon^c\}$ during a time increment dt is given as the summation of two terms as follows,

$$\{d\varepsilon^c\}= [C_c]\{d\sigma\}+\{d\varepsilon_c{}^c\} \quad (3)$$

Assuming that b, $\bar{\sigma}$ and $\{\sigma'\}$ vary linearly and constants don't change over a small interval dt, and integrating this creep strain rate during the time interval, the vector $\{d\varepsilon^c\}$ and matrix $[C_c]$ can be expressed as follows,

$$\{d\varepsilon_c{}^c\}= 1.5(K_1b+K_2db)\bar{\sigma}^{n-1}\{\sigma'\} \quad (4)$$

$$[C_c] = (K_2b+K_3db)\bar{\sigma}^{n-1}[c_{ij}] \quad (5)$$

here, K_1 =dt, K_2 =dt/2, K_3 =dt/3.

3.2 Stress-strain relation in elastic range

The total strain increment $\{d\varepsilon\}$ at a point is expresses as the summation of elastic, creep and thermal strains which are $\{d\varepsilon^e\}$, $\{d\varepsilon^c\}$ and $\{d\varepsilon^T\}$.

$$\{d\varepsilon\} = \{d\varepsilon^e\}+\{d\varepsilon^c\}+\{d\varepsilon^T\} \quad (6)$$

The elastic strain is expressed by

$$\{\varepsilon^e\} = [D^e]^{-1}\{\sigma\} = [C_c]\{\sigma\}$$

here, $[D^e]$=elasticity matrix.

The elastic strain increment is

$$\{d\varepsilon^e\} = [D^e]^{-1}\{d\sigma\}+\partial[D^e]^{-1}/\partial T\bullet\{\sigma\}dT \quad (7)$$

and the thermal strain increment is

$$\{d\varepsilon^T\} = \{\alpha\}dT \quad (8)$$

Substitution of Eqs. (3), (7) and (8) into Eq. (6) bring the result

$$\{d\sigma\}= [D_c{}^e]\{d\varepsilon\}-\{d\tau_0{}^e\} \quad (9)$$

here, $[D_c{}^e] = [C_e+C_c]^{-1}$

$$\{d\tau_0{}^e\} = [D_c{}^e][(\{\alpha\}+\partial[D^e]^{-1}/\partial T\bullet\{\sigma\})dT+\{d\varepsilon_c{}^c\}]$$

3.3 Stress-strain relation in the plastic range

With the additional component of the plastic strain increment $\{d\varepsilon^p\}$ to the components in the elastic range, the total strain increment $\{d\varepsilon\}$ in the plastic range is given by,

$$\{d\varepsilon\} = \{d\varepsilon^e\}+\{d\varepsilon^p\}+\{d\varepsilon^c\}+\{d\varepsilon^T\} \quad (10)$$

Yielding function f is defined as,

$$f = \bar{\sigma}^2-s_Y{}^2 \quad (11)$$

here, σ_Y=yield stress in uniaxial tension.

On the basis of the increment strain theory of plasticity, the plastic strain $\{d\varepsilon^p\}$ is expressed in the following form with a positive scalar λ.

$$\{d\varepsilon^p\} = \lambda\{\partial f/\partial s\} \quad (12)$$

The stress and strain relation can be written as follows,

$$\{d\sigma\}= [D_c^p]\{d\varepsilon\}-\{d\tau_0^p\} \quad (13)$$

here, $[D_c^p] = [D_c^e]-[D_c^e]\{\partial f/\partial\sigma\}\{\partial f/\partial\sigma\}^T[D_c^e]/S_0$

$\{d\tau_0^p\} = [D_c^p][(\{\alpha\}+\partial[D^e]^{-1}/\partial T\bullet\{\sigma\})dT+\{d\varepsilon_c{}^c\}] +[D_c^e]\{\partial f/\partial\sigma\}\{\partial f/\partial T\}dT/S_0$

$S_0 = \{\partial f/\partial\sigma\}^T[D_c^e]\{\partial f/\partial\sigma\}+4\sigma_Y^2H'$

H'=rate of strain hardening.

3.4 Stiffness matrix and equivalent nodal force

The stiffness matrix $[K]^e$ and equivalent nodal force $\{dL\}^e$ are expressed as,

$$[K]^e = \int [B]^T[D_c][B]dV \quad (14)$$

$$\{dL\}^e = \int [B]^T\{d\tau_0\}dV \quad (15)$$

The stiffness matrix $[K]^e$ and equivalent nodal force $\{dL\}^e$ contain the matrix $[D_c]$ and the vector $\{d\tau_0\}$, respectively. They are given explicitly by $[D_c^e]$ and $\{d\tau_0^e\}$ of Eq.(9) for the elastic range, and $[D_c^p]$ and $\{d\tau_0^p\}$ of Eq.(13) for the plastic one.

