Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

D02/4

Improvement of residual stress on material surface by water jet peening

Hirano K.(1), Enomoto K.(1), Mochizuki M.(1), Hayashi M.(2), Hayashi E.(2), Shimizu S.(2)
(1) Hitachi Ltd, Japan
(2) Hitachi Works, Hitachi Ltd., Japan

ABSTRACT: Water jet peening (WJP) is expected to become an effective maintenance technique in order to prevent stress corrosion cracking (SCC) and fatigue failure caused by the residual tensile stress in various components. The validity of WJP can be determined by producing compressive residual stress on the peened surface of a component. The effect of WJP toward improving SCC and fatigue resistance was examined by various experimental tests. The WJP can produce high resistance against SCC and fatigue. These results indicated that WJP is a useful technique for preventing SCC and fatigue in structural components.

1. INTRODUCTION

Water jets have been used in various fields such as construction, civil engineering, and machine production for cleaning, cutting, processing, or grinding. Water jets into still water have recently received a lot of attention because of their usefulness [1][2]. The conventional water jet technique has been used for cutting and polishing by mixing abrasive materials into the water. The main roles for the water jets were to transport the abrasive materials and to attack their targets.

On the other hand, the water jet can make highly-pressure so that it can be forced onto the surface of materials to produce a compressive residual stress due to the peening effect caused by cavitation collapse without abrasive materials. Water jet treatment turns the tensile residual stress into compressive stress by using highly-pressurized water into still water. We have developed this technique, and we call it the water jet peening (WJP) [3].

Stress corrosion cracking (SCC) is one type of accumulative damage in power-generating and chemical plants. It is caused by the combination of three factors, material sensitization, corrosive environment, and tensile stress. It is well known that changing the residual stress from tensile to compressive is one of the most effective countermeasures against SCC [4]. Furthermore, tensile residual stress often occurs fatigue failure or fatigue crack propagation in structural components with cyclic loads.

An objective of our study is to determine the validity and demonstrate the effectiveness of WJP at preventing SCC and fatigue. The effect of WJP toward improving SCC and fatigue resistance was examined by various experimental tests. We indicate that WJP is a useful technique for preventing SCC and fatigue in structural components.

2. EXPERIMENTAL METHOD

2.1 WJP Procedure

An outline and a photograph of the experimental apparatus for the WJP are shown in Fig. 1. Abrasive-free water was highly-pressurized by a plunger pump and jetted onto the specimen surface through a small nozzle. The material used in the experiment was type 304 stainless steel. The characteristics of WJP were examined using 100-mm × 100 (or 150) mm rectangular plate specimen, as shown in Fig. 2. The nozzle was placed in the test tank at a depth of either 0.3 or 1.5 m in water and scanned over the specimen surface. The WJP conditions were studied on total peening time, stand-off distance, and injection pressure, in order to find the optimum procedure condition.

2.2 Modified CBB Test Procedure

The configuration of the modified creviced bent beam (CBB) test specimen of type 304 stainless steel for proving the soundness of WJP against SCC was shown in Fig. 3. The modified CBB test was performed in hot water using smoothed and pre-cracked specimens, which were sensitized by a two-step heat treatment for 24 hours at 773 K followed by 2 hours at 923 K.

The conventional tests were usually used a 1-mm-thick specimen, but we performed this test using a 3-mm-thick specimen. We considered that it is necessary for more than 1-mm-thick to generate the residual stress before the modified CBB test. The surface of the specimen was strongly ground to produce high tensile residual stress before the test. The specimen was exposed to boiled 42% $MgCl_2$ solution for either 8 or 24 hours to introduce different pre-crack sizes with depths ranging from 100 to 400 μ m.

The pre-cracked and as-ground specimens were treated by WJP. The modified CBB test apparatus is shown in Fig. 4. Modified CBB specimens were exposed for two different periods, 500 and 1000 hours, in pure water at 562 K, which contained 8 ppm of dissolved oxygen. The water conductivity ranged from 0.25 to 0.6 μ S/cm, the pH was 6.5, and the water pressure was 8 MPa.

