A STUDY ON RESIDUAL STRESS IMPROVEMENT BY WATER JET PEENING

Masahito MOCHIZUKI, Kunio ENOMOTO and Shinji SAKATA
Mechanical Engineering Research Laboratory, Hitachi, Ltd., Japan

Koichi KUROSAWA, Hideyo SAITO and Hiroshi TSUJIMURA
Hitachi Works, Hitachi, Ltd., Japan

Kozo ICHIE
Uozu Factory, Sugino Machine, Ltd., Japan

ABSTRACT

This paper describes the effects of residual stress improvement by Water Jet Peening, which is expected to improve the residual stress on various component surfaces in nuclear power plants as a preventive maintenance technique for preventing stress corrosion cracking and fatigue fracturing. Numerical analysis is performed to clarify the fundamental mechanism of residual stress improvement, and various tests are done to determine the fundamental characteristics of and suitable conditions for the residual stress improvement. Fundamental tests confirm the applicability of the Water Jet Peening technique for nuclear power plants that can improve residual stress.

KEYWORDS

Water Jet Peening, Residual stress improvement, preventive maintenance technique, nuclear power plant, stress corrosion cracking, fatigue fracturing

1. Introduction

Water Jet Abrasion has recently become widely used for medical, public, and mechanical engineering applications because it does not generate a heat-affected zone, it cleans material surfaces, and it has various other merits. This technology has also been used to cut hard materials, such as pre-stressed concrete and thick metal plates.

Water Jet Peening, one expected application for Water Jet Abrasion, is used to improve residual stress on the surface of various components from tensile stress to compressive stress in nuclear power plants, and to act as a preventive maintenance technique for operating nuclear power plants. These components develop compressive residual stresses on the surface as shown in Fig. 1, and prevent stress corrosion cracking and fatigue fracturing under irradiation using the Water Jet Peening technique.

This paper describes a numerical analysis to clarify the fundamental mechanism of residual stress improvement, and it describes fundamental Water

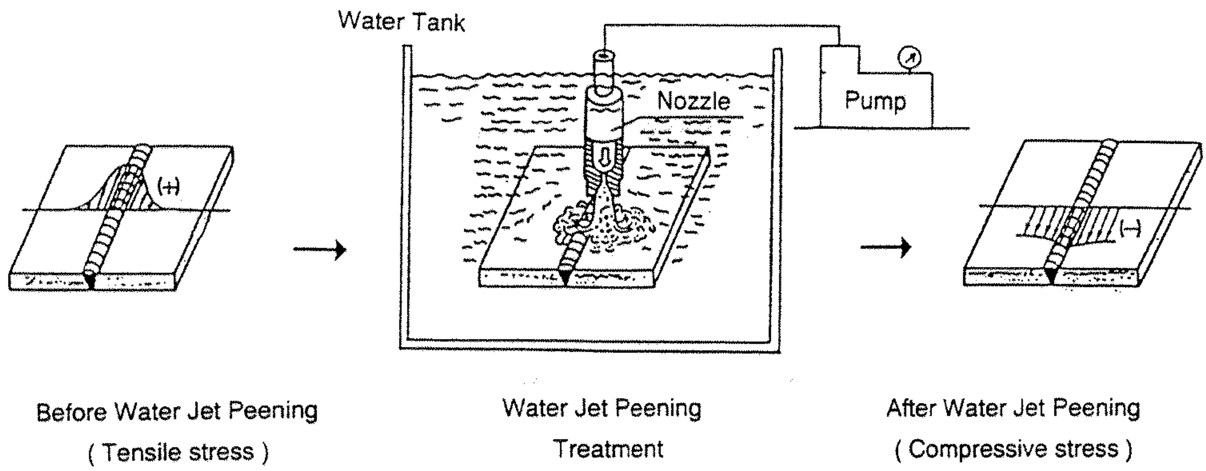


Fig. 1 Water Jet Peening technique

Jet Peening experiments for type 304 stainless steel. Experiments include the effects of residual stress improvement on the heat-affected zones of weldments, the influences of the peening conditions on residual stress, secular change characteristics of residual stress, and the tolerance of stress corrosion cracking.

