Application of Induction Heating Stress Improvement to Pipe Branches

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Summary:

Integranular stress corrosion cracking (IGSCC) is believed to occur when three factors, tensile stress, material sensitization, dissolved oxygen exceed some threshold simultaneously. It is well known that the welding residual stress is the one of the biggest contributer as a tensile stress source.

Induction Heating Stress Improvement (IHSI)[1] is a method to reduce this tensile residual stress at pipe inner surface or possibly to produce compressive stresses by plastic flow resulting from a large thermal stress due to a big temperature gradient through the pipe thickness.

It is rather easy to get such large ΔT in straight pipe and this technique has successfully been implemented as an IGSCC countermeasure for austenitic stainless steel weld joints of Boiling Water Reactor (BWR) piping systems in service or under construction in Japan. But as to pipe branches, the applicability of IHSI was not demonstrated.

There are two types of weld joint in pipe branches, namely, "set in" (welded in the main pipe) and "set on" (welded in the branch pipe or nozzle).

As the results of the stress measurement in as welded condition it was revealed that the residual stresses in "set in" type were much higher than those in "set on" type. The maximum residual stress reached 30 kgf/mm^2 approximately. This means that the "set in" type branch is very susceptible to IGSCC from the viewpoint of stress factor and some countermeasures should be applied.

In order to show the validity of IHSI as an IGSCC countermeasure for such joint, two mock-ups were prepared, which simulated the recirculation header to riser branches of 800 Mwe plant. The residual stresses were measured by using conventional strain gages. In addition, a three-dimensional elastic plastic analysis using FEM technique was performed.

The result showed that IHSI can change the high ($\simeq$ 30 kgf/mm^2) residual stresses to compressive ones ($\simeq$ -10 kgf/mm^2) or at least can lower the tensile stress level at the pipe branch connection.

1. Introduction

The intergranular stress corrosion cracking (IGSCC) have been found in the heat affected zones of the girth weld of type 304 stainless steel pipings in BWR plants.

The weld residual stresses are considered to be a big contributor to the IGSCC, since the pipe size dependency of the IGSCC occurrence and that of weld residual stresses are very much alike as shown in Fig. 1.

The IHSI (Induction Heating Stress Improvement) is a method to lower or change this welding tensile residual stresses on pipe inner surface to compressive ones.

The IHSI had been qualified and implemented successfully, as an IGSCC countermeasure, to many weld joints, except pipe to branch joints. The weld residual stresses in branch joints are also concerned to be enough high to cause the IGSCC, therefore, it is strongly requested to make IHSI applicable to such joints.

Based upon the preliminary studies, mock-up tests and a three dimensional elastro-plastic analysis were conducted to demonstrate the validity of IHSI to pipe branches.

This report describes the results of these experiment and analysis.

2. Preliminary Studies

2.1 Bending Moment Acting on Arbitrary Section

The thermal stress induced in a long and thin pipe with a temperature difference, ΔT between the outer and inner pipe surfaces can be written as follows(2).

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

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

This stress field is equivalent to that of a plate which has a uniform temperature difference (ΔT) between the two surfaces and is restricted from rotating at the all edges.

The stresses (σ_y, σ_{nt}) and moment (M_n, M_{nt}) acting on an arbitrary section of the plate are given by (3).

$$\sigma_n = \sigma_x\cos^2\alpha + \sigma_y\sin^2\alpha = \sigma_x = \sigma_y \qquad (2)$$

$$\tau_{nt} = \frac{1}{2}(\sigma_x - \sigma_y)\sin^2\alpha = 0 \qquad (3)$$

$$M_n = M_x\cos^2\alpha + M_y\sin^2\alpha = M_x = M_y = \frac{t^2E\alpha\Delta T}{12(1-\nu)} \qquad (4)$$

$$M_{nt} = \frac{1}{2}(M_x - M_y)\sin^2\alpha = 0 \qquad (5)$$

These equations show that the bending moment acting on any section is identical when plate (or a long thin pipe) has uniform temperature difference ΔT through the thickness.