The conventional CBB test specimens are usually strained up to 1% to evaluate their SCC sensitivity. Since the objective of this test was to evaluate residual stress reduction, we thought a 1% strain was too large. Therefore, we used applied strains of 0 %, 0.1 %, 0.15 %, 0.2% and 0.3%. This test differed from conventional typical tests in terms of specimen thickness and applied strain. After the modified CBB test had been conducted, each specimen was cut along the central line to give two widths. The axis of each specimen was divided into 30 sections each 1-mm-wide. Then the maximum crack depth was measured for each of these sections.

2.3 Fatigue Test Procedure

The fatigue test was examined to study the effect of WJP on fatigue strength. The three specimen of type 304 stainless steel are shown in Fig. 5. They are smoothed, circular-notched, and pre-cracked specimen. The specimens are subjected to a cyclic bending load in air at room temperature. The circular-notched specimen has stress concentration factor K_t=2. The pre-cracked specimens are introduced single edge crack 0.2 mm or 1.7 mm in depth.

3. RESULTS AND DISCUSSION

3.1 Residual Stress Improvement by WJP

The distribution of residual stress in the subsurface was measured by gradually removing the surface layer by electrochemical polishing from the surface to a depth of 250 μ m, as shown in Fig. 6. The residual stress was measured by X-ray diffraction, and the initial residual stress was from 60 to 100 MPa. After WJP, the residual stress on the surface became about -500 MPa and it gradually increased with depth. The residual stress was still compressive at a depth of about 250 μ m.

The distribution of residual stress reduction perpendicular to the nozzle scanning direction is shown in Fig. 7, which also shows the degree of residual stress improvement on the specimen surface. The residual stress improvement is defined by subtracting the initial value from that after WJP treatment. The maximum residual stress reduction corresponding to the nozzle center was about -480 MPa. The residual stress reduction increased with distance from the nozzle center. The effective width of WJP was about 6 mm. It is usually thought that the SCC occurs in heat-affected zones by welding. A heat-affected zone, which is usually around 20-mm-wide, could be covered by treating several scans of WJP.

3.2 Influence of WJP Conditions

The influence of various treatment conditions was examined to find the optimum WJP procedure. The effect of total peening time on residual stress reduction is shown in Fig. 8. The total peening time is defined as the number of repetitions multiplied by the peening time per unit of traveling distance. The residual stress improvement increased with peening time, and it became almost constant when the peening time exceeded 2.5 min/m.

The effect of stand-off distance on the residual stress improvement is shown in Fig. 9. The maximum residual stress improvement was obtained when the stand-off distance L was 30 mm. The nozzle diameter D was 1 mm in our experiment. The pressure distribution of water jet had two peaks at L/D = 30 and 80, where L/D is the stand-off distance L normalized by the nozzle diameter D [5]. If the pressure of the cavitation bubble collapse corresponds to the pressure of the water jet, two peaks are expected in the residual stress improvement near L= 30 and 80 mm. The first peak was observed at L = 30 mm corresponding to L/D = 30. Although the second peak at L = 80 mm was not observed, the residual stress reduction was found to be -200 MPa. It is considered that the generating mechanism is different between water jet pressure in liquid and residual stress improvement by cavitation collapse in solid.

The effect of the injection pressure of the water jet on residual stress improvement is shown in Fig. 10. The width of residual stress improvement became larger with increasing pressure. This result suggests that the high-speed turbulent flow by the higher injection produced the collapse pressure of the cavitation bubbles.

3.3 Results of Modified CBB Test

Residual stresses on the surfaces of the modified CBB specimens were measured by X-ray diffraction. The residual stress on the specimen surface before WJP were measured 200 MPa and 70 MPa, and the residual stress after WJP were about -300 MPa, respectively. The results of the 500-hour modified CBB test for smooth and pre-cracked specimens are shown in Figs. 11 and 12. The cracks initiated on the specimen surface are also shown in these figures. A number of cracks was observed for an as-ground non-pre-cracked specimen. The crack in 500 μ m depth was observed even when the applied strain was zero. SCC was not observed on the surface of the smoothed specimens treated by WJP with 10 min/m peening time when the applied strain was less than 0.15%. For the pre-cracked specimen as shown in Fig. 12, the crack depth was almost the same as that for the smoothed specimen without WJP. SCC was not observed on the surface of the pre-cracked specimens treated by WJP when the applied strain was less than 0.1%.