2. Principle Verification Using Numerical Analysis

It is important in the practical use of Water Jet Peening to understand the fundamental production mechanism of residual stress. However, it is difficult to obtain the residual stress production mechanism directly from the experimental results because this water jet phenomena has a very fast speed and is at too high a pressure to measure.

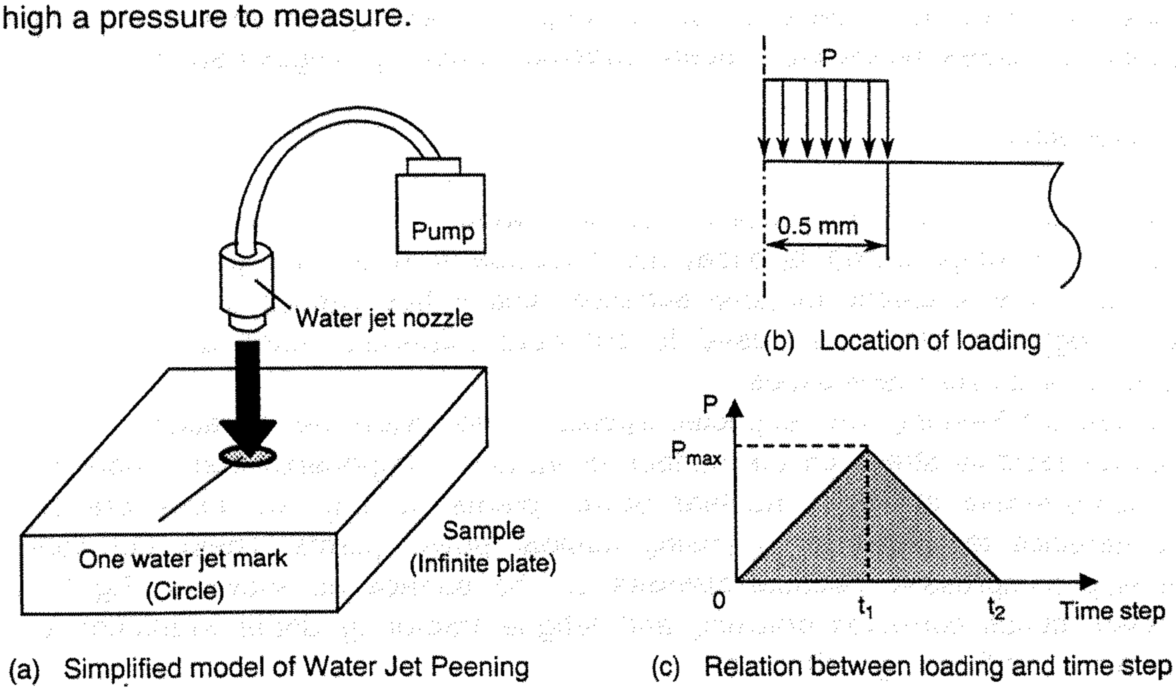


Fig. 2 Water jet model for Numerical analysis

Numerical analysis using the finite element method is performed to clarify the fundamental mechanism of residual stress improvement by the Water Jet Peening treatment. It is assumed that stress improvement is induced by the plastic deformation on the component surfaces due to the high pressure of the water jet.

The model for the numerical analysis is a thick plate, and Water Jet Peening is performed at the center of the plate as shown in Fig. 2 (a). The analysis uses axi-symmetrical static elasto-plastic finite element models. An infinite plate is modeled by tying the edge of the disk, and the resulting mesh consists of 2992 elements and 3105 nodes. Each element is a four-node axi-symmetrical iso-parametric element.

Material properties of the sample are elasto-plastic with von Mises yield function and a kinematic hardening rule. Material properties of the type 304 stainless steel sample are shown in Table 1.

