Tig Torch Re-Heating for Weld Residual Stress Improvement in Girth Weld of Thin Pipe

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Abstract

Intergranular stress corrosion cracking (IGSCC) has been a major problem in BWR pipings and many remedies have been proposed. THSI (Tungsten-electrode Heating Stress Improvement) is one of the stress related IGSCC remedies intended to reduce welding residual stresses to a level at which IGSCC will not occur. THSI needs only TIG welding unit and is expected to be cheap and easy to apply. But this process has not been widely used because the process parameters which dominate the residual stress pattern, have not been established. In this paper, these process parameter will be discussed in terms of weld heat input and cooling effect based on a simplified calculating method for weld residual stress estimation.

1. Introduction

THSI is very similar to the weld overlay (WOL) method. It, however, needs no weld filler metal but heats the last weld layer with tungsten electrode using suitable electric current and voltage. Therefore, this method has some advantage comparing with WOL. The first one is that it does not make any interference with ultrasonic in-service inspection (ISI) because it needs no additional weld deposit metal which may interfere with ISI. The second is that it is very suitable to thin pipe because it can select very small heat-input by which no welding can be performed. An excessively high heat-input is not proper for thin wall pipe because it may cause film boiling which decreases the temperature difference between the pipe outer and inner surfaces, and consequently reduce the benefit of re-heating to lower the residual stresses. In order to confirm the effectiveness of THSI, one series of tests and analytical studies were conducted.

2. Simplified Approach to Weld Residual Stresses

A number of studies have been pursued through experiments and also analyses to obtain the value of weld residual stresses. Reviewing these works, the author derived the following equations to calculate the weld residual stresses on a pipe girth weld.

$$\sigma_R = K\varepsilon^n \quad \cdots\cdots (1)$$

$$\varepsilon = \sigma_x/E \text{ or } \sigma_\phi/E \quad \cdots\cdots (2)$$

$$\sigma_x = \left(\sqrt{\frac{3}{1-\nu^2}}\,G(\mu/\beta) - \frac{\beta p\Delta T}{2(1-\nu)}\cdot\frac{1}{T_a}\right)E\alpha T_a \quad \text{(on pipe ID)} \quad \cdots\cdots (3)$$

$$\sigma_\phi = \left[1-H\left(\frac{\mu}{\beta}\right)+\nu\sqrt{\frac{3}{1-\nu^2}}\,G\left(\frac{\mu}{\beta}\right) - \frac{\{1+\mu\beta P/(1-\nu)\}\Delta T}{2T_a}\right]E\alpha T_a \quad \text{(on pipe ID)} \quad \cdots (4)$$

where

$$G(\mu/\beta) = \frac{(\mu/\beta)^2}{(1+\mu/\beta)[1+(\mu/\beta)^2]} \quad \cdots\cdots (5)$$

$$H(\mu/\beta) = \frac{1+\mu/\beta+(\mu/\beta)^2}{(1+\mu/\beta)[1+(\mu/\beta)^2]}$$

$$T_a = (T_o+T_i)/2 \quad \cdots\cdots (6)$$

$$\beta^4 = 3(1-\nu^2)/(a^2h^2) \quad \cdots\cdots (7)$$

$$l_0 = 1/\mu = 1.665\ Fh,\ F = \kappa\tau/h^2 \quad \cdots\cdots (8)$$

$$P = \text{Plastic Core Size (mm)} = \sqrt{2q}/\sqrt{e\pi c\rho T_o} \quad \text{(for thick pipe)} \quad \cdots\cdots (9)$$

σ_R : Residual stresses (kgf/mm^2)

σ_x : Fictitious elastic residual stress in axial direction (kgf/mm^2)

σ_ϕ : Fictitious elastic residual stress in circumferential direction (kgf/mm^2)

T_o : Recrystallization temperature (°C)

q : Heat input (J/mm)

c : Specific heat (J/kg·°C)

ρ : Specific weight (kg/mm^3)

h : Plate thickness (mm)

a : Mean radius (mm)

E : Young's modulus (kgf/mm^2)

ν : Poisson's ratio

α : Coefficient of linear expansion (mm/mm·°C)

K : Stress multiplier ≈ 135 (kgf/mm^2)

n : Strain hardening exponent ≈ 0.35

ΔT : Temperature difference between OD and ID

$= T_o \; [1-2 \exp\{-\pi T_o c\rho h^2/(2q)\}]$ (for Insulated Pipe) .... (10)

In the above mentioned equation, β is the shell flexibility parameter, l_0 is a temperature distribution parameter in axial direction and corresponds to the distance from weld center line to the point where temperature is 0.5 T_o when the weld cools down to T_o, and P means a size of plastic core in which the material has been heated to or above the recrystallization temperature and shows a significant shrinkage after cooling.

From equation (3) and (4), compressive residual stresses are expected only when $\beta P \Delta T$ is sufficiently large. β becomes smaller as the pipe size goes up. P and ΔT vary with welding conditions. In order to get large $\beta P \Delta T$, a wider P and a larger ΔT should be attained simultaneously.