The results of extreme value statistics are shown in Fig. 13. The extreme value statistics were determined from the maximum crack depth for each of the sections. The horizontal axis shows the maximum crack depth *di* at each section, arranged in order of increasing length, and the vertical axis shows the reduced variate, $Yi=-\ln(-\ln(i/(n+1)))$. The crack depth of the specimen with WJP was much smaller than that without WJP, and WJP kept the resistance against the crack propagation until the cracks developed.

Photographs of the penetration-tested specimens after the 1000-hour modified CBB test are shown in Figs. 14 and 15. These figures show that the crack depth of specimens with WJP were smaller than those without WJP when all areas are observed. This depends on the applied bending strain. The relationship between the modified CBB exposure time and the critical applied strain is shown in Fig. 16. The critical applied strain after 1000 hours of exposure was identical to that after 500 hours. This result suggests that the critical applied strain was constant beyond 500 hours.

The cross-sections of specimens after the modified CBB test are shown in Fig. 17. Intergranular cracks were observed initiating both from the surfaces of smoothed specimens and from pre-cracked specimens. The behavior of SCC propagation did not differ or depend on whether the specimen was treated by WJP or not. In the modified CBB test, WJP was found to be useful in preventing SCC initiation.

3.4 Results of Fatigue Test

The results of the fatigue test are shown in Fig. 18. The fatigue strength is found to be slightly increased by WJP for the smooth specimen. The fatigue limits (10^7) of as-ground and water-jet-peened specimens are 280 and 290 MPa, respectively. The fatigue strength is increased by WJP for the circular-notched specimen. The fatigue limits of as-ground and water-jet-peened are 225 and 260 MPa, respectively. The effect of fatigue strength improvement in circular-notched specimen by WJP is larger than that in the smooth specimen. These results have a same tendency as the other test results with surface treatment specimens, such as quench hardening, shot peening, grinding. The fatigue strength seems not to be influenced by WJP processing time.

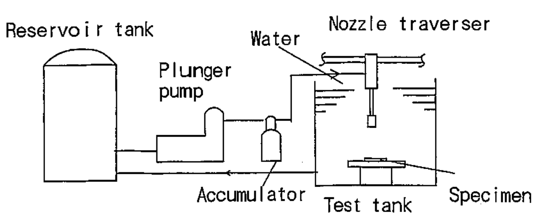
The fatigue strength is remarkably increased by WJP for the pre-cracked specimens. The fatigue limits of as-ground and water-jet-peened are respectively 92 and 166 MPa, when the pre-crack depth is 0.2 mm, or 57 and 137 MPa, when the depth is 1.7 mm. The fatigue limits are increased almost doubled by WJP for pre-cracked specimens. It is considered that the stress intensity factor K of 0.2 mm pre-cracked specimen becomes smaller than that of 1.7 mm pre-cracked, once the collapsed pressure is loaded as a crack opening pressure. The results of pre-cracked fatigue test, the fatigue strength of 1.7 mm pre-cracked specimen is smaller than that of 0.2 mm pre-cracked, are validated this consideration.

4. SUMMARY

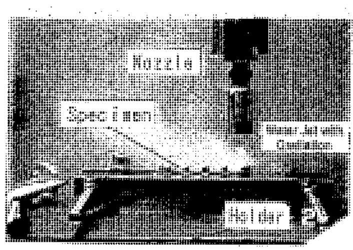
We showed that the water jet peening is an effective maintenance technique in preventing the SCC and fatigue. Residual stress is reduced from tensile to compressive stress by WJP. We clarified the effects of total peening time, stand-off distance, and injection pressure on the residual stress improvement in order to determine the optimum WJP conditions. SCC and fatigue tests were performed using water-jet-peened specimens to examine the efficiency of WJP. We found that WJP is useful in preventing SCC and fatigue.

