RESIDUAL STRESS IMPROVED BY WATER JET PEENING USING CAVITATION FOR SMALL-DIAMETER PIPE INNER SURFACES

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As one of degradation conditions on components used in water, the overlapping effect of environment, material and stress might cause stress corrosion cracking (SCC). Especially, for the tensile residual stress produced by welding, it is particularly effective to reduce the tensile residual stress on the material surface to prevent SCC. In this paper, the residual stress improvement method using cavitation impact generated by a water jet, called Water Jet Peening (WJP), has been developed as the maintenance technology for the inner surfaces of small-diameter Ni-Cr-Fe alloy (Alloy 600) pipes. As the results, by WJP for the inner surface of Alloy 600 pipe (inner diameter; approximately 10-15mm), we confirmed that the compressive stress generated within the range from the surface to the inner part about 0.5 mm deep and took a maximum value about -350MPa on the surface.

Introduction

One of the degradation conditions of structures used in high-temperature water is stress corrosion cracking (SCC). The cause lies in the tensile residual stress produced by welding, it is effective to reduce the residual stress in order to prevent SCC. There are several ways to reduce (improve) the residual stress on the surface attributed to SCC by contacting reactor coolant, such as shot peening, etc., carried out in air. However, it will be difficult to carry out shot peening in air depending on circumstances, so that the technology for peening in water becomes necessary. As a method of residual stress improvement to be carried out in water, the water jet peening (WJP) technology has come to draw attention in recent years [1]. This technology makes use of the shock pressure generated when the cavitation bubbles disappear. The water jet injection nozzle can be made smaller to match with the application spot, namely the inner surface of small diameter pipe with severe spatial limitation. So we have been studied the WJP technology as one of residual stress improvement methods for the inner surface of small diameter pipe.

Outline of residual stress improvement method using WJP

As shown in Figure 1, when a high-speed water jet is injected out in water through the nozzle, a strong shearing force acts on the boundary of the still water around the nozzle and the high-speed jet because of a strong vortex flow and turbulence. The pressure in this zone drops down to the level of the steam pressure of water at this temperature, causing the water to get locally evaporated to form cavitation bubbles. The cavitation bubbles move as they grow at the downstream of the jet. As the bubbles move toward the downstream, the vortex flow gets diffused, causing the pressure to return to the normal level and the cavitation bubbles to get rapidly shrunk. This phenomenon is called the "collapse of cavitation bubbles." The collapse generates an extremely large shock pressure (of several hundred MPa) [2]. The generation of an extremely large shock pressure causing reduction of residual stress on the metal has long been a known fact [3][4]. It is possible to make use of this huge shock pressure in reducing the residual stress in and around the metal surface by creating plastic deformation on the metal surface.

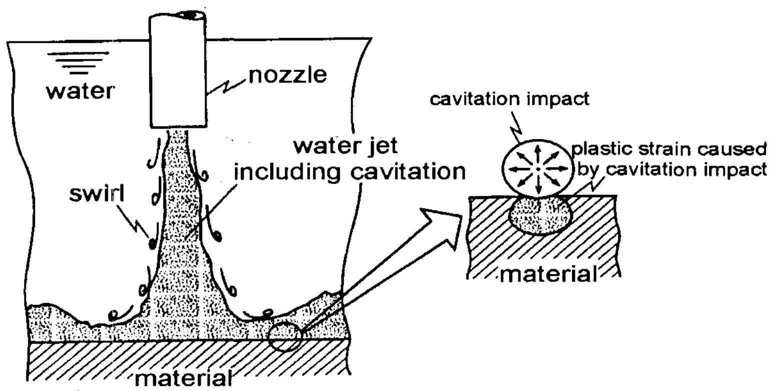
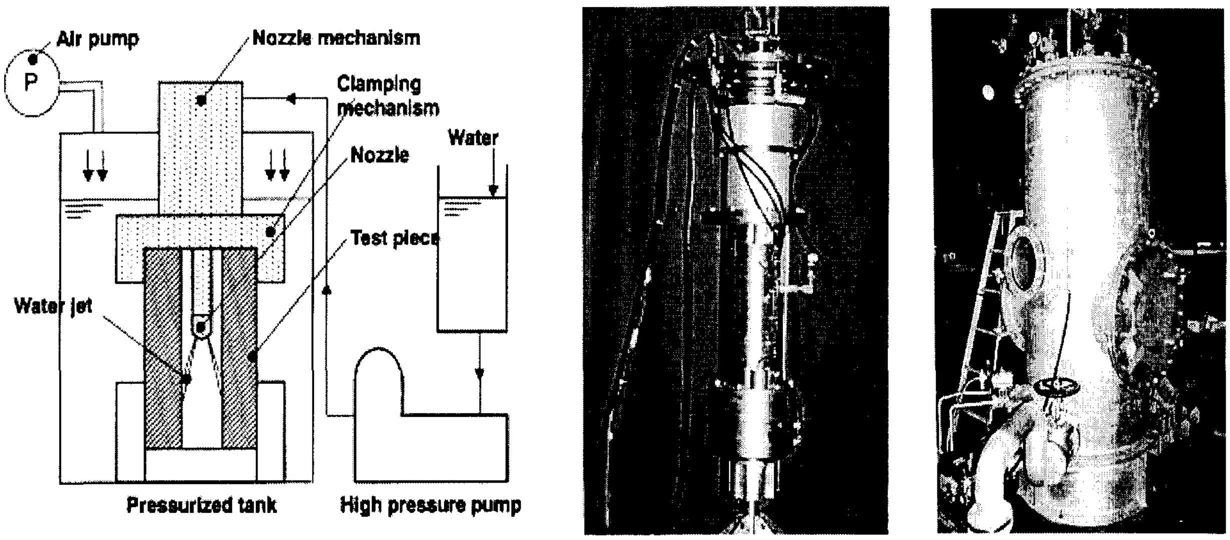