For a wider P, it is easily understood from eq. (9) that large heat input is essential. However, a cooling condition to get large ΔT is not clearly understood. Therefore, the cooling condition will be discussed in the next paragraph.

3. Temperature Distribution in Finite Thickness

When the welding speed is sufficiently higher than the temperature diffusion rate in the weld material, the heat mainly flows in the direction perpendicular to the weld line. Then the temperature distribution can be approximated by a case in which the welding line is instantaneously heated over the full length of the weld and cooled.

Applying the mirror principle to a semi-infinite body, the temperature distribution of completely insulated plate with a finite thickness can be expressed as shown in Fig. 2.

Introducing two non-dimension parameters x, F and $\bar{q}$, we can easily derive the following equations for temperature at x mm from the outer surface of insulated pipe T_{IX}

$$\frac{T_{IX}}{T_o} = \bar{q}\cdot\frac{1}{F}\,[e^{-\frac{1}{4F}X^2} + \sum_{N=1}^{\infty}\{e^{-\frac{1}{4F}(2N-X)^2} + e^{-\frac{1}{4F}(2N+X)^2}\}] \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

where

$$X = x/h,\; F = \kappa\tau/h^2 \text{ (Fourier Number)} \quad \ldots\ldots\ldots\ldots \quad (12)$$

$$\bar{q} = \sqrt{q}/\sqrt{2\pi c\rho T_o h^2}$$

It is clear from this equation that different materials which have different c's, ρ's and h's show equivalent temperature distribution at one non-dimensional time, F (eq. (12)) if the non-dimensional heat input, $\bar{q}$ are equal to each other.

4. Effect of ID Cooling

By the effect of cooling from pipe inner surface, the temperature decreased by some amount from the insulated condition. This amount of temperature drop varies with cooling time and distance from the cooled surface. The complete expression for this is not known, so the following is assumed.

$$\Delta T_{wx} = T_{Ii}\ \Psi[1-e^{-(\frac{\pi}{2})^2 F} \cos(\frac{\pi}{2}x)] \quad \text{.......} \quad (13)$$

where,

ΔT_{wx} : Temperature drop at x mm from outer surface due to ID cooling (°C)

Ψ : Cooling efficiency (See Fig. 2)

Then the temperature distribution (T_{wx}) in the pipe wall with inside surface cooling can be expressed as follows:

$$\frac{T_{wx}}{T_o} = \bar{q}\cdot\frac{1}{F}\ [e^{-\frac{1}{4F}X^2} + \sum_{N=1}^{\infty} \{e^{-\frac{1}{4F}(2N-X)^2} + e^{-\frac{1}{4F}(2N+X)^2}]$$

$$-2\Psi \sum_{N=1}^{\infty} e^{-\frac{1}{4F}(1N-1)^2} \{1-e^{-\frac{\pi^2}{4}F} \cos(\frac{\pi}{2}X)\}] \quad \text{.......} \quad (14)$$

5. Cooling Efficiency

The energy (Q_h) corresponding to the temperature drop in the pipe wall is equal to the energy (Q_α) removed through the inside surface by water cooling. Using some simplification, we get the following expression for Ψ:

$$\Psi = \frac{B}{K_F/I_F+B} \quad \text{.......} \quad (15)$$

where

$$K_F = (\sum_{N=1}^{\infty} e^{-\frac{1}{4F}(2N-1)^2})\ (2-e^{-\frac{\pi^2}{4}F})\cdot/\sqrt{F} \quad \text{.......} \quad (16)$$

$$I_F \simeq 0.882\ F - 0.1426\ [1-\mathrm{EXP}\{-(8.65F)^{1.2}\}] \quad \text{.......} \quad (17)$$

$B = \alpha_m h/\lambda$, α_m: Heat transfer coef. λ: Conductivity .... (18)

6. Plastic Core Size

For a thick pipe with insulated surfaces, the plastic core size is given by eq. (9). This size can be divided into two parts; the one is the melted region (M_C) and the other is the surrounding region. In theoretical calculation M_C is the radius of the melted semi-circler core as shown in Fig. 3, however, in actual weld this region corresponds to weld metal very like an ellipse. Then the width of weld bead, W_b can be expressed by the following equation by assuming the bead height is one third of the bead width.

$$W_b = 1.03 \sqrt{q}\ h \quad \text{(for insulated pipe)} \qquad (19)$$

This size seems to be almost independent from the cooling condition. The size of surrounding area, $p-M_C$ depends on the cooling time F and the actual plastic core size P_a can be written as:

$$P_a = W_b + 0.376\sqrt{F}\ h \qquad (20)$$

By the same way as above, we can get a new expession for 1_o as:

$$1_o = W_b + 0.828\sqrt{F}\ h \qquad (21)$$

7. Results and Discussion

The effect of weld heat input is shown in Fig. 4 for three pipe sizes. It is clear that the weld heat input has a significant effect on the residual stress after THSI, namely large heat input is generally preferable and a higher heat input is required for a larger pipe. This phenomenon can be expected from eqs, (3), (19) and (20).

