The Induction Heating Stress Improvement of a Nozzle with a Thermal Sleeve

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Abstract

The Induction Heating Stress Improvement (IHSI) process is regarded as one of the most effective remedies for intergranular stress corrosion cracking occuring in the heat affected zone of susceptible stainless steel in some boiling water reactor piping systems. In this process, cooling water must flow at a velocity high enough to keep the inside surface of the pipe relatively cool, creating a high temperature gradient through the pipe wall. However, nuclear plant pipings, where forced flowing during this process may be difficult, have been welded. This paper presents a computer simulation analysis of post-IHSI residual stress distribution of the welded portion of a nozzle with a thermal sleeve, where forced water cooling is difficult. From these analyses, the residual stress on the inner surface of the safe end is improved by the stagrant water cooling, but better stress improvement after IHSI can be achieved by using forced water cooling in the clearance between the RPV nozzle and the thermal sleeve.

1. Introduction

The first observation of Inter-Granular Stress Corrosion Cracking (IGSCC) was in stainless steel pipes in a Boiling Water Reactor (BWR) plant in the mid-1960's in the United States. Cracks were subsequently found in the piping of other BWR Plants. This IGSCC was found in some welded joints in the piping system where very high tensile residual stress, sensitization of the material due to welding heat-input, and a corrosive environment, all occur simultaneously.

Investigation has shown that at least one of the above factors must be eliminated to prevent IGSCC. The Induction Heating Stress Improvement (IHSI) process has been developed as a very effective measure in preventing IGSCC. It changes the residual stress on the pipe inner surface near the heat affected zone (HAZ) from tensile to compressive. The principle of the IHSI is shown in Fig. 1. Induction heat is generated by the heating coil surrounding the welded portion of components, while simultaneously cooling the inside with flowing water. Thermal expansion due to induction heating causes compression outside and tension inside, during heating. After cooldown, contraction of the outside causes the stress states to reverse, leaving the inside, which is exposed to a corrosive environment, in a compression state. In Japan, the IHSI process has been applied to many weld lines in operating BWR plant, such as butt weld pipes, reducers, T-junctions, cross joints, and elbows and so on[1,2], as shown in Fig. 2. Sufficient temperature gradient through the pipe wall for the improving stress characteristics, can be generated by the forced flow of cooling water on the inside of the pipe. In a nuclear power plant, however, forced water cooling during the IHSI process cannot always be accomplished. The weld lines in a nozzle with a thermal sleeve are places where forced water cooling during the IHSI process is difficult. In applying IHSI to this weld line, the inside cooling condition is assumed to be stagnant water cooling rather than forced water cooling.

This paper describes efforts toward the IHSI applicability evaluation, analyzed by computer simulation, to a nozzle with a thermal sleeve with stagnant water cooling in the clearance between the RPV nozzle and the thremal sleeve. Forced water cooling in this clearance is also evaluated.

2. Analytical Conditions

2.1 Analytical Model

The analytical model consists of a Reactor Pressure Vessel (RPV) nozzle with cladding , piping, a safe-end, a thermal sleeve and welded joints, as shown in Fig. 3. The weld line to be evaluated in this study is the joint between the RPV nozzle and the safe end (Weld A in Fig. 3). The main dimensions of this weld line are :

Pipe Outer Diameter:	ϕ	350	mm
Pipe Thickness:		30	mm
Clearance between RPV Nozzle and Thermal Sleeve:		10	mm
Thickness of Thermal Sleeve:		10	mm

The material types are :

RPV Nozzle:	Low Alloy Steel
Inner Cladding:	Type 308/309 Stainless Steel
Safe-End:	Type 304 Stainless Steel
Piping:	Type 304 Stainless Steel
Welded Joints:	Type 308/309 Stainless Steel

It was assumed that cooling between the RPV nozzle and the thermal sleeve is accomplished using stagnant water cooling, because the water in this clearance is isolated from the main flow of the recirculation loop. With regard to residual stress distribution after IHSI, it is uncertain whether it is possible to generate a sufficient temperature gradient through the pipe wall without forced water cooling. Therefore, thermo-elastic-plastic analysis, based on heat transient analysis of the IHSI heat input process, was performed using the following methods and the analytical model as shown in Fig. 4.

Analytical Model: 3 dimensional axial symmetrical type
Element type: 8 node isoparametric quadrilateral
Hardning Low: kinematic
Yield Condition: J_2 incremental
Stress-Strain Relation : bi-linear approximation
Number of Nodes : 779
Number of Elements : 222

2.2 Induction Heating Condition

The following conditions were used to simulate the induction heat-input process :

Induction Coil type: cylyndrical
Coil Length: 3 / RT
Induction Frequency: 3 kHz
Heating Time: 250 sec.
Max. Temperature: 500 ± 75 °C (outside of the pipe)
where, R = pipe mean radius, and T = pipe thickness.

