Application of Induction Heating Stress Improvement to Re-Circulation Inlet Nozzle Safe-End of BWR

T. Umemoto, A. Tanaka, A. Matsushita
Ishikawajima-Harima Heavy Industries Co., Ltd., Nuclear Power Division,
Isogo-ku, Yokohama 235, Japan

Abstract

IHSI$^{(1)(2)}$ is a well known fix against IGSCC which may occur at HAZ of BWR stainless steel pipe welds. IHSI is a process to reduce high tensile stresses induced by welding, and to reverse them into compressive, utilizing sufficient cooling water circulation in the pipes. The application of IHSI has been made to many weld HAZs of most BWR pipe joint geometries, but was not possible until recently to nozzle welds with a thermal sleeve which prevents the water from running inside the nozzles. 3 step IHSI was developed specifically to the nozzles application, being composed of three heat treatments in sequence, a preheat giving an axial bending stress to HAZ, the major IHSI treatment to induce through-wall temperature gradient, and a post-heat controlling the cooling curves at the safe-end branch portion so as to avoid an undesirable bending stress at the nozzle to safe-end weld joint.

1. Introduction

The intergranular stress corrosion cracking (IGSCC) has been found in the heat affected zones (HAZ) of the girth weld of type 304 stainless steel pipings in BWR plants. The weld residual stresses are considered to be one of the major ingredient to the IGSCC. Induction Heating Stress Improvement (IHSI) is a method to reduce or to alter this welding tensile stresses on the pipe inner surface to compressive. IHSI has been qualified and successfully implemented to many BWR pipe joints as an effective IGSCC countermeasure. Due to the limited cooling capability the IHSI application was not possible for Reactor Pressure Vessel (RPV) nozzle to safe-end welds which are also considered to be possible IGSCC areas, till the recent 3 step IHSI development. The paper describes the concept of 3-step IHSI, mock-up test results, and elasto-plastic analyses to demonstrate the method validity.

2. Concept of 3 Step IHSI

For conventional IHSI, the thermal stress induced in a long and thin pipe with a linear temperature difference, ΔT between the outer and inner pipe surfaces can be written as follows$^{(3)}$.

$$\sigma_y = \sigma_x = \pm \frac{E\alpha\Delta T}{2(1-\nu)} \tag{1}$$

where, σ_y, σ_x: Thermal stresses in circumferential and axial direction respectively.

E: Young's modulus, ν: Poisson's ratio

α: Thermal expansion coefficient

It is easily understood from eq. (1) that sufficiently large thermal stresses to cause a plastic flow can be induced by a large ΔT. This plastic flow should lower tensile weld residual stresses on pipe inner surface. Based on this concept, conventional IHSI was developed for different sizes and geometries including pipe to elbow, and pipe branch welds(4), and the essential operating parameters have been well established as summarized in Table 1.

In the conventional IHSI process, the cooling capability on the inner surfaces of piping components is sufficient to prevent film boiling and is nearly uniform all over the heated region. Therefore, piping components are heated for a sufficient time to obtain almost steady (through thickness) and uniform temperature distribution all over the heated region. This is, however, impossible for a joint between safe-end and reactor pressure vessel nozzle in which a thermal sleeve is provided because of the limited cooling capability in the thermal sleeve portion.

Two difficulties arise from the limited cooling capability; one is the film boiling which may occur due to relatively long time heating, another is the temperature gradient in axial direction caused by the difference of cooling capability between pipe and thermal sleeve portion. If such a nozzle safe-end is heated by the conventional way, the thermal sleeve portion will be over heated without getting sufficient ΔT and undesirable temperature gradient in axial direction will be induced which results in less effective IHSI.

In order to overcome these situation, 3 step IHSI was proposed. Concept of IHSI and the operation sequence of 3 step IHSI to a nozzle to safe-end is schematically illustrated in Figure 1 and explained as follows.

Step I Safe-end branch portion is heated expanding its radius to give a favorable bending moment to HAZ of the nozzle to safe-end weld joint. This operation will produce a margin to the bending moment induced by ΔT which generated by the next (Step II) heating.

Step II The HAZ portion is heated giving a temperature difference between outside and inside surfaces for a short duration.
This operation will provide a large ΔT without causing film boiling.

Step III The safe-end branch portion is continuously heated having a cooling rate at the safe-end branch portion same as or slower than that of the safe-end. This longer heating will prevent an undesirable bending moment.

3. Experimental

3.1 Preparation of Mock-ups

Two identical mock-ups of the joint between recirculation inlet nozzle and safe-end of 800 MWe BWR plant as shown in Figure 2 were fabricated. The nominal diameter of the nozzle is 12 inches, and the materials used in the mock-ups are typical AISI 304 stainless steel with chemistries and mechanical properties as given in Table II. Build up weld of Nozzle end was made by ordinary SMAW (Shield Metal Arc Welding) process. Weld joint between Nozzle to safe-end was made by automatic TIG welding. This weld joint of the mock-up simulates typical weld joint.