2.2 Compatibility Condition at Pipe to Branch Joint

Let us now consider the thermal stresses at the connection between the main pipe to the branch which have a uniform temperature difference (ΔT) across the thickness (t) as shown in Fig. 2 (a). This model can be divided into two parts as shown in Fig. 2 (b). Applying the bending moment corresponding to eq. (4) to the cut edges, the stress state becomes

equivalent to that of uniform long cylinder and no distortion takes place. The deflection angles (ω) at the edges are:

$$\omega_M = 0 \text{ (for main pipe)} \quad (6)$$

$$\omega_B = 0 \text{ (for branch pipe)} \quad (7)$$

Thermal expansions in radial direction at the cut edges are:

$$\delta_M = \alpha r\, Tm \quad (8)$$

$$\delta_B = \alpha r\, Tm \quad (9)$$

where Tm : Mean temperature

From equations (6), (7), (8) and (9), it is known that no discontinuity stresses and displacements take place at the branch connection having a uniform temperature difference across the thickness and the thermal stresses induced are given by eq. (1).

2.3 Conclusion of Preliminary Studies

From the above discussion, it can be concluded that the thermal stresses in a pipe branch connection induced by IHSI are equivalent to those of a straight pipe and therefore the same IHSI effects are expected in a branch connection as a straight pipe.

3. Experimental

3.1 Preparation of Mock-ups

As the preliminary tests showed that the residual stresses in "Set in" type were much higher than "Set on" type connection (See Fig. 3), two "Set in" type mock-ups were prepared.

The both mock-ups simulated the joints between recirculation header and riser pipe of 800 Mwe BWR plant. As shown in Fig. 4, the main pipe was curved slightly to simulate the actual recirculation header. The nominal diameter of main pipe and riser are 22 inches and 12 inches respectively. The chemical composition and mechanical properties of the mock-up are shown in Table 1. The branch was welded to the main pipe by ordinary SMAW (Shield Metal Arc Welding) process to duplicate the actual branch weld.

3.2 Induction Heating

Induction Heating was performed on one mock-up using a specially designed coil to obtain uniform temperature distribution. The temperature was monitored by CA thermocouples directly mounted on the mock-up. The heating condition is shown in Table 2.

3.3 Residual Stresses

One as welded mock-up was immersed in boiling 42% $MgCl_2$ solution for 40 hours to check the residual stress level of the inner surface of the pipe branch in as welded condition.

The other mock-up was used to obtain the residual stresses after IHSI. Putting the conventional strain gages (gage length: 2mm) 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 were calculated.

4. Results and Discussion

The cracking pattern obtained by SCC test in 42% $MgCl_2$ solution is shown in Fig. 5. The cracks propagated in both parallel and normal directions to the weld joint. Considering the threshold stress[4] in 42% $MgCl_2$ solution for 40 hours, the residual stresses in as welded condition were judged to be sufficiently higher than 10 kg/mm^2.

The measured residual stresses after IHSI treatment are shown in Fig. 6. At the almost all points the residual stresses were changed to compressive ones by IHSI. The stresses parallel to the weld were rather uniform but the normal stresses to the weld had somewhat steep transition near the joint. The trend and also the residual stress level did not change in all section experimented.

Fig. 6 also shows the results of 3-dimensional thermo-elasto-plastic analysis on the same mock-up using MARC program[5]. This results showed the same tendency as the strain gage results.

The discussion mentioned in Section 2 suggests that the residual stresses are identical in both circumferential and axial direction. But in that discussion, the material thickness was assumed to be uniform while the nozzle (branch) in the mock-up had thicker section than the main pipe.