4. One Dimensional Relax Model

An analysis of annealing in the one dimensional stress state at 600 °C was introduced to check the accuracy of the present method. The material properties and creep law are given as follows,

$E = 94000$ MPa

$\mu = 0.3$

$\alpha = 0.000013$

$n = 4.2$

$b = 2.7\bullet 10^{-9}\bullet 0.1^{4.2}$

As seen in **Fig.2**, the initial stress σ_0 is 200 MPa and taking the interval dt = 1 min, the solution by FEM is supposed to completely coincide with the analytical solution given by Eq.(16),

$$t = (\sigma^{-n+1}-\sigma_0^{-n+1}) / [bE(n-1)] \quad (16)$$

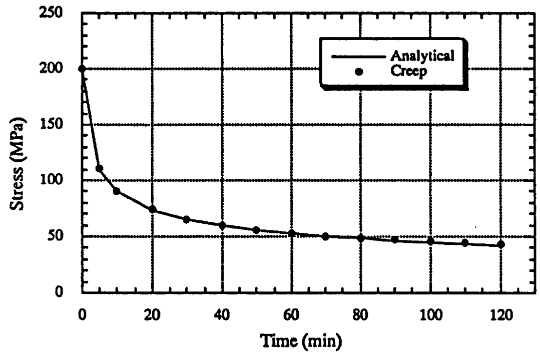

Fig.2 Solution at a constant temperature

5. Thermal Stresses and Residual Stresses Induced by the Local PWHT

There is no thermal stress during the ideal uniform heating and cooling cycle. However the thermal stresses and residual stresses must be taken into account in the process of local PWHT. Because of the long time in local PWHT, it is necessary to introduce creep phenomena and to consider the temperature dependency of the material properties in the analysis of the thermal stresses. The material properties used in the analysis are as **Table 1**.

Half of the pipe was analyzed with the 1000 mm of the diameter, 25 mm of the thickness and 1000 mm of the length. The maximum temperature of local PWHT is 600 °C with the 220 °C/hr of the heating rate. The hold time is one hour. Two heated widths B=80 mm and 175 mm are used for comparison. **Figure 3** and **Fig. 4** show the thermally induced bending stress cycles (at the inside center of the pipe) for heated widths which are 80 mm and 175 mm respectively.

It can be seen that the residual stress induced by local PWHT including creep analysis is larger than that without creep analysis. As seen from **Fig.4** it is interesting that the residual stress is zero if the creep analysis is not adopted and the residual stress is not zero

Table 1 Material properties

Temperature (°C)	0	200	400	600
Heat conductivity (W/cm °C)	.546	.469	.385	.268
Thermal capacity (J/g °C)	.410			.913
Density (g/cm^3)	7.82			7.61
Yield stress (MPa)	275	275	200	100
Young's modulus (GPa)	210	210	170	94
Heat transfer coefficient ($W/cm^2 °C$)	0.0003			
Thermal expansion coefficient ($°C^{-1}$)	0.000013			
Poisson's ratio	0.3			

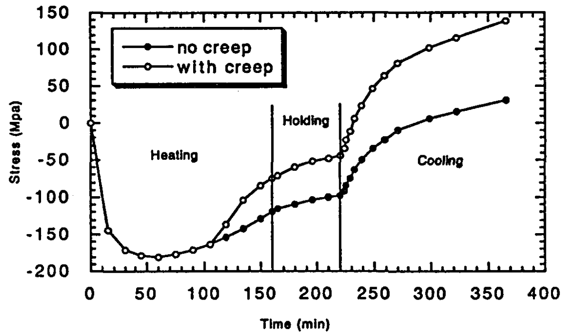

Fig.3 Thermal stress cycle affected by creep (B=80 mm)

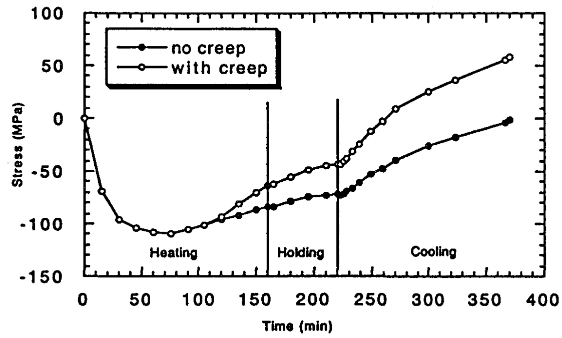

Fig.4 Thermal stress cycle affected by creep (B=175 mm)