Table 1 Material properties and analytical conditions of sample plate

Material	Type 304 stainless steel
Yield function	Elasto-plastic with von Mises
Young's modulus (MPa)	199000
Poisson's ratio	0.30
Yield stresses (MPa)	280
Coefficient of strain hardening (MPa)	18000
Hardening rule	Kinematic

The water jet pressure is assumed to be loaded on the center of the model as shown in Fig. 2 (b). The water jet is distributed at a 0.5mm radius, because each water jet bubble on the component surfaces before explosion was observed to be a sphere which has about a 1mm diameter. The sample is loaded from 0 to P, and unloaded from P to 0 as shown in Fig. 2 (c). The value of P is experimentally unknown. Therefore, residual stresses are computed at both P=2000 (MPa) and P=5000 (MPa). Program MARC-K4 was used for the stress analysis.

The residual stress distributions on the surface of the sample at P=2000 (MPa) are shown in Fig. 3. Both circumferential and radial stress remained as compressive residual stress on the water jet mark. There are tensile circumferential residual stresses near the border line of the water jet mark. The residual stresses along the direction of thickness at P=2000 (MPa) are shown in Fig. 4. Peak compressive stresses are distributed at about 0.2mm from the surface. Compressive stresses are also distributed on the surface.

Fig. 5 shows the residual stress distributions on the surface of the sample, and Fig. 8 shows along the direction of thickness at P=5000 (MPa). Both distributions have the same tendency as that of P=2000 (MPa). There are higher compressive residual stresses at P=5000 (MPa) than at P=2000 (MPa).

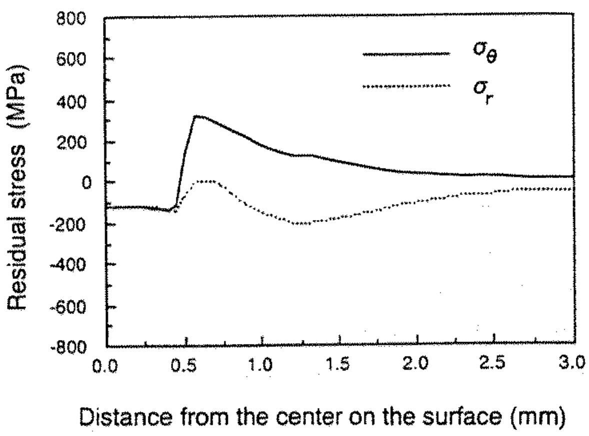


Fig. 3 Residual stress distribution on the surface of the sample at loading P=2000 (MPa)

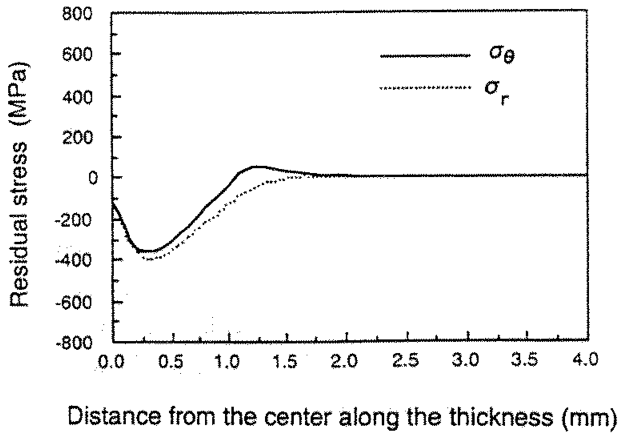


Fig. 4 Residual stress distribution along the direction of the thickness of the sample at loading P=2000 (MPa)

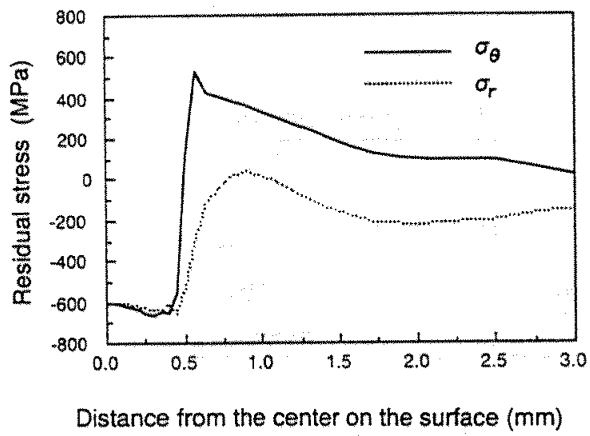


Fig. 5 Residual stress distribution on the surface of the sample at loading P=5000 (MPa)