The bending moment induced by ΔT is proportional to the square of the thickness as shown by eq. (4), therefore larger moment must be induced in the branch. The bending moment in the main pipe must somewhat increase to maintain the stress equivalence with that of the branch. This additional moment would act to produce more deep normal residual stresses than the parallel one. Usually weld joints are located in the thinner section, when the thickness of the components are different, therefore this additional moment will preferably act to improve the residual stresses more thoroughly.

5. Conclusion

The mock-up tests, 3-Dimensional analysis and the discussion mentioned above led to the following conclusion.

(1) IHSI for pipe branch connection is essentially equivalent to straight pipe.

(2) $MgCl_2$ cracking test revealed that branch connection had sufficiently high tensile residual stresses to cause SCC in as welded condition.

(3) IHSI is applicable to pipe branch connection and is expected to be effective as an IGSCC countermeasure.

(4) 3-Dimensional thermo-elasto-plastic analysis results showed the same tendency as the experimental.

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(2) Timoshenko, S., Woinowsky-Krieger, S., "Theory of Plates and Shells", McGraw-Hill (2nd Edition), p 497.

(3) Timoshenko, S., Woinowsky-Krieger, S., ibid. p 39.

(4) Denhard, E. E., "Effect of composition and Heat Treatment on the Stress Corrosion Cracking of Austenitic Stainless Steels, "Corrosion, Vol. 16, No. 7, (1960).

(5) Okamoto, A., Umemoto, T., "Analysis of the Residual Stress at welded pipe branch under Induction Heating Stress Improvement", Proceedings of 6th SMiRt, G/540 (1981).

(6) Fox, M., "An Overview of Intergranular Stress Corrosion Cracking in BWRs", Proceedings of EPRI Seminar on Countermeasures for BWR Pipe Cracking, Jan. (1980).

(7) Sasaki, T. et. al, "Mitigation of Inside Surface Residual Stress of Type 304 Stainless Steel Pipe Welds by Inside Water Cooling Method", Proceedings of EPRI Seminar on Countermeasures for BWR Pipe Cracking, Jan. (1980).

TABLE I CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES

SPECIFIED VALUES / PARTS	CHEMICAL COMPOSITION (%)							MECHANICAL PROPERTIES			REMARKS
	C	Si	Mn	P	S	Ni	Cr	$\sigma_{0.2}$	σu	EL (%)	
	MAX. .80	MAX. 1.00	MAX. 2.00	MAX. .040	MAX. .030	8.00 11.00	18.00 20.00	21*	53*	45	
HEADER NOZZLE	0.06	0.61	1.60	0.035	0.003	8.90	18.46	23	58	70	

* STRESSES ARE IN kgf/mm^2

Table II HEATING CONDITION

ESSENTIAL VARIABLES	REQUIRED	RESULTS
COIL WIDTH (mm)	$\geqq 2.7\sqrt{rt}$ $= 287$	640
HEATING DURATION (sec)	$\geqq 0.7\frac{t^2}{a}$ $= 477$	500
TEMPERATURE DIFFERENCE (°C)	$\geqq \frac{4(1-\nu)}{E\alpha}\sigma y$ $= 189$	329
MAXIMUM TEMPERATURE (°C)	$\leqq 550$	460