Fig. 5 shows that strong cooling is essential to obtain compressive stresses and higher cooling capacity is required for a large weld heat input. However the cooling capacity greater than B=200 (for stainless steel case) is hardly attainable because film boiling will take place in an extremely high heat flux (large heat input) case.

Finally, the calculated residual stresses are compared with experimental ones in Fig. 6. A fairly good agreement was obtained in both results which mean that the simplified calculation method can accurately predicat residual stresses after THSI.

8. Conclusion

The following can be concluded from the calculation and experiment conducted in this study.

1. THSI can reverse weld residual stresses of a girth weld in a small and thin pipe.
2. The thicker a pipe is, the greater the required heat input is.
3. High cooling capacity is essential to get compressive residual stresses after THSI

REFERENCE

/1/ UMEMOTO, T., TANAKA, S., "A Simplified Approach to Calculate Weld Residual Stresses in a Pipe", IHI Engineering Review, Vol.17 No.3, pp177-183, July 1984.

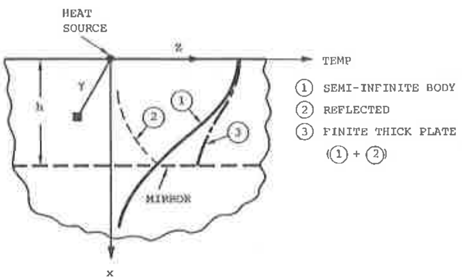


Fig. 1 APPROXIMATION OF TEMEPRATURE IN A FINITE THICKNESS PLATE BY MIRROR METHOD

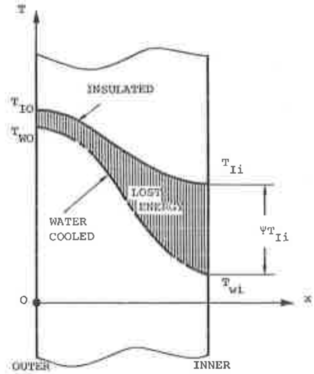


Fig. 2 TEMPERATURE DECREASE BY INSIDE COOLING

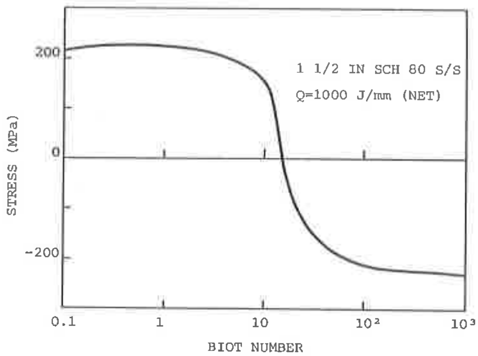
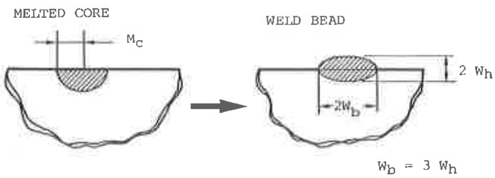


Fig. 4 EFFECTS OF WELD HEAT INPUT AND PIPE SIZE ON RESIDUAL STRESS AFTER THSI



$1/2\ \pi M_c^2 = \pi \cdot W_b \cdot W_h$

Fig. 3 ESTIMATION OF WELD BEAD WIDTH FROM MELTED CORE SIZE

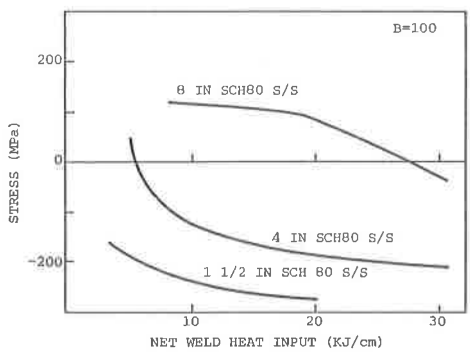


Fig. 5 EFFECT OF COOLING CAPABILITY ON RESIDUAL STRESS AFTER THSI

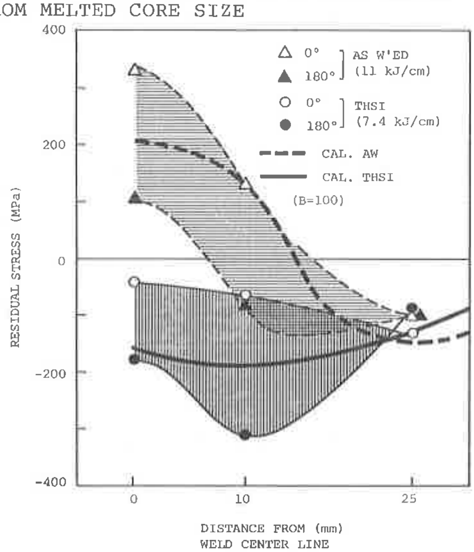


Fig. 6 COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL RESIDUAL STRESSES IN AS WELDED AND AFTER THSI (48.6 MM DIA. X 5.1 THICK, TYPE 304 STAINLESS STEEL)