3.2 Induction Heating

3 step IHSI was performed to the mock-ups using a specially designed coil tailored to the process and the geometries. The temperature transition monitored at various parts of the mock-up is illustrated in Figure 3, while Figure 4 shows the temperature distribution at the end of the first, and the second step.

Heating durations for each step are 180 seconds, 50 seconds and 120 seconds, respectively. Fourier number of the second step is 0.5 which is rather short compared to criterion for the conventional IHSI. Pipe branch portion is heated satisfactory high temperature at the end of the first step heating. The temperature difference between outside surface and inside surface at HAZ of the safe-end is about 250°C which is considered to be satisfactory.

3.3 Residual Stresses

Two mock-ups were used to obtain the residual stresses after IHSI. One was immersed in boiling 42% $MgCl_2$ solution for 72 hours to check the residual stress level of the inside surface of the safe-end. The other mock-up was used to measure residual stresses using conventional strain gauges (gauge length: 2 mm) put on the required points near the joints. The mock-up was carefully cut into small cubes (approximately 20 mm x 20 mm x thickness) by saw and fine cutter. The relieved strains were measured and the residual stresses calculated.

4. Results and Discussion

No cracking were observed by SCC test in boiling 42% $MgCl_2$ solution. Considering the threshold stress(5) in boiling 42% $MgCl_2$ for 72 hours, the resultant residual stresses were estimated to be less than 8 kg/mm^2.

The results of the strain gage method are summarized in Figure 6. The inner surface hoop stress is made to be well compressive everywhere, and the axial stress as well except at the weld center. Figure 6 includes the results of the 2-dimensional thermo-elasto-plastic analysis made for the same mock-up testing using IEPTC program. The analytical results agree with the experimental but slightly differs at the weld line probably due to the difference in the strain hardening behavior of the deposit metal from the base metal.

Residual stresses of as welded condition is also shown in Figure 6. From Figure 6, 3 step IHSI was proven effective.

Effectiveness of 3 step IHSI depends on ΔT through thickness of the safe-end and heating duration of the second step heating.

ΔT at HAZ of the safe-end at the end of the second step heating is about 250°C which is considered to be satisfactory. According to Table I, 250°C is effective for 29 kg/mm^2 of yield point. Criterion at ΔT is same as that of the conventional IHSI.

From Figure 4, film boiling occurs in the annulus if heating duration of the second step heating is larger than 75 seconds (Fourier number = 0.75). Therefore, for this mock-up case the heating duration of the second step heating in Fourier number is decided as maximum 0.7. ΔT of the second step heating is satisfactory, but the heating duration of the second step heating is rather short (F = 0.5) compared to the required value (F = 0.7) for the conventional IHSI. The bending moment due to the first step heating is considered to make up for the short heating duration of the second step heating. Because residual stresses were improved although the heating duration of the second step is short.

Some difficulties were found during the mock-up test. One is that nucleate boiling must occur but film boiling must be avoided. To avoid film boiling, a combination of the first and the second step heating was studied and selected appropriately.

Air usually remained at the twelve o'clock portion and it prevented sufficient heat convection from inside surface of the safe-end.

Air purge heating was carried out. That is to heat the whole circumferences of annulus to 300°C for several minutes. This process causes nucleate boiling and the air was easily removed with the steam produced by the boiling. The removal of air can be assured by measuring the temperature on the outer surface of the safe-end.

5. Conclusion

The mock-up tests, 2-dimensional analysis and the discussion mentioned above led to following conclusion.

(1) 3 step IHSI is effective for Nozzle to safe-end weld joint with the thermal sleeve.

(2) 2-dimensional thermo-elasto-plastic analysis results showed near same tendency as the experimental.

(3) Air purge heating method was established.

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Table I Summary of parameters for conventional IHSI

No.	PARAMETERS	CONTROLLING RANGE	REMARKS
1	TEMPERATURE DIFFERENCE	$\Delta T \geq \frac{4\,\sigma Y(1-\nu)}{E\alpha}$	
2	HEATING DURATION	$\tau \geq 0.7\,\frac{t^2}{a}$	
3	COIL WIDTH	$L \geq 3\sqrt{Rt}$	
4	COIL LOCATION	$\alpha \geq 15^{MM}$ OR $\frac{t}{2}$	APPLIED WHICHEVER IS GREATER
5	MAXIMUM TEMPERATURE	To $\leq$ 550°C	

σY: Material Yield Strength (kg/mm^2)
ν: Poisson's Ratio
E: Young's Modulus (kg/mm^2)
α: Thermal Expansion Coefficient (m/m. °C)
t: Wall Thickness of Pipe (mm)
R: Mean Radius of Pipe (mm)
a: Temperature Conductivity (mm^2/sec.)
X: Distance from Weld Center to Coil End (mm)
To: Pipe Outside Temperature (°C)