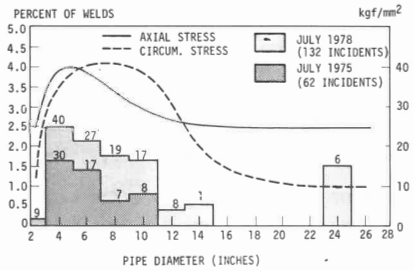


FIG. 1 IGSCC FREQUENCY(6) AND WELD RESIDUAL STRESSES AS A FUNCTION OF PIPE SIZE

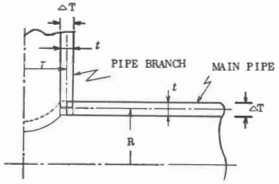


FIG. 2 (a) PIPE BRANCH HAVING ΔT THROUGH THE THICKNESS

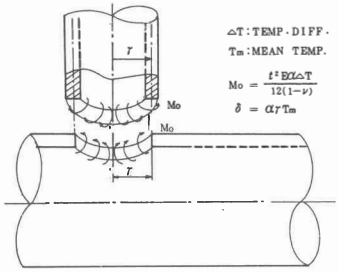


FIG. 2 (b) COMPATIBILITY CONDITION OF PIPE BRANCH HAVING ΔT THROUGH THE THICKNESS

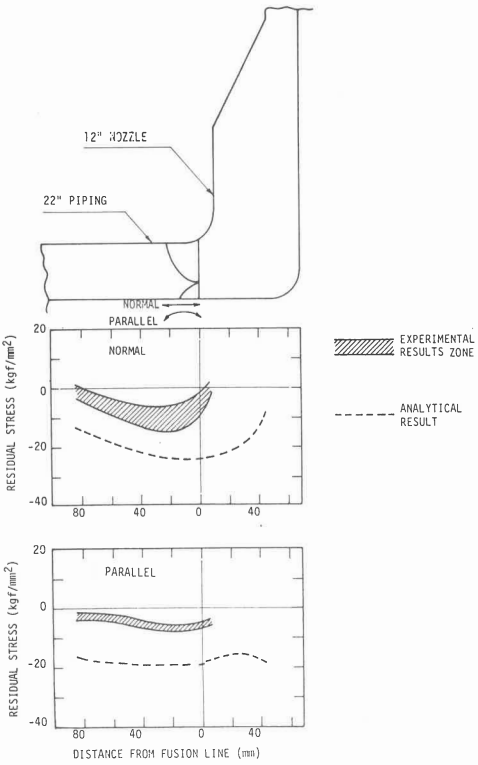


FIG. 3 (a) RESIDUAL STRESSES IN SET-IN TYPE WELDING JOINTS

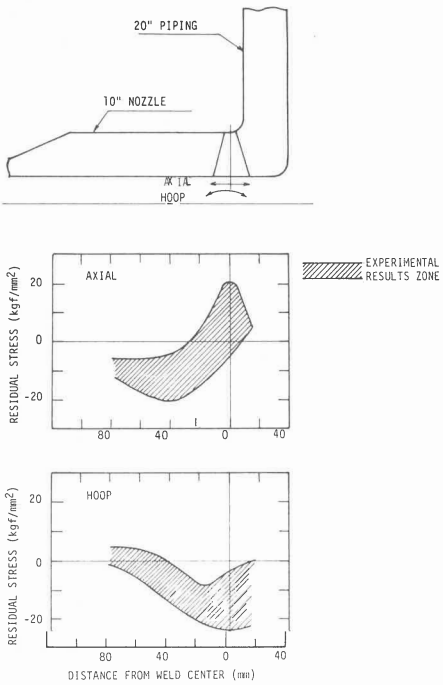
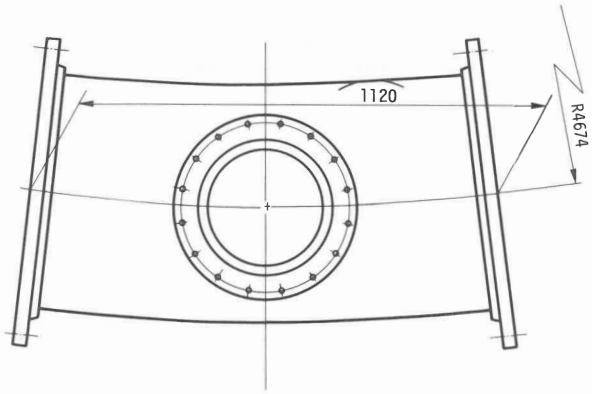