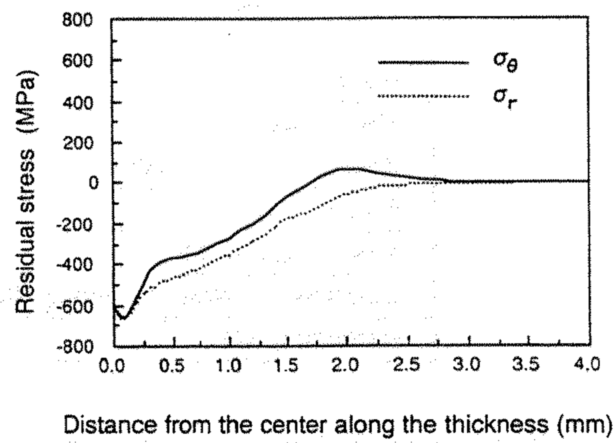


Fig. 6 Residual stress distribution along the direction of the thickness of the sample at loading P=5000 (MPa)

These values of P are much larger than the yield stresses of the type 304 stainless steel σ_y=280 (MPa). Residual stresses after Water Jet Peening are considered to be improved to compressive stresses by high water jet pressure, which induces the plastic deformation of the sample surface.

3. Residual Stress Improvement Experiment

The samples used were type 304 stainless steel plates, 100mm long, 150mm wide, and 9mm thick. Water Jet Peening was performed on each sample in the water as shown in Fig. 1. The sample surface was exposed to the high-pressure water jet in the water tank. The samples before Water Jet Peening were done so that tensile residual stresses were already distributed on their surface through mechanical grinding.

The type 304 stainless steel plate after Water Jet Peening treatments under various jet conditions are shown in Fig. 7. Both the distance between the plate and the nozzle, and the peening velocity of the traveling nozzle on the plate were varied. The peening width became larger in proportion to the distance from the surface, but the difference in peening velocity had no influence on the peening width.

The residual stress difference before and after Water Jet Peening was measured on the surface of the sample plate by X-ray diffraction method. Electro-chemical polishing on the surface was not treated before X-ray measurement. The exposed X-ray area was usually 12.5mm long and 1mm wide, and the residual stress was measured on the same direction of Water Jet Peening treatment.

Angle of the nozzle : Perpendicular	
Hydraulic pump pressure : 69 MPa	
Water depth : 300 mm	
Repetition of numbers : 1 time	
X-ray exposed area : (1× 12.5) mm^2	
Jet distance	Nozzle traveling speed
60 mm	0.4 m / min
50 mm	0.4 m / min
40 mm	2.0 m / min
	1.2 m / min
	0.8 m / min

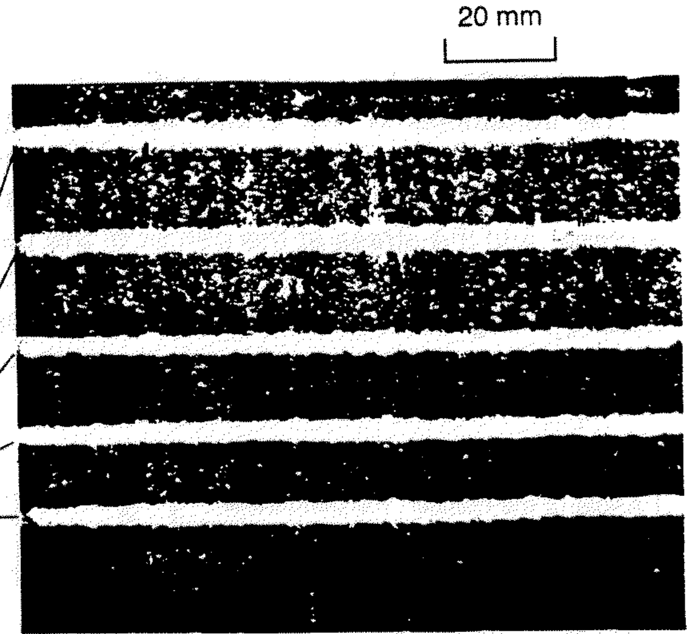


Fig. 7 Type 304 stainless steel plate after Water Jet Peening treatment

4. Results and Discussions

4.1 Efficiency at heat-affected zone

It is necessary for the welding structures to confirm the application of Water Jet Peening on the heat-affected zones of the weldments. The sample with the heat-affected zone of the weldment was performed by Water Jet Peening. The Water Jet Peening was completely done on the heat-affected zones of the sample by traveling the water jet nozzle. The residual stress was measured at 2.5mm and 25mm from the fusion line of the weldment.

