THEORETICAL AND EXPERIMENTAL STUDY ON INDUCTION HEATING STRESS IMPROVEMENT (IHSI) OF NUCLEAR PRIMARY PIPING

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The intergranular stress corrosion crackings (IGSCC) of austenitic stainless steel piping in nuclear primary system are considered to occur when material sensitization, stress and corrosion environment exceed some critical values simultaneously. In relation to the welding residual stress which is one of the most important causes of the IGSCC, a new technique to improve the stress called the induction heating stress improvement (IHSI) is developed and applied to the several pipings in the boiling water reactors in Japan.

The technique is simply explained from the fact that the welding residual tensile stress in the inner surface of pipe is reduced by the inelastic thermal stress when a pipe is heated from its outside surface using induction coil and cooled inside surface with spray water or running water simultaneously.

The objective of the present paper is to describe the effectiveness of the technique by conducting full-scaled demonstration tests as well as nonlinear finite element analyses.

Assuming the existence of small initial flaws in the inner surface of piping, the finite element calculations using the programs EPAS and ANSYS are performed for the unsteady as well as nonlinear behaviors of austenitic stainless steel pipes during the course of the induction heating.

The calculations are made parametrically changing the pipe diameter, the thickness, the crack size compared to wall thickness, the orientation of crack, the heating condition and the initial welding residual stress. The results of the finite element analyses show that the initial welding residual stress of tensile direction is effectively altered after the treatment of the IHSI to compressive stress near the inner surface where the IGSCC is considered to occur in most case, and also that the crack opening displacements during and after the treatment of the IHSI are small enough compared with the critical value.

In order to confirm that the pipe with small initial crack keeps safe during the IHSI treatment, a series of tests are conducted. The one is the test using the 12 inches diameter pipes with artificially fatigued crack in the inner surface. The other is the test using the 4 inches diameter pipes with cracks by electric discharge near girth weld portion in the inner surface, in which the pipes are dipped in $MgCl_2$ environment to verify that the IGSCC is avoided by the IHSI treatment. The results of these two series of tests reveal that the IHSI treatment is very effective for the improvement of the welding residual stress around the initial small crack in the inner surface of the pipe.

A new technique IHSI developed for the improvement of the tensile welding residual stress in the inner surface of pipe is proved effective and safe even in such a severe condition that there exists small initial crack which is impossible to be found out by the ultrasonic testing. It is concluded that the IHSI can be applied to the piping of nuclear plants under construction as well as operation.

1. INTRODUCTION

The intergranular stress corrosion crackings (IGSCC) have been observed in austenitic stainless steel piping (type 304) of several BWR plants. As already known, IGSCC would preferentially occurs when the three key factors, i.e. material sensitization, high stress and corrosion environments are overlapped. As the welding residual stress is sufficiently high and of tension in the inner surface of the piping, then the IGSCC will be considered to occur around there. To reduce the residual stress in the inner surface of the piping will be, then, effective to mitigate the IGSCC.

A new method to improve the residual stresess using the induction heating is reported in this paper. The technique called the "Induction Heating Stress Improvement (IHSI)" aims to improve the condition of the residual stress in the inner surface of the pipe using the thermal stress through temperature difference in the pipe wall, which is produced when a pipe is heated from the outside surface by induction coil and cooled inside surface by spray water or running water in the same time.

Analysis by the finite element method and full-scaled demonstration test are conducted. Also this technique is proved effective and safe even in such a condition that there exists small initial crack which is impossible to be found out by the ultrasonic testing.

2. CONCEPT OF IHSI

When a linear temperature gradient is given across the thickness of pipe, the thermal stress produced can be approximately written as follows [1].

$$\sigma = \frac{E\alpha\Delta T}{2(1-\nu)}$$

where σ : Thermal stress E : Young's modulus

α : Linear thermal expansion coefficient ν : Poisson's ratio

ΔT : Temperature difference between inner and outer surfaces

When this thermal stress is below the yield stress (e.g. point ① in Figure 1), the stress is relieved when the temperature difference is removed, and no residual stress remains behind. However, if the thermal stress exceeds the yield stress (e.g. point ② in Figure 1), the subsequent removal of the temperature difference changes the condition from point ② to point ③. Thus a compressive residual stress occurs as shown in the figure. The object of the IHSI is to introduce a large temperature difference between the inner and outer surfaces of a pipe in order to produce the sufficient thermal stress which exceeds the yield stress and consequently to obtain a compressive residual stress in the inner surface of the pipe. The large temperature difference can be introduced by heating the pipe from the outside with induction coil while cooling water is supplied to the inner surface of the pipe simultaneously.

