Analysis of the Residual Stress at Welded Pipe Branch Under Induction Heating Stress Improvement

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Summary :

The induction heating stress improvement (IHSI) has been widely used in Japan as one of the most effective countermeasures for the intergranular stress corrosion cracking (IGSCC) of BWR piping weld joints.

IHSI has been applied to many straight pipes or elbows, but not to a weld joint in a pipe branch. It is required to control the significant parameters within a suitable range to get a succesful results. These parameters and their controlling ranges for pipe branches have not been established. Therefore in this study, they are investigated.

Firstly, to find the basic character of residual stress distribution, three dimensional analysis was performed using computer program MARC. Considering symmetry, the model of one-quarter of the complete structure with 20 node isoparametric elements was used. The analysis shows that there is not so many difference between the stress distribution in the transverse section and that in the longitudinal section near the pipe branch corner.

The weld pipe branch was also analyzed with a two-dimensional model. Comparing with the results of three-dimensional analysis the applicability of two-dimensional approximation for this study is concluded.

Then the parameter survey was performed to get the controlling factors by a two-dimensional computer program of finite element method.

The main results of the analysis are as follows.

(1) The limit of the ratio of pipe to branch thickness is specified. The range covers the general cases of BWR weld pipe branches.

(2) Both weld geometries of a set-in type (junction in the pipe side) and a set-on type (junction in the branch side) can be treated by IHSI.

(3) When there is reinforcement in the branch, a certain length of the reinforcement is required for successful IHSI. The length is a variable of the branch thickness and diameter.

In the last part of this paper, the comparison between the results of analysis and experiment is described. The proof test of IHSI for a weld pipe branch was performed using the heating factors determined by the analysis. Temperature distribution around the branch corner was measured by thermocouples. Good agreement was found between the analysis and the experiment.

1. Introduction

The induction heating stress improvement (IHSI) has been widely used in Japan as one of the most effective countermeasures for the intergranular stress corrosion cracking (IGSCC) of BWR piping weld joints.

IHSI aims to improve the state of residual stresses, that is, to reduce the high tensile stresses at inside surface of pipes or if possible to change them to compressive stresses.

IHSI has been applied to many straight pipe or elbows, however, no weld joint in a pipe branch has been treated by IHSI.

It is required to control the significant parameters within a suitable range to get a successful results. These parameters and their controlling ranges for pipe branches have not been established. Therefore in this study, these parameters, especially the following are investigated.

(1) Length of the induction coil for the pipe and the branch respectively.

(2) Heating density at the regions of the pipe and the branch.

(3) Effect of the ratio of branch to pipe diameter.

(4) Effect of the ratio of branch to pipe thickness.

For this purpose, three-dimensional elastic-plastic analysis of a pipe branch using computer program MARC [1] and parameter survey by a two-dimensional FEM computer program were carried out.

2. Concept of IHSI

The concept of IHSI is briefly explained as follows. The large temperature gradient is introduced in a pipe by heating from the outside with an induction coil, while cooling from inside with water simultaneously.

If the temperature gradient is large enough to produce tensile yielding at inner surface, the compressive residual stress will be developed after the temperature gradient is removed. IHSI is the method to improve the stress state by the above thermal elasto-plastic mechanism.

The effect of IHSI is influenced by many parameter; temperature difference, heating duration, induction coil width, coil location and so on. For the successful treatment of IHSI these parameters, called "essential variables", should be suitably controlled. As for straight pipes or elbows, the essential variables have been specified as follows by experience and calculation using the finite element method [2].

(1) Temperature difference ; ΔT

$$\Delta T \geq \frac{4(1-\nu)}{E\alpha}\,\sigma y \qquad (1)$$

where E : Young's modulus

α : Linear thermal expansion coefficient

ν : Poisson's ratio

σy : Yield stress

(2) Heating duration ; τ

$$\tau \geq 0.7\, t^2/a \qquad (2)$$

where t : Pipe thickness

a : Thermal diffusivity coefficient

(3) Coil width ; ℓ

$$\ell \geq 3\sqrt{RT} \qquad (3)$$

where R : Means radius of pipe

T : Pipe thickness

(4) Coil setting location

The weld center should be located at least the greater of 15 mm or t/2 inside from the coil end.

3. Objective and Methodology

Weld pipe branches in a nuclear power plant have generally the heat affected zones (HAZ) for which some countermeasures of SCC are required. The application of IHSI would be desirable.

However, for pipe branches, the additional study is necessary to determine the essential variables, because of the complexity of configulation comparing to straight pipes or elbows.

Therefore, farther investigation was performed to find the required heating area and the geometrical restrictions.

The program of the study was as follows.

(1) In order to find the characteristic of inside metal temperature and residual stress distribution, a three-dimensional elastic-plastic analysis was performed.

(2) Comparing two and three-dimensional calculation results, equivalent two-dimensional models for the parametric survey were determined.

(3) Essential variables for pipe weld branches ware obtained.

(4) For the final confirmation, a proof test was performed using a mock-up model.

There are two types of weld geometry of pipe branch, a set-in type and a set-on type. The former has a junction in the pipe side while the latter has in the blanch side. In the following analysis, residual stresses at the both weld location will be discussed.