The residual stress differences before and after the Water Jet Peening procedure are shown in Fig. 8. The residual stress improvement was about 200MPa on both lines when the distance between the plate and the nozzle was less than 40mm. Therefore, Water Jet Peening has the ability to improve the residual stresses on the heat-affected zones.

Angle of the nozzle : Perpendicular
Hydraulic pump pressure : 69 MPa
Water depth : 300 mm
Repetition of numbers : 1 time
Nozzle traveling speed : 0.4 m / min
X-ray exposed area : (5 × 2.5) mm^2
Measuring point ○ : 2.5 mm HAZ
Measuring point ◇ : 25 mm HAZ

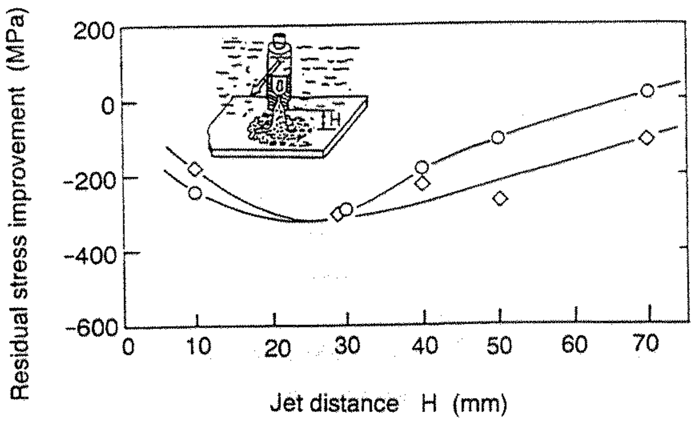


Fig. 8 Influence of Water Jet Peening on residual stress improvement on the heat-affected zone

4.2 Influences of the peening conditions

The influences of the Water Jet Peening conditions on the effect of residual stress improvement are considered in this section. The Water Jet Peening treatment was performed on type 304 stainless steel plates with a planed surface, and the stress at the center of the peening line was measured.

The relation between the jet distance from the surface of the sample to the nozzle's edge and the residual stress improvement are shown in Fig. 9. The residual stresses are reduced more than 200MPa when the jet distance is changed about from 10mm to 40mm.

Angle of the nozzle : Perpendicular
Hydraulic pump pressure : 69 MPa
Water depth : 300 mm
Repetition of numbers : 1 time
X-ray exposed area : (1× 12.5) mm^2
Nozzle traveling speed V
○ : 0.4 m / min
● : 0.8 m / min
△ : 1.2 m / min
▲ : 2.0 m / min

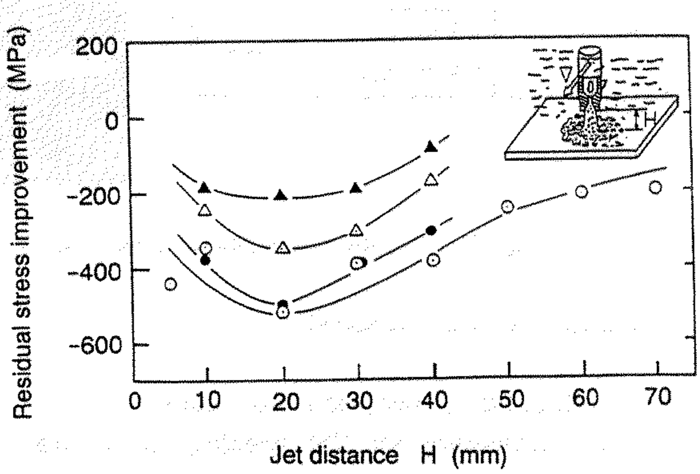


Fig. 9 Influence of jet distance on residual stress improvement

The influence of the hydraulic pressure of the water jet pump is shown in Fig. 10. This test was performed with a hydraulic pressure of 30MPa to 90MPa. In this range, the efficiency of the residual stress improvement increases with the pressure. Residual stress improvement is very effective above 70MPa.