REFERENCES

1. Matsumoto, K., S. Nakadachi & K. Okumura. 1990. *J. Resource & Materials*, 106: 127-132 (in Japanese).
2. Shimizu, S. 1993. *Trans. JSME*, B59: 2964-2968 (in Japanese).
3. Mochizuki, M., K. Enomoto, S. Sakata, K. Kurosawa, H. Saito, H. Tsujimura & K. Ichie 1993. A study on residual stress improvement by water jet peening. *Proc. Int. Conf. Shot Peening* 5: 295-303. Oxford: United Kingdom.
4. Nuclear Handbook 1983. *Ohm-sha*, 694-695 (in Japanese).
5. Soyama, H., Y. Yamauchi, K. Satou, T.Ikohagi R. Oba & R. Oshima 1993. *Trans. JSME*, B-59: 3714-3719 (in Japanese).



(a) Outline of procedure.



(b) Photo of experiment.

Fig. 1 Experimental procedure using rectangular plate specimen.

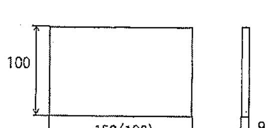


Fig. 2 WJP optimum condition specimen.

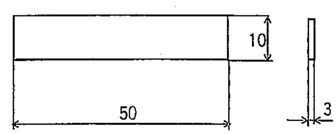


Fig. 3 Modified CBB test specimen.

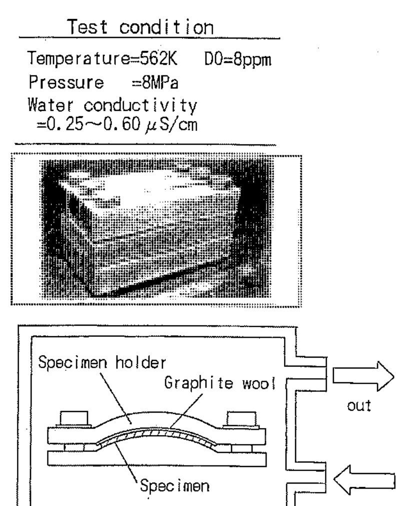
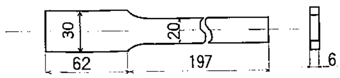
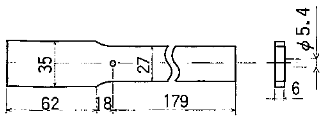


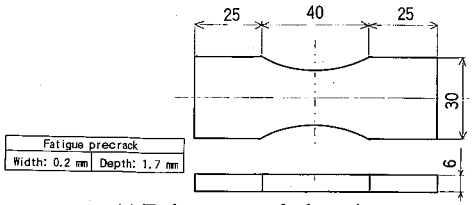
Fig. 4 Modified CBB test apparatus.



(a) Smooth specimen.



(b) Circular-notched specimen.



(c) Fatigue pre-cracked specimen.

Fig. 5 Fatigue test specimen.

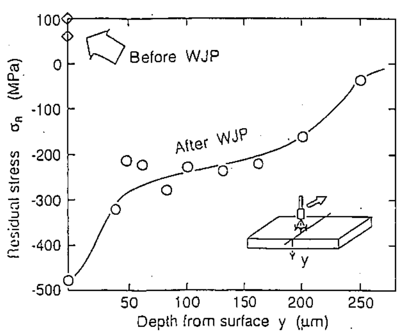


Fig. 6 Residual stress distribution through thickness direction.

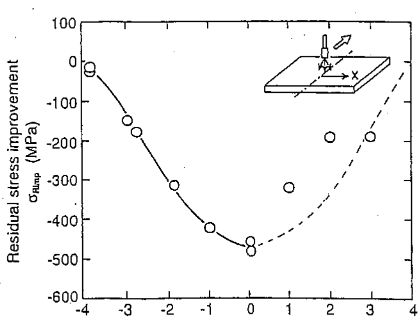


Fig. 7 Residual stress distributions along transverse direction.