With regard to material properties, thermal conductivity, specific heat, Young's modulus, Poisson's ratio, yield strength, coefficient of work hardening and thermal expansion were used in the heat transient and thermo-elastic-plastic analyses.

In these analyses, the cooling conditions in the clearance between the RPV nozzle and the thermal sleeve were utilized as the analytical parameters to simulate the water conditions inside the component. The cooling conditions corresponding to the analytical cases are as follows.

Application Area	Cooling Condition	Analytical Case
Pipe Outer Surface	Air Cooling	All Cases
Pipe Inner Surface	Forced Water Cooling (1 m/sec.)	All Cases
Clearance Area	**Stagnant Water Cooling**	**Case 1**
Clearance Area	**Forced Water Cooling (0.01 m/sec.)**	**Case 2**
Clearance Area	**Forced Water Cooling (0.1 m/sec.)**	**Case 3**

In addition, the following empirical fomulas were used to evaluate the convection[3,4] :

$$Nu = a_i d_e / r_f \qquad \cdots\cdots\cdots\cdots\cdots \ (1)$$

(Case 1 : stagnant water cooling)

$$Nu = 1.02\, Re^{0.45}\, Pr^{0.5}\, Gr^{0.05} f(n_1)^{0.14} f(k_1)^{0.4} f(k_2)^{0.8} \qquad \cdots\cdots\cdots\cdots\cdots \ (2)$$

(Cases 2 and 3 : forced water cooling)

$$\mathbf{Nu = 0.023\, Re^{0.8}\, Pr^{0.4}} \quad \cdots\cdots\cdots\cdots\cdots \quad \mathbf{(3)}$$

where Nu = Nusselt number, Re = Reynolds number, Pr = Prandtl number,
Gr = Grashof number, a_i = convection, $d_e/2$ = clearance,
r_f = thermal conductivity, $f(n_l)$ = viscous function, $f(k_1)$, $f(k_2)$ = form function

3. Analytical Results

3.1 Stagnant Water Cooling (Case 1)

(1) **Heat Transient Analysis :** In this case, numerical analysis was performed under these conditions : the weld line was induction heated for 250 sec. by the 3 / RT Heating Coil on the outside of the pipe, and the coefficient of heat transfer in the clearance was 1,200 kJ/hr. m^2 °C, calculated from Eqs. (1) and (2). The computed temperature distribution at the end of the heating (after 250 sec.) is shown in Fig. 5. The temperature gradient through the pipe wall exceeds 200 °C on the safe end side and is much lower on the RPV nozzle side. This insufficiency of the temperature gradient on the RPV nozzle side is assumed to be caused by the relatively high thermal conductivity ratio of the low alloy steel compared to the stainlees steel.

(2) **Thermo-Elastic-Plastic Analysis:** The computed residual stress distribution after IHSI, based on the heat transient analysis mentioned above, is shown in Fig. 6. According to this analysis, the IHSI application with stagnant water cooling produces a residual stress level of - 245 to + 2 MPa on the inner surface of the safe-end side. A relatively high stress level of + 4 to + 6 MPa on the inner surface of the RPV nozzle side is explained by the less-temperature difference between the outer and inner surfaces and the greater stiffness of the component as compared to the safe-end side. With regard to the stress level at the RPV nozzle side, however, this does not cause significant problems because of the higher IGSCC resistance of the cladding material (Type 308/Type 309 stainless steel) on the inside surface of the RPV nozzle.

The conclusion is that the IHSI application with stagnant water cooling has no significant problems, but for improvement stress of characteristics would be improved by using forced water cooling in this clearance.

3.2 Forced Water Cooling (Cases 2 and 3)

(1) **Heat Transient Analysis:** These two simulations show the effect of forced water cooling inside the pipe. Considering the narrow clearance, the velocity of the cooling water is very slow. The water velocities and corresponding coefficients of heat transfer, calculated from Eqs. (1) and (3) for each analytical case are is follows :

Analytical Case	Cooling Water Velocity	Coefficient of Heat Transfer
2	0.01 (m/sec.)	3,400 (kJ/hr m^2 ^oC)
3	0.1 (m/sec.)	21,400 (kJ/hr m^2 ^oC)

The other conditions are identical to those in Case 1. The calculated temperature distribution at the end of heating (after 250 sec.) for each case is shown in Fig. 5. The through-wall temperature difference is more than 450 ^oC in Case 3, and more than 300 ^oC in Case 2. According to this evaluation, forced water cooling seems to produce better temperature distributions than those calculated with stagnant water cooling.