Figure 2 shows the diagram of the heating and cooling method. Figures 3(a) and (b) illustrate the stress distribution, deformation and temperature distribution during heating and after treatment, respectively. Applying the above technique to a weld joint of a pipe, it has already been shown that the IHSI produces a relatively high compressive residual stress on the inside surface of the pipe throughout the weld heat affected zone [2].

3. FINITE ELEMENT ANALYSES

Assuming the existance of small initial crack in the inner surface of the pipe, the finite element calculations using the programs EPAS [3] and ANSYS [4] are performed for the case of the transient temperature as well as the inelastic behaviour of type 304 stainless steel. A summary of the analyses is shown in Table 1.

In this section, we describe only the case 6 in Table 1. First, the proper initial welding residual stress is given in the pipe. Second, the crack is propagated step by step until the specified depth by reducing the elastic modulus at the crack position to a very small value. Third, the thermal elastic plastic analysis of the pipe with crack is performed with the transient temperature distribution of the induction heating as shown in Figure 4. Finally, the operating internal pressure of 100 kg/cm^2 is applied to the pipe after the treatment of the IHSI.

Figure 5 shows the crack opening displacements versus the crack depth at the time of maximum temperature difference (=180 sec.) and after the treatment. Figure 6 shows the distributions of the stresses on the prolongation of the crack in the perpendicular direction to the cracked plane after the treatment of the IHSI and the application of the operating internal pressure.

4. DEMONSTRATION TESTS

In order to evaluate the features of the IHSI, the demonstration tests are carried out.

The propagation test is made with a pre-cracked pipe to confirm that no cracks initiate from the pre-crack tip during the IHSI, though the relatively high tension stress occurs at the crack tip. Figure 7 shows the procedure of the test. Figure 8 shows the micro-fractography of the failured surface and the micro-fractography of the pre-crack tip after the IHSI treatment. As can be seen from the figure, no crack propagations are observed between the pre-crack and the subsequent fatigue crack, though the micro-fractography shows that the stretched-zone of 2 ∿ 3μ length is seen at the pre-crack tip.

The another test is made to confirm that the residual stress is improved by the IHSI. The procedure of the test is shown in Figure 9. Figure 10 shows the results of the stress improvement test of the pre-cracked pipes with and without the IHSI improvement. As shown in the figure, no stress corrosion cracks occur after the immersion of the test pieces with the tensile residual stress in $MgCl_2$ if the IHSI treatment is made, and vice versa.

As for the safety of the pre-cracked pipe, the theoretical CTOD (Crack Tip Opening Displacements) of the pipe with the pre-crack during the IHSI are compared with the critical CTOD. It is found from the comparison that the safety factor is more than 30.

5. CONCLUSION

The induction heating stress improvement, a new technique for the improvement of the tensile welding residual stress in the inner surface of the nuclear pipe, is proved to be effective and safe even in such a condition that small crack exists initially. It may be concluded that the IHSI can be applied to the primary pipings of nuclear plants under construction as well as operation.

REFERENCES

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[3] G. Yagawa, et al. : EPAS-Finite Element Program for Analysis of Nonlinear Behavior of Nuclear Power Piping, 5th SMiRT, M6/4, 1979.