FIG. 3 (b) RESIDUAL STRESSES IN SET-ON TYPE WELDING JOINTS



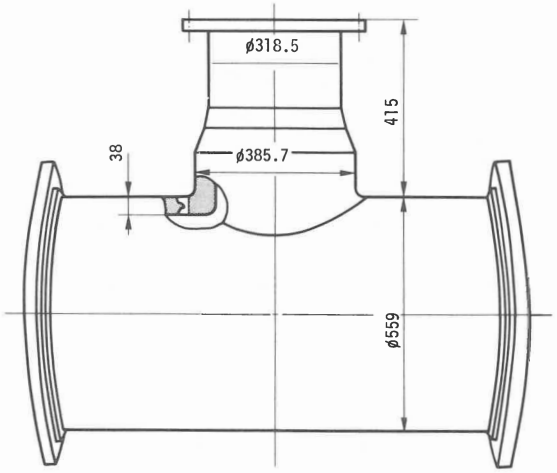
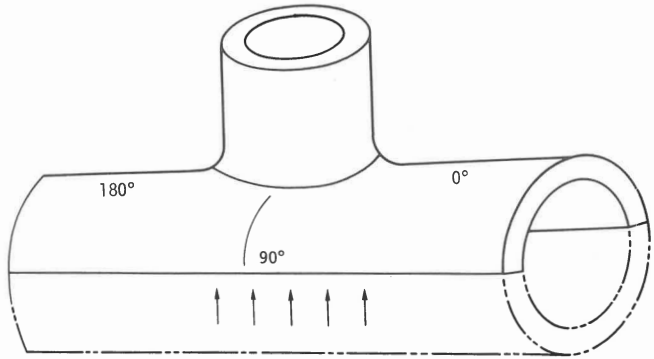