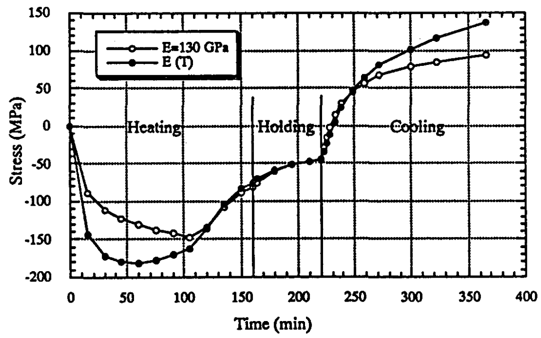

Fig.5 Thermal stress cycle affected by Young's Modulus (B=80 mm)

if the creep analysis is adopted. This means that residual stresses can be caused by creep strains.

Figure 5 shows the thermal stress cycle affected by Young's Modulus which is constant (E=130 GPa) and temperature dependency respectively. The results show

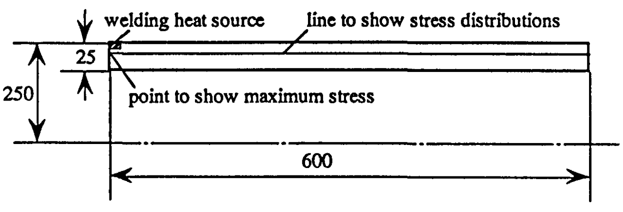

Fig.6 Welding model of a pipe

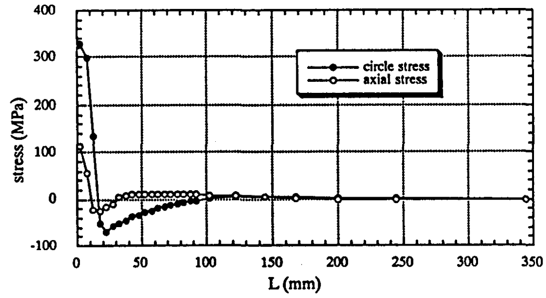

Fig.7 Distributions of welding residual stresses

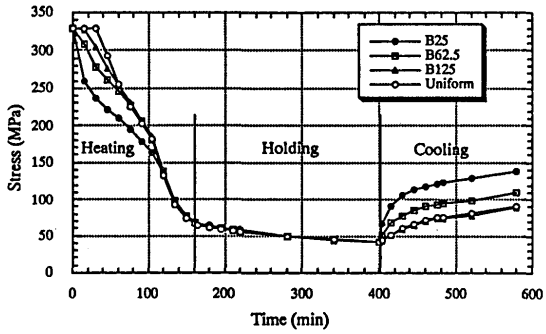

Fig.8 Stress relief cycle under different conditions

that the temperature dependency of Young's Modulus should be considered. The residual stress is larger when the Young's Modulus becomes larger at room temperature.

6. Welding Residual Stresses

The size of the analyzed model is 500 mm of the diameter, 25 mm of the thickness and 600 mm of the length. One circle bead is applied on the pipe and four elements were heated with 11 KJ/cm of effective heat input during welding as shown in **Fig.6**. Because of the rapid heating and cooling during welding, it is not necessary to introduce creep analysis. So only thermo-elasto-plastic FEM was used[4] with an axisymmetrical model. **Figure 7** shows the distributions of the residual stresses at the line which is about 8 mm from the outer radius of the pipe where maximum residual stress is shown.

7. Creep Analysis of Stress Relief in Local PWHT.

The creep behavior must be introduced in the mechanical analysis of the local PWHT. A pipe with the original residual stresses and plastic strains is analyzed under four conditions of PWHT. The initial data for the residual stresses and plastic strains after welding were

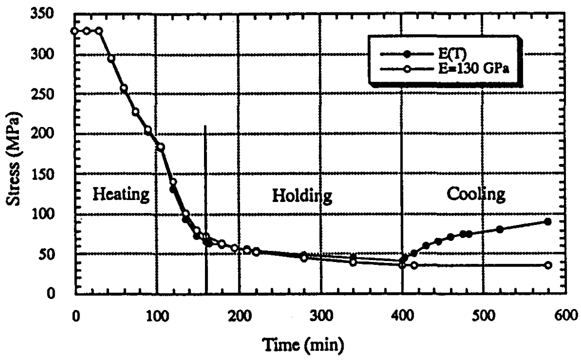

Fig.9 Stress relief cycle affected by Young's Modulus (uniform PWHT)