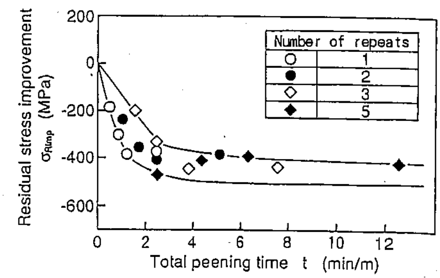


Fig. 8 Influence of peening time on residual stress improvement.

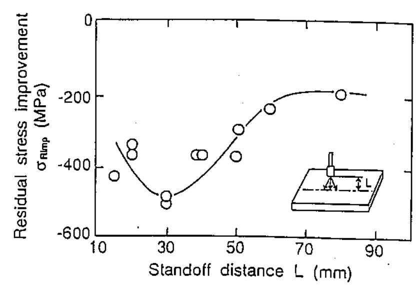


Fig. 9 Influence of stand-off distance on residual stress improvement.

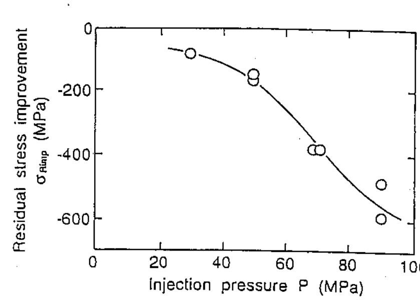
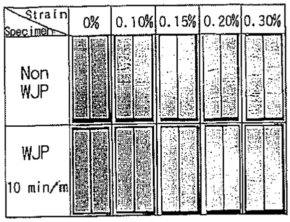
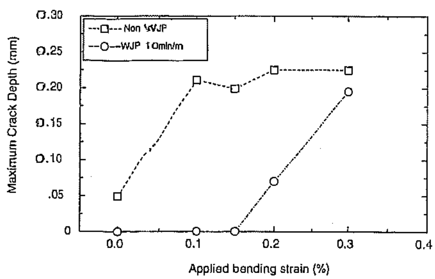


Fig. 10 Influence of injection pressure on residual stress improvement.

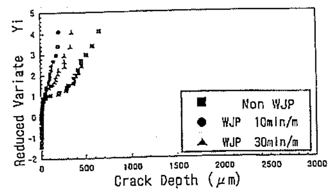


(a) Results of penetration tests.
(after modified CBB test)

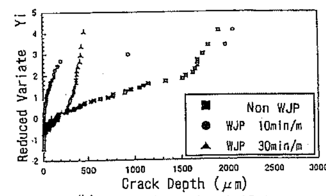


(b) Applied strain vs. maximum crack depth

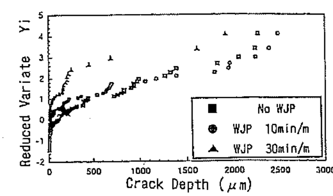
Fig. 11 Modified CBB test results for non-precracked specimens.
(exposure time=500 hr)



(a) Applied Strain=0 %

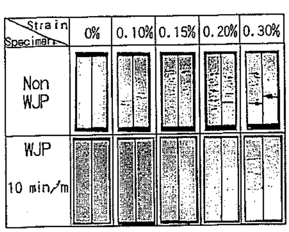


(b) Applied Strain=0.15%

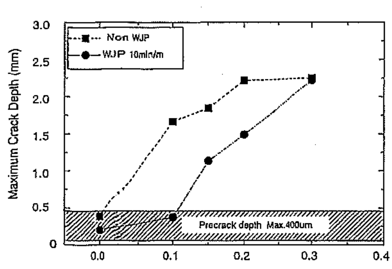


(c) Applied Strain=0.30%

Fig. 13 Extreme value statistics of modified CBB test results.