FIG. 4 DETAILS OF MOCK UP



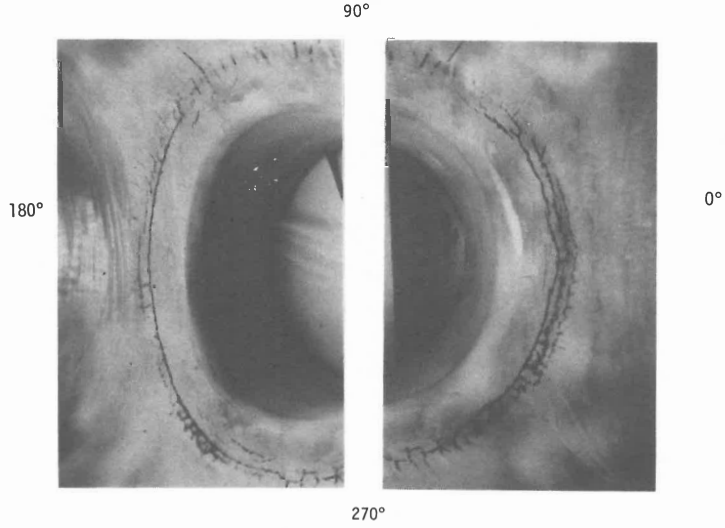


FIG. 5 RESULTS OF CRACKING TEST IN 42 % $MgCl_2$ SOLUTION

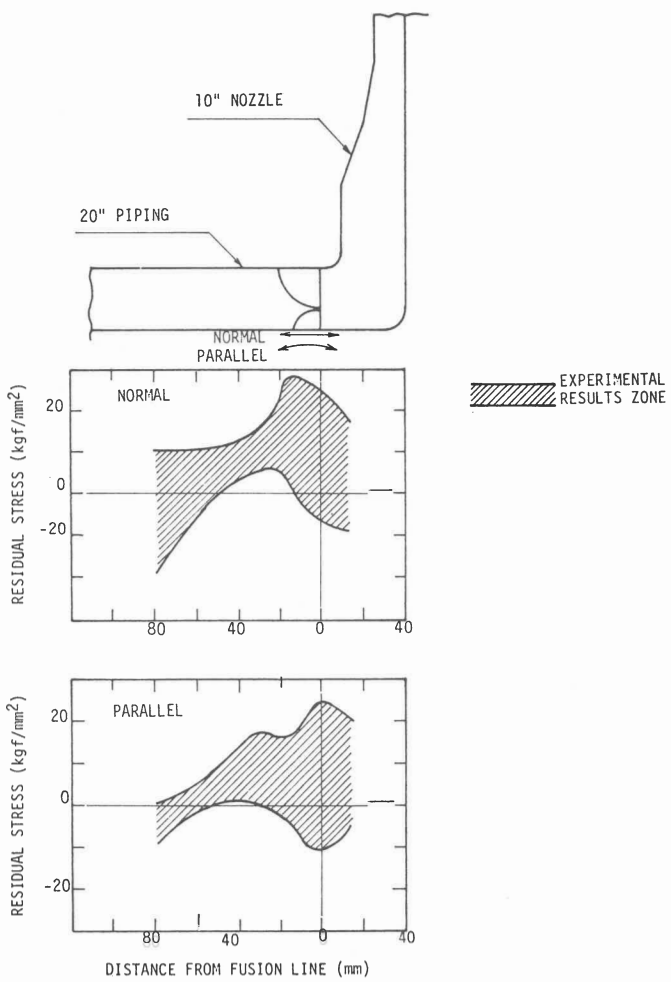


FIG. 6 (a) RESIDUAL STRESSES AFTER IHSI (AXIAL SECTION)

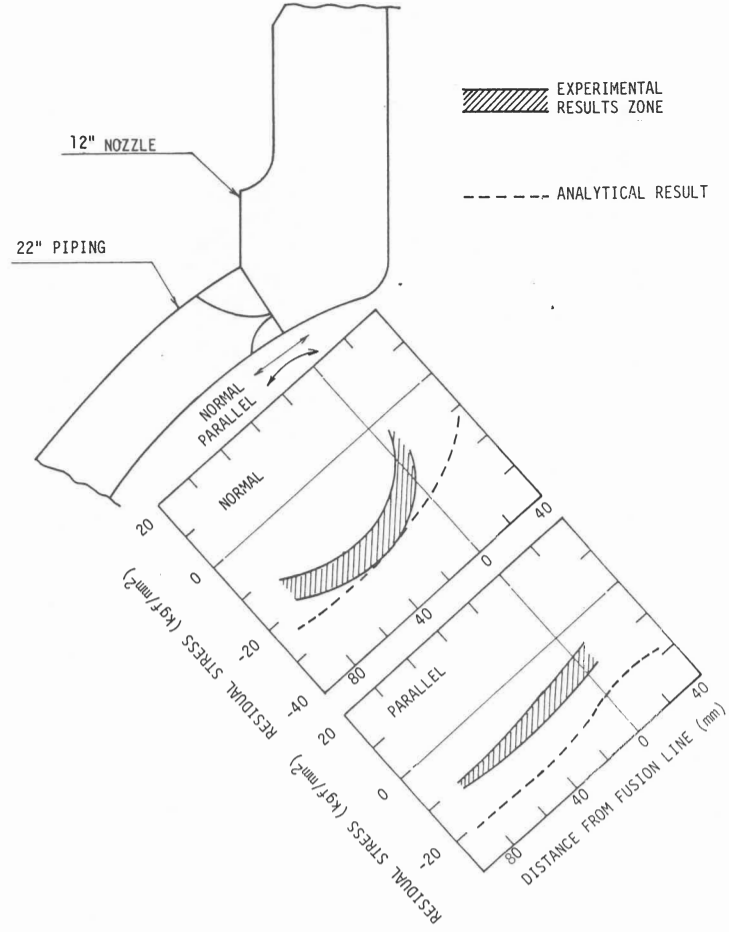


FIG. 6 (b) RESIDUAL STRESSES AFTER IHSI (CIRCUMFERENTIAL SECTION)