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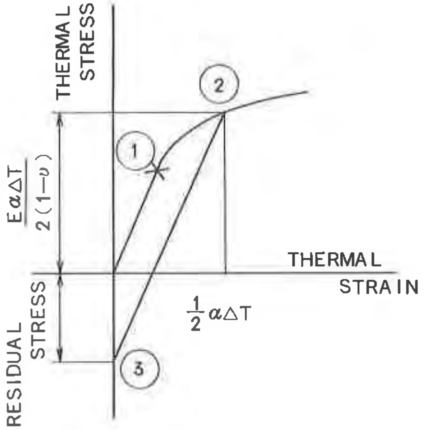


FIG.1 STRESS-STRAIN DIAGRAM

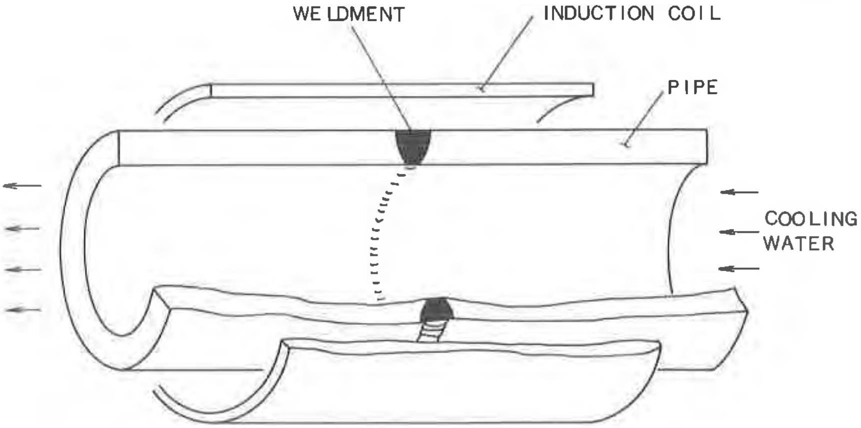


FIG.2 DIAGRAM OF HEATING AND COOLING

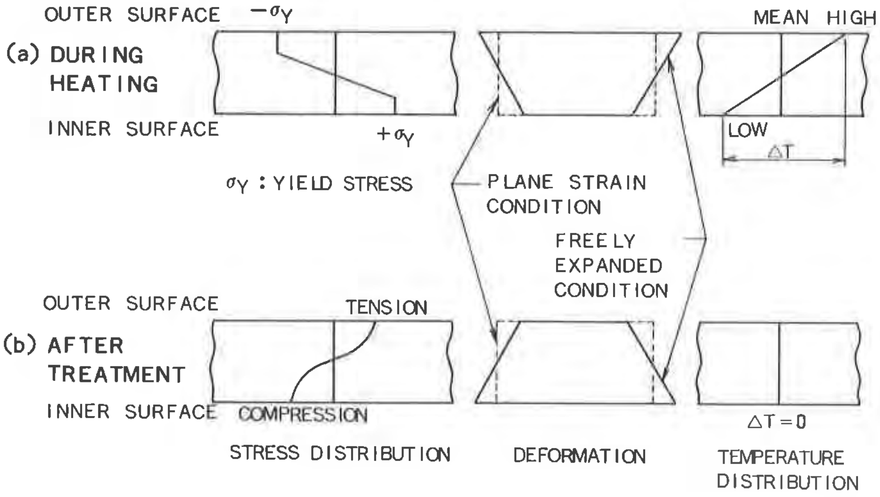


FIG.3 CONCEPT OF IHSI