(2) **Thermo-Elastic-Plastic Analysis:** Corresponding to the better temperature distribution, the residual stress level after IHSI processing is improved by forced water cooling in each case, especially for the axial stress, as shown in Fig. 6.

It can be concluded that the better residual stress distribution after IHSI is obtained by the forced water cooling on the inside of the pipe as compared to the stagnant water cooling, even if the water velocity is very slow.

4. Conclusion

The computer simulation results of the stress distribution after applying the Induction Heating Stress Improvement process to a nozzle with a thermal sleeve were described in this paper. The effect of the IHSI process under conditions where the cooling water in the clearance between the RPV nozzle and the thermal sleeve is stagnant was described. This study showed that the residual stress on the inner surface is improved by the stagnant water cooling, but better stress improvement after IHSI can be achieved by using forced water cooling in this area.

REFERENCE

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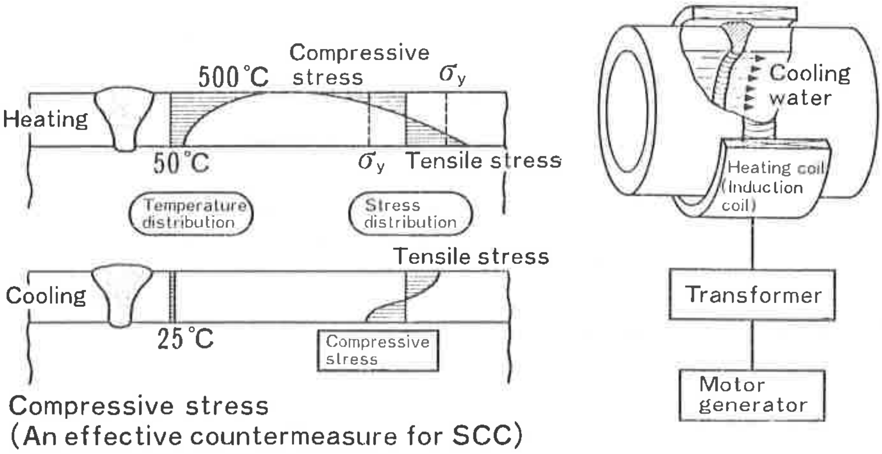