4. 3-D Elastic Plastic Analysis Results

A typical weld pipe branch was subdivided into three-dimensional isoparametric elements with 20 nodes using a mesh generator. The model is given in Fig. 1. It consists of 120 elements and 825 nodes.

General purpose computer program MARC was used for the analysis.

Transient temperature distribution was obtained using TYPE 44 elements. The values of heating density and heating time for the main pipe and the branch were selected after some trial calculations to obtain similar temperature distribution to the actual one.

The temperature transition data ware stored in a post tape for the succeeding stress calculation using TYPE 21 elements.

The thermal residual stress calculation need 300 min. of CPU time by IBM-3032 computer.

The temperature transition curves are shown in Fig. 2 which are in good agreement with the trend of the experiment which will be mentioned later.

The calculated residual stresses on the inner and outer surface are shown in Fig. 3.

The residual stresses along the circumference of the two types of weld location are shown in Fig. 4 and 5 , which show that the effect of three-dimensional restrictions is not so strong and it can be neglected for this kind of problem. This output suggests that the two-dimensional calculation may be useful to obtain a good approximate value.

5. Parameter Survey for Control Value

For the purpose of parameter survey two-dimensional axisymmetric models were used. In advance, comparing with the stress distribution by three-dimensional analysis the application of two-dimentional approximation for this study is concluded to be reasonable.

The following are the conclusions derived from the parameter survey.

(1) Coil length

The effect of the coil length is shown in Fig. 6 (a), (b). The length is sufficient for both weld types if it extends more than $1.0\sqrt{RT}$ from the branch corner in the meridional direction for the pipe and the branch respectively, where R is the midsurface radius and T is the thickness for each shell.

(2) Heating density

As is shown in Fig. 2, the temperature of the outer surface at the thinner part rises faster than at thicker part. Although the heating density is not a essential variable, the technique how to give it to each part is important for successful IHSI treatment.

The investigations, up to this time, suggest the following.

a. Heating density should be given at the level about being invers proportion of the thickness ratio.

b. Heating density at thinner part should not be given at so high level. If it is, the temperature at thinner part will go over maximum specified temperature when the thicker part reaches the specified temperature.

c. The restriction of heating duration for straight pipe, eq.(2), is applicable for pipe branch too.

(3) Geometrical factors

The effect of the geometical factors are shown in Fig. 6 (c), (d).

When there is reinforcement in the branch and consequently there is a thickness change within the coil length, it is observed that some reduction of the effect of IHSI can be taken place as shown in Fig. 6 (d).

In the other cases, all the results of the calculations show that the sufficient compressive stress can be obtained at HAZ by controlling the above mentioned factors. Especially it is found that the ratio of pipe to branch diameter does not effect significantly.

Therefore the following limits are specified as the geometrical essential variables.

(a) Ratio of branch to pipe thickness

$$0.35 \leq T_2/T_1 \leq 1.5 \qquad (4)$$

(b) Length of reinforcement ; H

$$H \geq 0.75\sqrt{R_2T_2} \quad \text{for set-in type} \qquad (5)$$

$$H \geq 1.0\sqrt{R_2T_2} \quad \text{for set-on type} \qquad (6)$$

where T_2 : Thickness of branch

T_1 : Thickness of pipe

R_2 : Mean radius of branch

6. Mock-up test results

The proof test of IHSI for a weld pipe branch was performed [3]. A mock-up model was

made for the header to riser connection of primary loop in BWR. The heating factors obtained by the analysis were used. Temperature distribution around the branch corner was measured by thermocouples.

From the measurement, it is concluded that the expected thermal gradient can be produced by induction heating with the parameters specified by the analysis.

7. Conclusions

The essential variables for effective IHSI treatment for a weld pipe branch were examined by elastic-plastic finite element method.

The main results of the analysis are as follows.

(1) The limit of the ratio of pipe to branch thikness is specified. The range covers the general cases of BWR weld pipe branches.

(2) Both weld geometries of a set-in type (junction in the pipe side) and a set-on type (junction in the branch side) can be treated by IHSI.

(3) When there is reinforcement in the branch, a certain length of the reinforcement is required for successful IHSI. The length is a variable of the branch thickness and diameter.

(4) The results obtained were confirmed by a mock-up test. Good agreement was found between the analysis and the experiment.

References

[1] "MARC General Purpose Finite Element Program", MARC Analysis Research Corporation

[2] TANAKA, S. and UMEMOTO, T. "Residual Stress Improvement by Means of Induction Heating" Proceedings of Seminar on Countermeasures for BWR Pipe Cracking, EPRI, January, 1980.