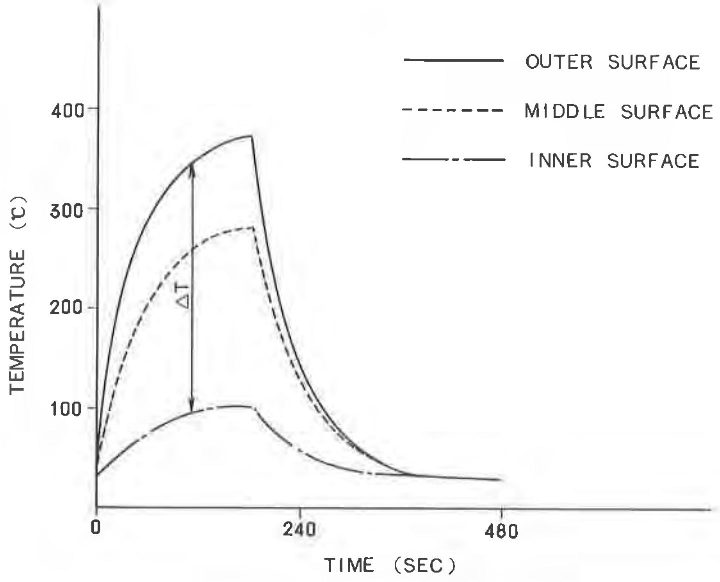


FIG.4 CALCULATED TEMPERATURE HISTORIES

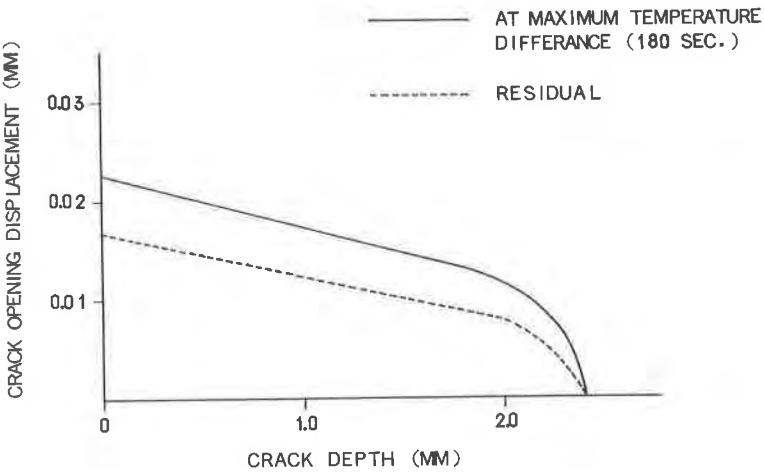


FIG.5 CONFIGURATIONS OF CRACK OPENING DISPLACEMENT (CASE No.6)

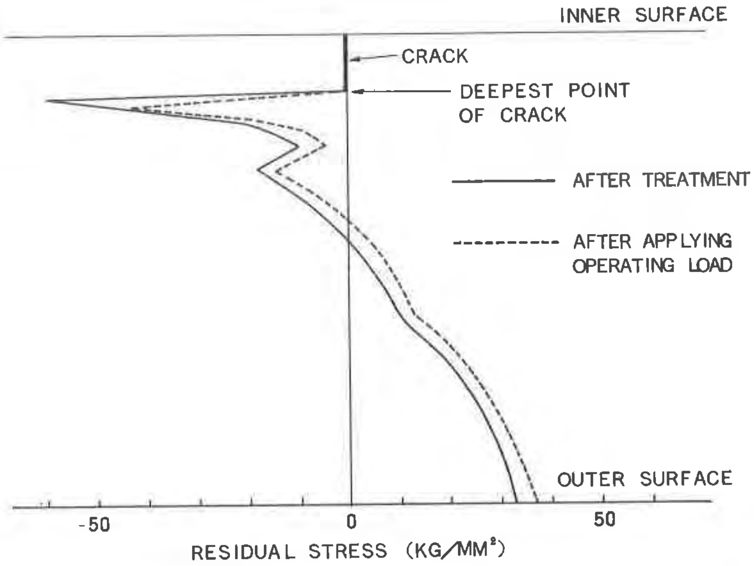


FIG.6 RESIDUAL STRESS DISTRIBUTIONS PERPENDICULER TO CRACK SURFACE (CASE No.6)