i) Principle

σ_y : Yield stress
SCC : Stress corrosion cracking

ii) Procedure

Fig. 1 Principle of IHSI Process

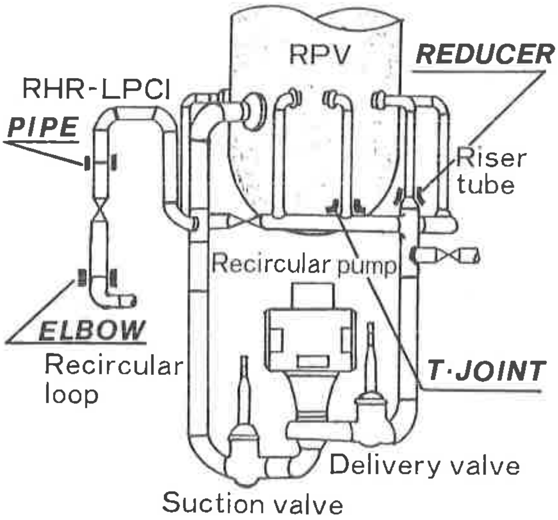

Fig. 2 Actual IHSI Application Experience

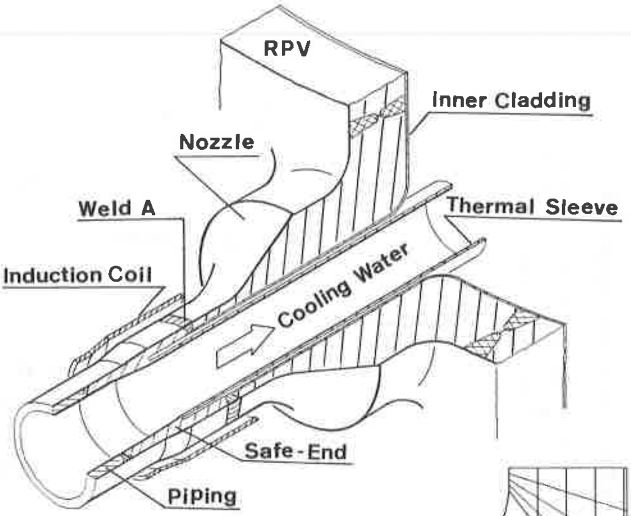

Fig. 3 RPV Nozzle with A Thermal Sleeve

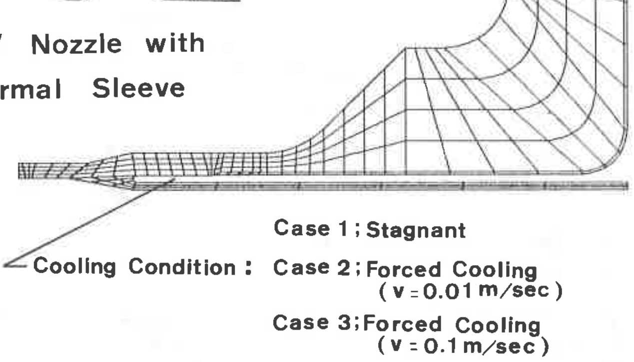

Fig. 4 Analytical Model

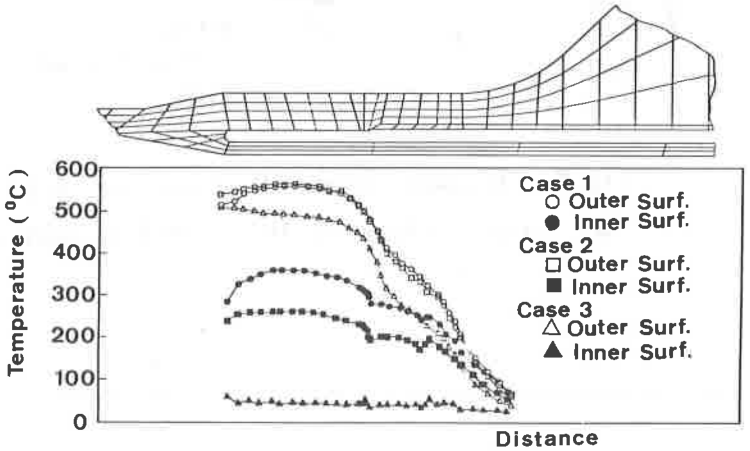

Fig. 5 Results of Heat Transient Analysis (at 250 sec)

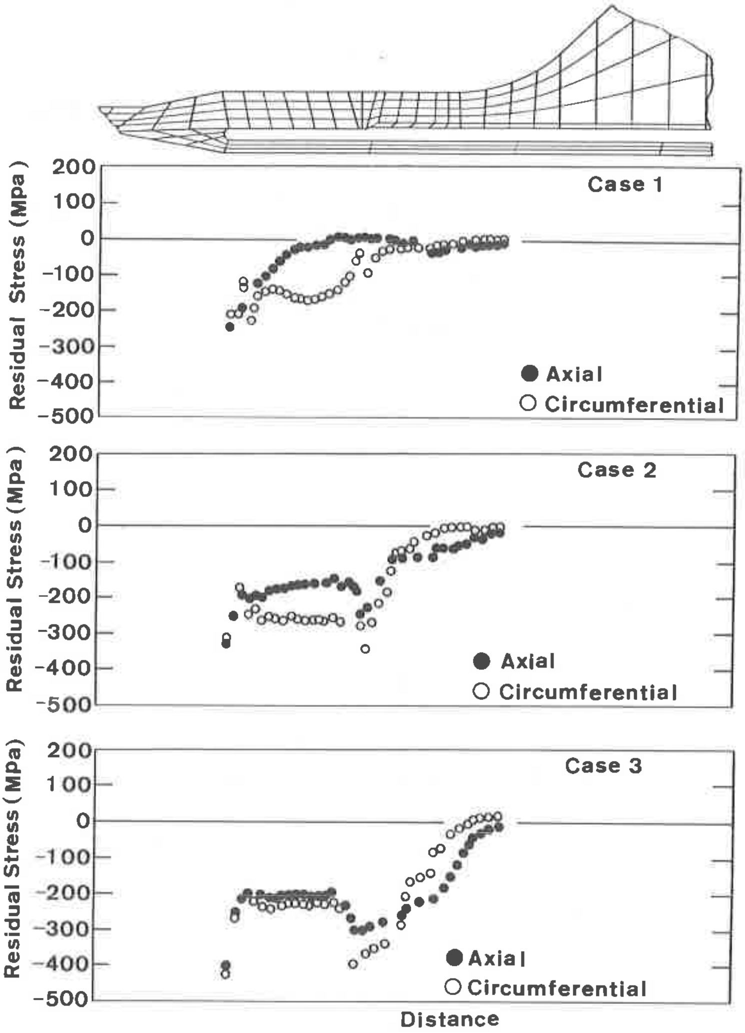

Fig. 6 Residual Stress Distributions After IHSI on Inner Surface of The Safe-End and The Nozzle