Figure 1. Model diagram of WJP Using Cavitation

TEST APPARATUS

Figure 2 shows the outline of the test apparatus. The water jet is injected to the concerned inner surface of the pipe from the high-pressure water pump using injection nozzle. The injection nozzle rotates around the inner surface of the test pipe at a constant speed, carrying out up-down stroke reciprocating motion in the axial direction of the pipe. The used high-pressure water pump is horizontal triple plunger pump (with flow rate Q=20 /min and max. pressure P=120MPa). The water depth of the test pipe is approximately 0.4m but tests have been carried out in a pressurized tank under the pressure of 0.15MPa (equivalent to the water depth 15m). The zone where the distance between the injection nozzle and the concerned metal (standoff distance) is, for instance, about 10-20 times larger than the inner diameter of the nozzle, the cavitation erosion caused by water jet is excessively large. Hence, the standoff distance suitable for peening is considered to be 80-120 times of the inner diameter of the nozzle [5]. The test pipe used in the test is a small-diameter pipe of size 15mm, so we injected the water jet in inclined direction instead of vertical direction to the pipe wall in order to secure the appropriate standoff distance. Here, we made an effective use of the WJP which has little effect of the angular injection because the effective region of the shock pressure generated at the time of the collapse of cavitation bubbles is isotropic.



(a) Overall schematic diagram (b) Nozzle drive system (b) Pressurized tank

Figure 2. WJP test apparatus

Verification of residual stress improvement effects

The major factors for carrying out WJP are given the follows.

- Injection pressure and flow rate
- Standoff distance
- Injection time per area
- Angle of injection
- Atmospheric pressure (depth of water) around the WJP site.

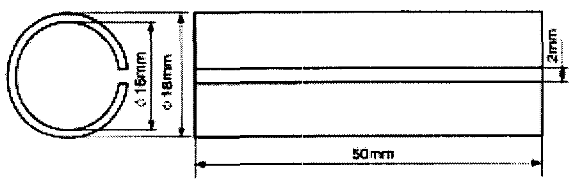
Taking these factors into consideration, the test was carried out under the following conditions. Figure 3 shows the most popular test conditions for the peening test.

Item		Condition range
High-pressure pump	Injection pressure	100- 120 MPa
	Flow rate	Max. 20 /min
Injection nozzle	Peening time	33- 267 min/m(per axis length 1m)
	Rotational speed	20 rpm
Ambient pressure	Internal pressure of pressurized tank	0.15 MPa (Equiv. to water depth 15m)

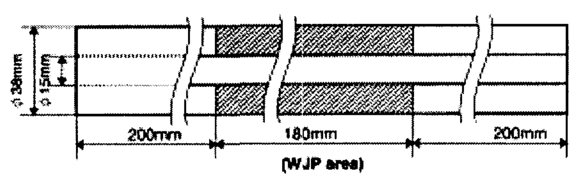
Figure 3. WJP test conditions

Index of peening strength: In the case of shot peening, plastic strain is applied to the proximity of the surface. When the peening is conducted on a thin plate, the surface of the shot strikes get extended and swollen in convex shape, causing deformation of the plate. This phenomenon is effectively used in expressing the index of peening strength by the deformation (arc height) of the thin plate after shot peering [6]. The standard thin plate used for such purpose is called "Almen strip." Under the peening conditions that provide the same arc heights when the shot diameters are equivalent, the residual stresses can also be considered equivalent. Therefore, WJP can also be considered (like shot peening) to be a processing where compressive residual stress is applied by applying plastic strain to the proximity of the metal surface. Hence, it is possible to control the peening conditions by means of the arc height of the Almen strip. Since an Almen strip cannot be used due to spatial limitation when carrying out peening on the inner surface of a small-diameter pipe, a thin slit pipe (material: SUS316) shown in Figure 3(a) is used. When plastic strain is applied through WJP to the whole inner surface of the thin pipe, the pipe gets deformed so as to enlarge the radius of curvature. This change in the curvature is measured by the pre-installed slit width. Since the change in slit width corresponds to the arc height of Almen strip, it can be used as an index of the generated plastic strain. In this research, therefore, the slit width change is regarded as the index of peening strength.