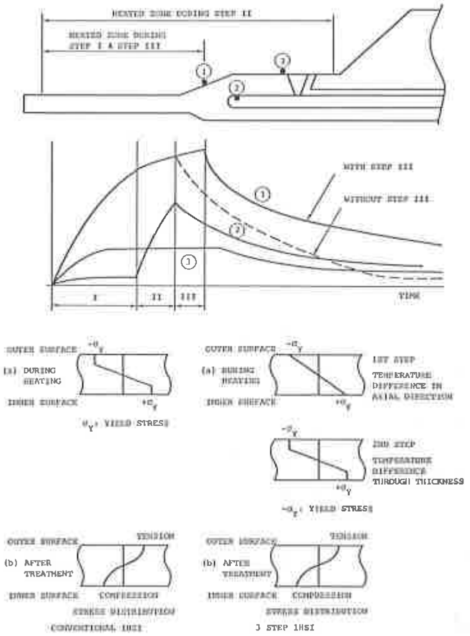

FIG. 1 HEATING SEQUENCE OF 3 STEP IHSI

Table II Chemical composition and mechanical properties

	Chemical Composition (%)							Mechanical Properties			
	C	Si	Mn	P	S	Ni	Cr	Yield Strength (kg/mm^2)	Tensile Strength (kg/mm^2)	Elon-gation (%)	Reduction Area (%)
Nozzle	0.25	0.23	0.95	0.023	0.018	-	-	34.7	53.5	30.0	58.7
Safeend	0.05	0.43	1.59	0.039	0.020	8.19	18.95	24.8	60.2	64.0	71.4

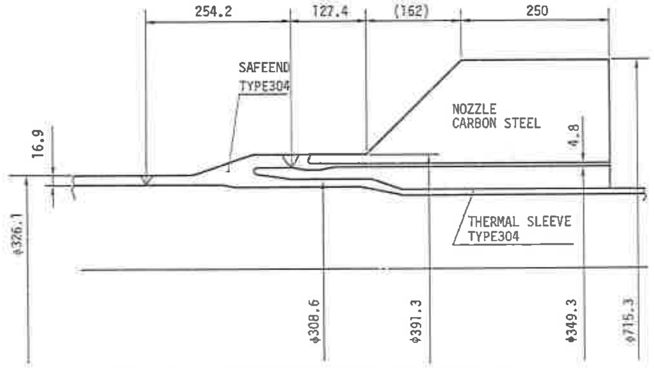

FIG. 2 CONFIGURATION OF MOCK-UP

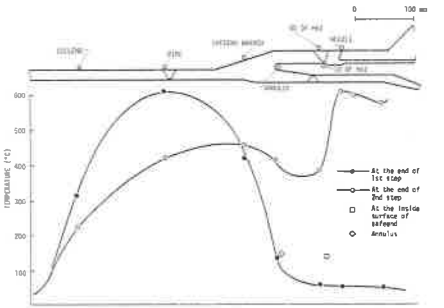

FIG. 4 TEMPERATURE DISTRIBUTION

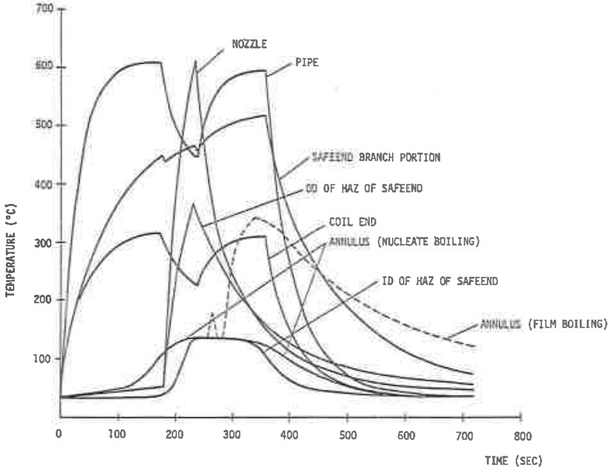

FIG. 3 TEMPERATURE TRANSITION CURVE

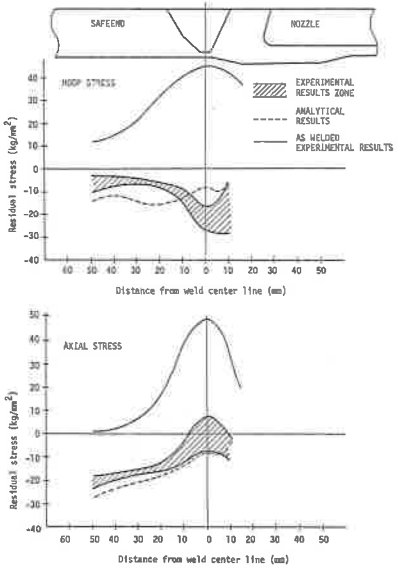

FIG. 5 RESIDUAL STRESSES