The relation between peening time and the residual stress is shown in Fig. 11. Peening time is determined by the traveling speed of the nozzle and the repetition of peening applications. A peening time of greater than four minutes / meter is necessary to improve residual stress more than 300MPa.

Jet distance : 30 mm
Angle of the nozzle : Perpendicular
Water depth : 300 mm
Repetition of numbers : 1 time
X-ray exposed area : (1× 12.5) mm^2
Nozzle traveling speed V
○ : 0.4 m / min
● : 0.8 m / min
□ : 1.2 m / min
■ : 2.0 m / min

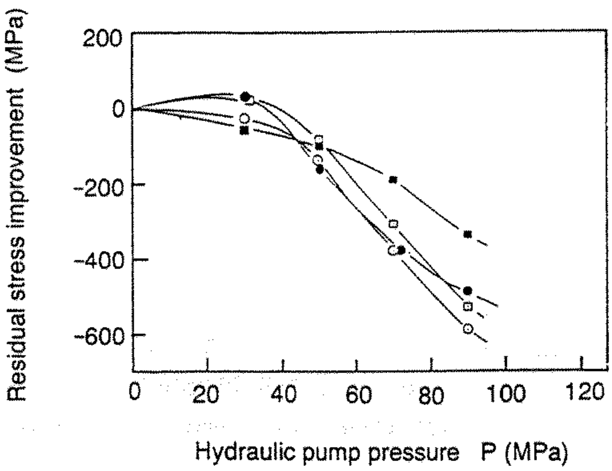


Fig. 10 Influence of hydraulic pressure of water jet pump on residual stress improvement

Jet distance : 30 mm
Angle of the nozzle : Perpendicular
Hydraulic pump pressure : 69 MPa
Water depth : 300 mm
X-ray exposed area : (1× 12.5) mm^2
Nozzle traveling speed V
○ : 0.4 m / min
● : 0.8 m / min
□ : 1.2 m / min
■ : 2.0 m / min

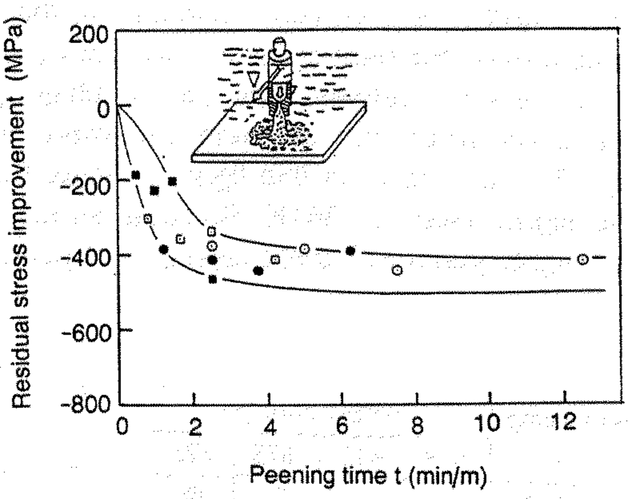


Fig. 11 Influence of peening time on residual stress improvement

Jet distance : 30 mm
Hydraulic pump pressure : 69 MPa
Water depth : 300 mm
Repetition of numbers : 1 time
X-ray exposed area : (1× 12.5) mm^2
Nozzle traveling speed : 0.4 mm/min