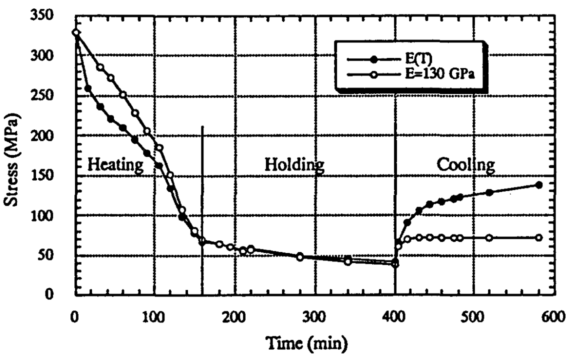

Fig.10 Stress relief cycle affected by Young's Modulus (B=25 mm)

already obtained in advance as mentioned above. The four cases are,

(1) locally headed band width B= 25 mm;
(2) locally headed band width B= 62.5 mm;
(3) locally headed band width B= 125 mm;
(4) uniform heat treatment.

The heating rate is 220 °C/hr and the hold time is 4 hour. **Figure 8** shows the stress relief cycle under four conditions. The changed stress is the maximum circle stress mentioned in **Fig.6** and **Fig.7**. As seen in **Fig.8** the stresses decrease quickly in the heating stage because of the low values of yielding stresses of the material at high temperature. The changes of stresses under four conditions are almost same in the holding stage and they decrease slowly according to the creep law. However the stresses suddenly increase and are separated when the cooling stage starts. The creep phenomenon is also considered in the heating and cooling stages when the temperature is larger then 400 °C. From the **Fig.8** it can be seen that the residual stress after local PWHT with 125 mm of the heated band width is almost the same as for uniform heat treatment.

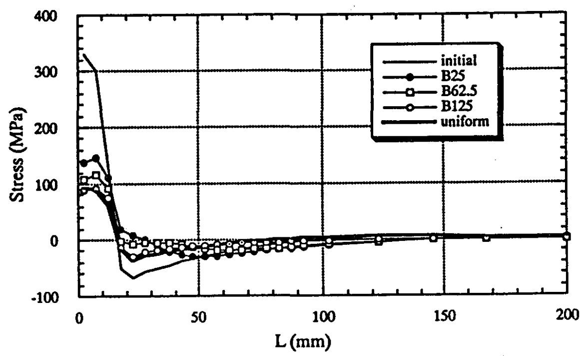

Fig.11 Distributions of welding residual stresses after different PWHT

Two reasons for the increase of residual stresses in the cooling stage can be explained. One is that there are additional residual stresses induced by the local PWHT. The heated width is small, the residual stress induced by local PWHT is high so the final remaining residual stress is also high. The other reason is the return of the Young's Modulus at the lower temperature. This is why the stresses increase in the cooling stage, even under the conditions of uniform heat treatment .

Figure 9 and **Fig. 10** show the effects of Young's Modulus on the stress relief cycles. **Figure 9** is the case during uniform heat treatment when there is no residual stress induced by PWHT. The increase of the stress in cooling stage is because of the changes of Young's Modulus only. **Figure 10** is the case of 25 mm of the heated width during local PWHT. It is shown that the increase of stress in the cooling stage is because of both the changes of the Young's Modulus and the residual stress induced by local PWHT.

Figure 11 shows the distributions of welding residual stresses after different PWHT. The definition of stress mentioned is as before.

8. Conclusions

The main conclusions drawn from the present study are summarized as follows:

(1) The power creep law and the creep analysis are introduced in the mechanical studies of the local PWHT. The results of creep behavior show good accuracy and good coincidence with those of the analytical solutions using a one dimensional model.
(2) The thermal and residual stresses induced by local PWHT are much affected by creep behavior and the changes of Young's Modulus very much, so it is necessary to introduce the creep behavior and to

consider the temperature dependency of Young's Modulus in the mechanical analysis of local PWHT.

(3) The stress relief cycles under different PWHT conditions are studied using the present method. The results show that the stresses decrease quickly in the heating stage, they decrease slowly according to the creep law in the holding stage and then the increase suddenly when the cooling stage starts. Two reasons for increase of residual stresses in the cooling stage can be offered. One is that there are additional residual stresses induced by the local PWHT. The other is the return of the Young's Modulus at the lower temperature.

(4) This study provides a direct method to assess the effects of many conditions and optimum parameters can then be obtained. In the case of this study, the residual stress after local PWHT with 125 mm of the heated width is almost same as with uniform heat treatment. A series of proper conditions for local PWHT can be obtained by further investigations using this method.

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