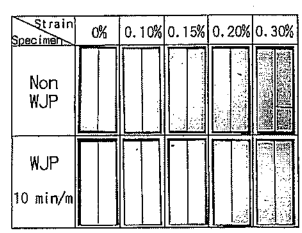


(a) Results of penetration tests.
(after modified CBB test)

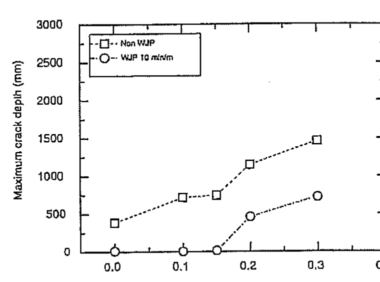


(b) Applied strain vs. maximum crack depth

Fig. 12 Modified CBB test results for precracked specimens.
(exposure time=500 hr).

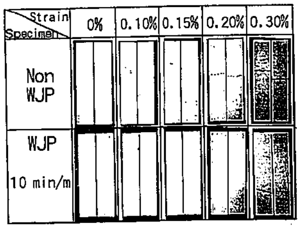


(a) Results of penetration tests.
(after modified CBB test)

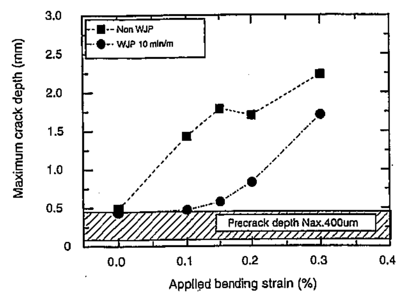


(b) Applied strain vs. maximum crack depth

Fig. 14 Modified CBB test results of non-precracked specimens.
(exposure time=1000 hr).



(a) Results of penetration tests.
(after CBB test)



(b) Applied strain vs. maximum crack depth

Fig. 14 Modified CBB test results of precracked specimens (exposure time=1000 hr).

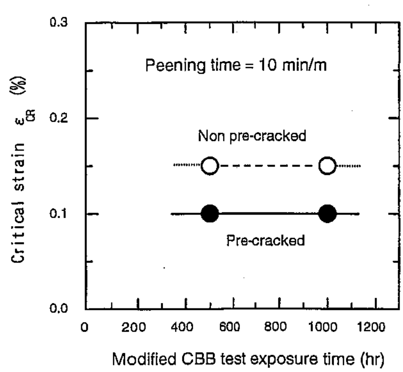
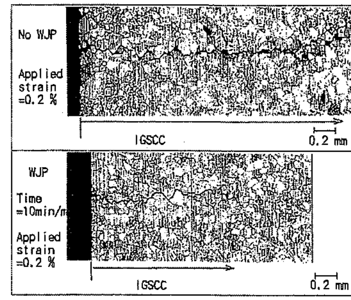
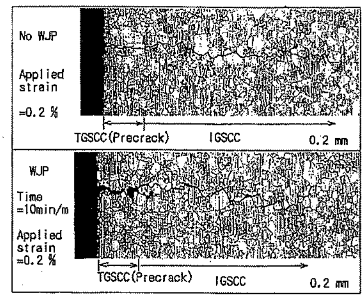


Fig. 15 Effects of modified CBB test exposure time on critical strain.



(a) Non-pre-cracked specimen

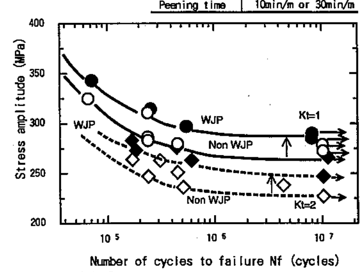


(b) Pre-cracked specimen

Fig. 16 Photograph of SCC cracks.

Conditions of WJP

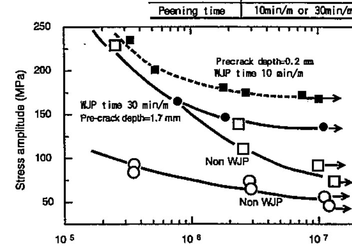
Pump pressure	60 MPa
Jet angle	90°
Stand-off distance	160 mm
Peening time	10min/m or 30min/m



(a) Smooth and notched specimens

Conditions of WJP

Pump pressure	60 MPa
Jet angle	90°
Stand-off distance	160 mm
Peening time	10min/m or 30min/m



(b) Pre-cracked specimen

Fig. 17 Fatigue strength test results.