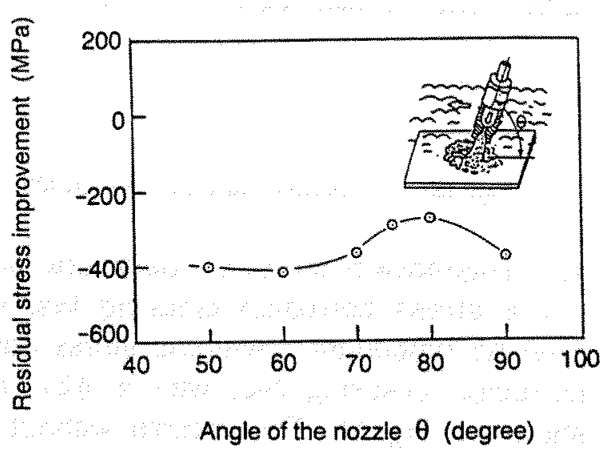


Fig. 12 Influence of nozzle angle on residual stress improvement

The influence of the nozzle angle is shown in Fig. 12. The perpendicular line of the plate and the center line of the water jet nozzle, which is inclined backwards, define this angle. The angle of the nozzle has no influence on the residual stress improvement.

There are a lot of narrow corners and edges in nuclear power plants, so it is effective for practical use that nozzle angle can be changed with no loss of efficiency in nuclear power plants.

4.3 Secular change characteristics of residual stresses

A thermal aging test was performed to evaluate the residual stress relaxation and secular change characteristics. The residual stress relaxation was evaluated using the Larson-Miller parameter. The Larson-Miller P is shown in this equation,

$$P = T\,(D + \log t) \qquad (1)$$

where T is the temperature of thermal aging (K), t is the time of thermal aging (hour), and D is a constant number. In this case, D = 8. The residual stress was measured on the heat-affected zones of weldment.

The relation between the Larson-Miller parameter P and the residual stress relaxation when the peening treatment is repeated three times is shown in Fig. 13. The arrows in this figure indicate the Larson-Miller parameter P after forty and eighty years at 561K. Residual stress will hold, at most, -200MPa after forty and eighty years with three repetition of peening treatments.

Measuring point	Temperature (K)			
	573	623	673	723
6mmHAZ	○	○	○	●
12mmHAZ	□	□	□	■
Repetition of numbers : 3 time				

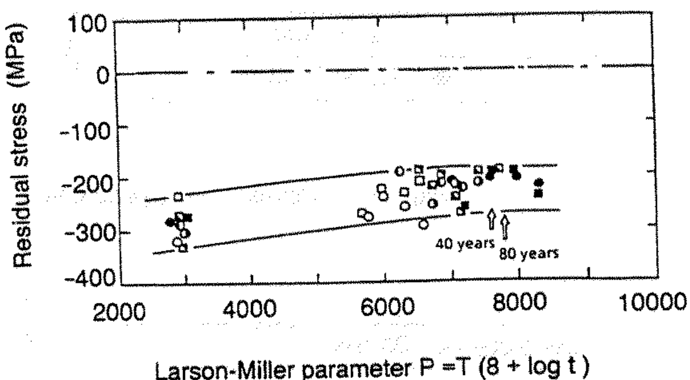
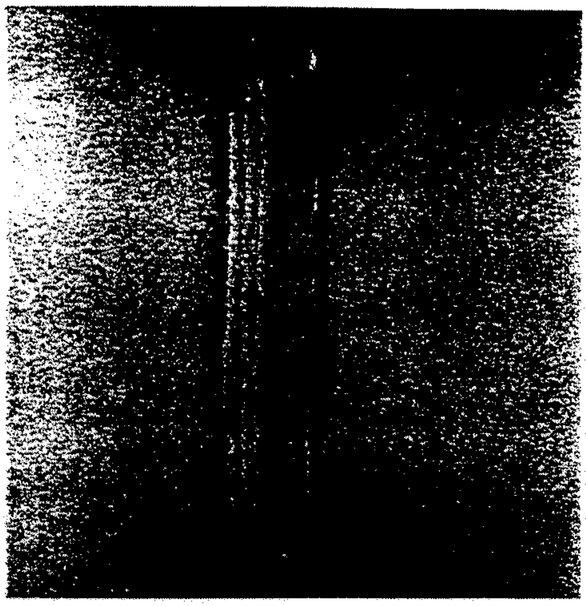
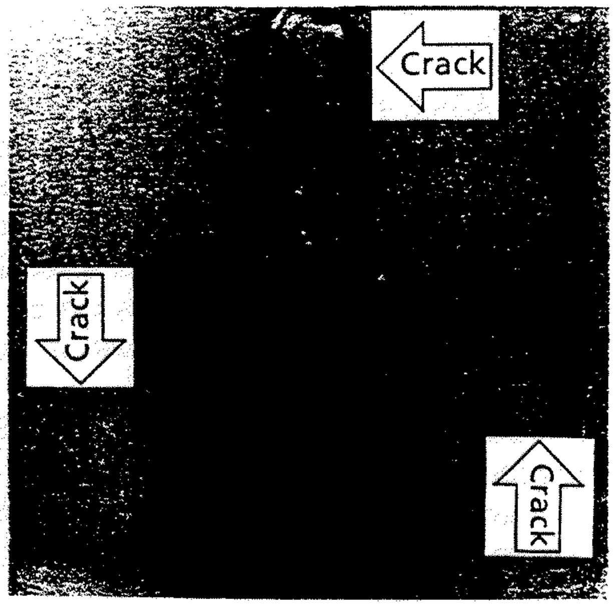