SLIT CUT

⇩

FATIGUE PRE-CRACK
BY FATIGUE TEST
MACHINE

⇩

TEMPER COLOUR
BY HEAT TREATMENT

⇩

IHSI TREATMENT

⇩

SUBSEQUENT FATIGUE
BY FATIGUE TEST
MACHINE

⇩

FRACTURE BY
TENSION

⇩

VISUAL TEST AND
MICRO-AND MACRO-
FRACTGRAPHIES

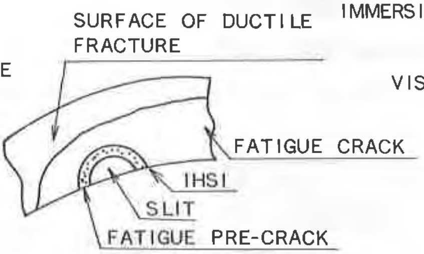


FIG.7 PROCEDURE OF PROPAGATION TEST

GIRTH WELD ON TWO PIPES

⇩

PRE-CRACK BY ELECTRIC DISCHARGE
ON INSIDE SURFACE

⇩ ⇩

IHSI-TREATMENT

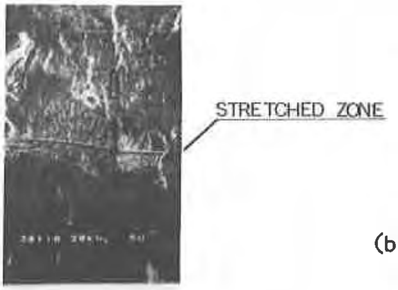
⇩

IMMERSION IN $MgC\ell_2$

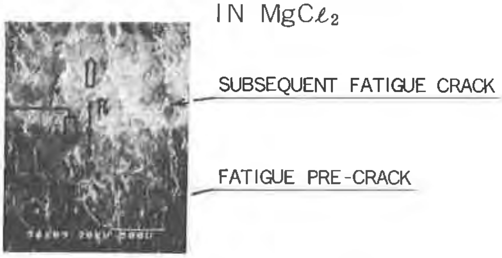
⇩

VISUAL TEST

FIG. 9 PROCEDURE OF IMMERSION TEST IN $MgC\ell_2$



(a) MICRO–FRACTGRAPHY
(×1000)

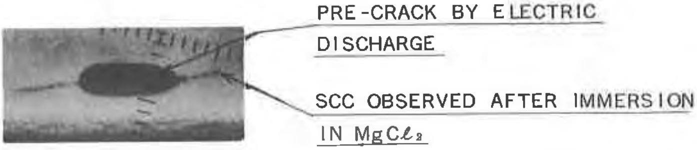


(b) MACRO–FRACTGRAPHY
(×50)

(c) CROSS SECTION OF PIPE

FIG.8 MICRO- AND MACRO-FRACTGRAPHIES OF PROPAGATION TEST SPECIMEN AFTER IHSI TREATMENT

(a) PRE-CRACK



(b) WITHOUT IHSI TREATMENT (DYE PENETRATION TEST AFTER IMMERSION IN $MgC\ell_2$)

(c) WITH IHSI TREATMENT (DYE PENETRATION TEST AFTER IMMERSION IN $MgC\ell_2$)

FIG.10 RESULTS OF STRESS IMPROVEMENT TEST USING IMMERSION IN $MgC\ell_2$ OF PRE-CRACKED PIPES WITH AND WITHOUT IHSI TREATMENT

TABLE 1. SUMMARY OF FINITE ELEMENT CALCULATIONS

CASE NO.	PIPE SIZE *)			CRACK SHAPE		ANALYTICAL MODELS
	NOMINAL SIZE	OUTER DIAMETER (D_O)	THICKNESS (t)	DEPTH	ORIENTATION	
1	12 IN. SCH. 100	(MM) 318.5	(MM) 19	(MM) 2.4	CIRCUMFERENTIAL CRACK	AXISYMM.
2	12 IN SCH. 100	318.5	19	4.8	CIRCUMFERENTIAL CRACK	AXISYMM.
3	24 IN. SCH. 100	609	38	4.8	CIRCUMFERENTIAL CRACK	AXISYMM.
4	24 IN. SCH. 100	609	38	2.4	CIRCUMFERENTIAL CRACK	AXISYMM.
5	12 IN. SCH. 100	318.5	19	2.4	AXIAL CRACK	GENERALIZED PLANE STRAIN
6	12 IN. SCH. 100	318.5	19	2.4	CIRCUMFERENTIAL CRACK	AXISYMM.
7	12 IN. SCH. 100	318.5	19	(2.4×14.4)	SEMI-ELLIPTICAL CRACK	3-D

Note: *) PIPE LENGTH $\ell \geqq 2.5\sqrt{D_O t}$