[3] UMEMOTO, T., TANAKA, A., "Application of Induction Heating Stress Improvement to Pipe Branches", 6th Intl. Conf. on Structural Mechanics in Reactor Technology, Paris, France, 1981. paper L530/

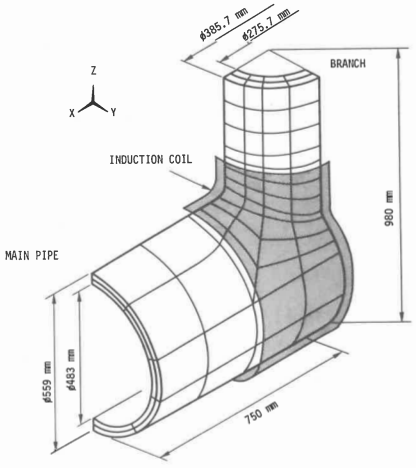

Fig. 1 Finite element idealization of a typical pipe weld branch

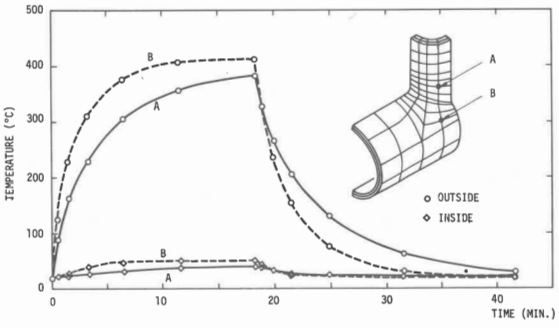

Fig. 2 Temperature transition curve

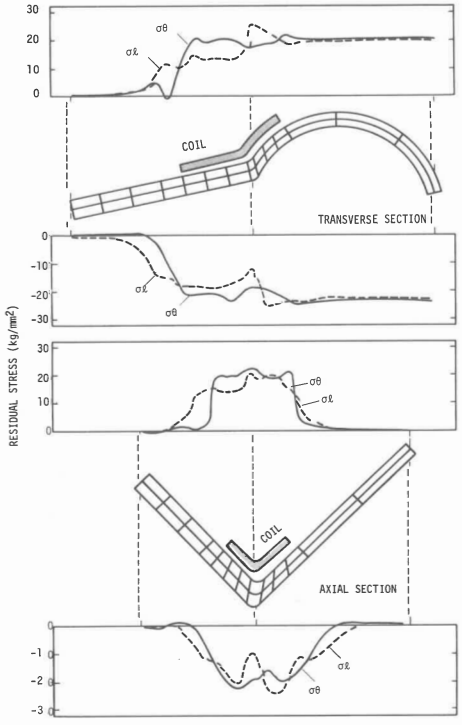

Fig. 3 Residual stress distribution

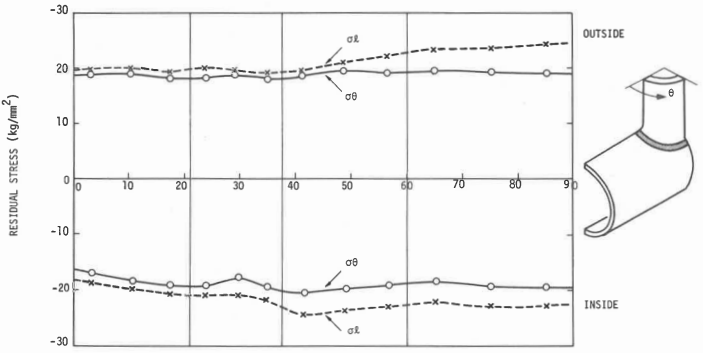

Fig. 4 Residual stresses along set-in welding

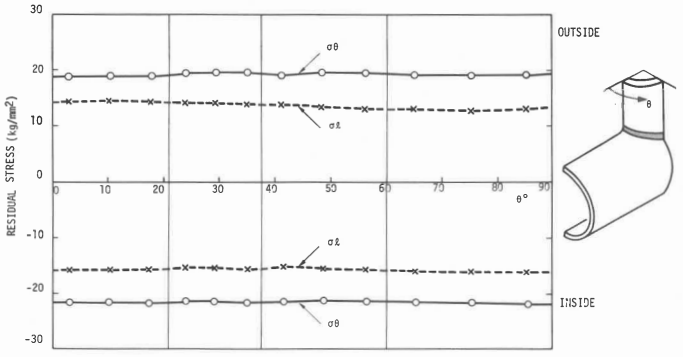

Fig. 5 Residual Stresses along set-on welding

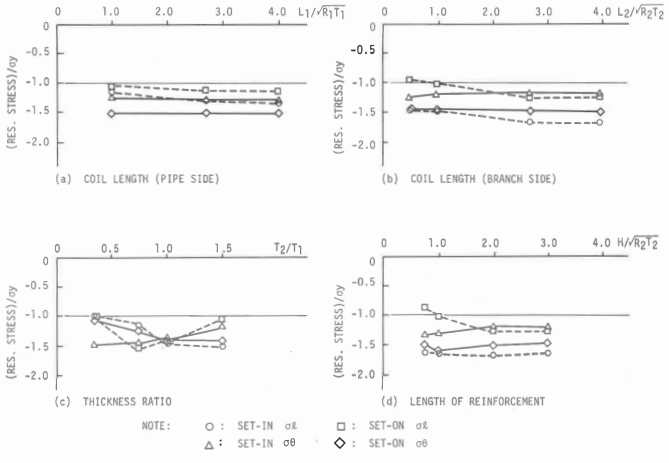

Fig. 6 Results of parameter survey