Fig. 13 Relation between Larson-Miller parameter P and residual stress relaxation

4.4 Tolerance of stress corrosion cracking

The stress corrosion cracking test was used to confirm that the Water Jet Peening procedure prevented stress corrosion cracking. The results of the stress corrosion cracking test with a 42% magnesium chloride boiled solution are shown in Fig. 14. The sample without Water Jet Peening incurred cracks, but another sample with Water Jet Peening had no cracks. This test proved that Water Jet Peening prevented stress corrosion cracking in the components of nuclear power plants.





(a) Specimen M1 (with Water Jet Peening) (b) Specimen M2 (without Water Jet Peening)

Fig. 14 Results of stress corrosion cracking test

5. Conclusions

Water Jet Peening has been developed as a preventive maintenance technique for nuclear power plants particularly to prevent stress corrosion cracking and fatigue fracturing. Numerical analysis was performed to clarify the fundamental mechanism of stress improvement, and various tests were performed to apply this technique to the components of nuclear power plants.

(1) Numerical analysis shows that high water jet pressure influences the compressive residual stress due to the plastic deformation of the surface.

(2) Water Jet Peening effectively improves the residual stress on the heat-affected zones of the weldments.

(3) Jet distance, hydraulic pressure of the water jet pump, peening time, and nozzle angle were studied to effectively improve residual stress with this method.

(4) A thermal aging test with the Larson-Miller parameter P shows that Water Jet Peening repeated three times will maintain about -200MPa of compressive residual stress for 40 and 80 years.

(5) Water Jet Peening treatments prevent stress corrosion cracking in the components of nuclear power plants.

REFERENCES

1. Al-Obaid Y F : *A Rudimentary Analysis of Improving Fatigue Life of Metals by Shot-Peening*, Trans ASME J Appl Mech, 57, 6, 307-312, 1989

2. Enomoto K, et al : *Water Jet Peening for Residual Stress Improvement* (in Japanese), Proc Atomic Energy Society Japan, 1991

3. Hashish M : *Characteristics of Surfaces Machined with Abrasive-Waterjets*, Trans ASME J Eng Mat Tech, 113, 354-359, 1991

4. Iino N, et al. : *Fatigue Strength Improvement of Weldments* (in Japanese), Proc Japan Welding Society, 43, 368-369, 1991

5. Kobayashi R, et al. : *Local Structure of a Water Jet and Related Damage Mechanism of a Metallic Material*, Proc 9th Intern Sym Jet Cutting, 155-160, 1989

6. Takahashi N, et al. : *Application of Ultrasonic Cavitation to Metal Working and Surface Treatment of Mind Steel* (in Japanese), Trans Japan Society Mechanical Engineering, A, 53, 46-53, 1987

7. Tonshoff H K, et al. : *Influence of Grinding and Cavitation on Surface Integrity of Stainless Steel*, ASME Proc Eng Div, 22, 143-150, 1986

8. Yanaida K, et al. : *Wall Effect on a Submerged Jet Cavitation*, 3rd United States Water Jet Conference, 1985