Measurment of residual stress; In order to confirm the effect of the improvements on surface residual stress due to WJP, a test pipe of corrosion-resisting and heat-resisting super alloys of Ni-Cr-Fe alloy (equivalent to NCF600, JIS G4901) with outer diameter 38mm × inner diameter 15mm was used as shown in Figure 3(b). The residual stress of the pipe inner surface has been reduced to less than ±10MPa because the test pipe has been annealed at approx. 900°C to remove the residual stress caused by mechanical processing. Since the residual stress due to WJP is generated near the surface, residual stress is measured by using the X-rays diffraction method.



(a) Thin pipe with slit



(b) Thick pipe (small diameter pipe)

Figure 4. Shape of test pipe

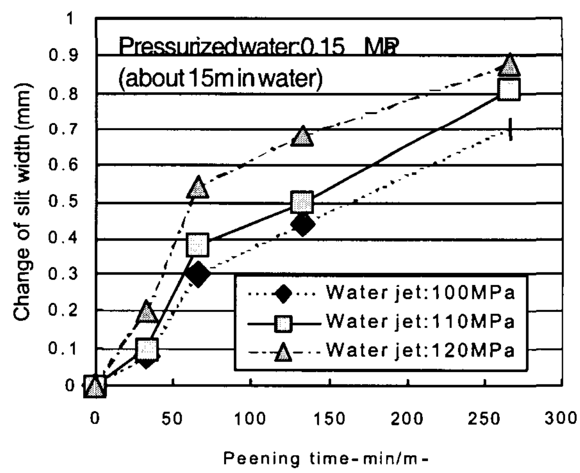
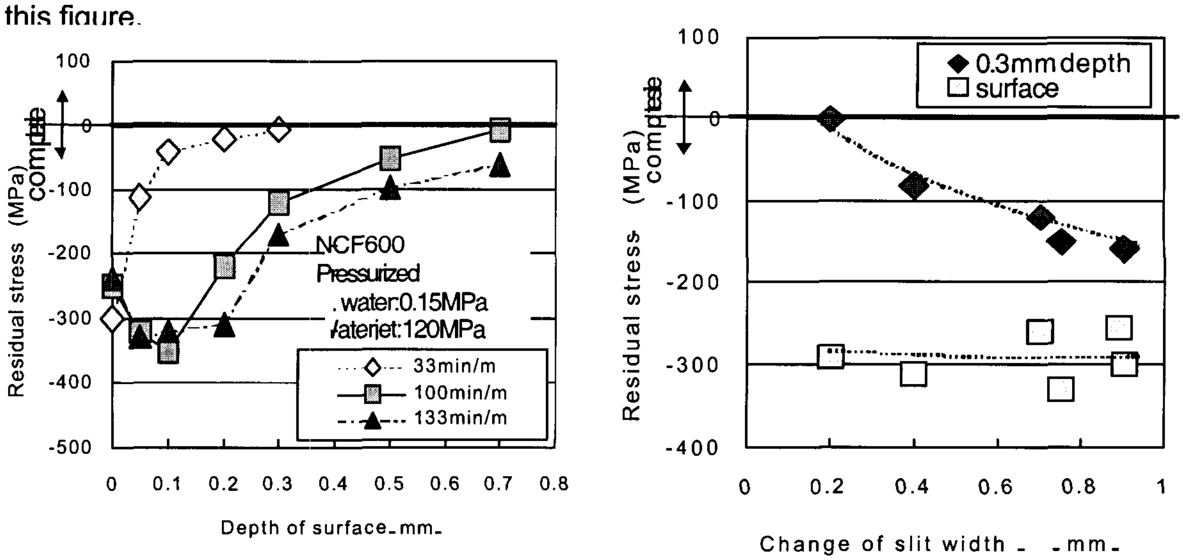


Figure 5. Change in slit width of pipe due to WJP

Test results and observation

Effect of peening conditions on the slit width change of the thin pipe: The results of WJP carried out at varied times under three different pump pressures 100MPa, 110MPa and 120MPa when the atmospheric pressure inside the pressurized tank is 0.15MPa are given in Figure 5. The horizontal axis in the figure indicates the total peening time per 1 m of pipe axial length. Although the slit width change increases with the peening time, the increment rate declines with the elapse of time. Further, the slit width change tends to increase with the pump pressure. The increase of change with time and the tendency of the increment rate getting decreased show similarity with the change in arc height in shot peening. In the zone where the slit width shows a sharp increase, when the coverage (the percentage of plastic dent caused by WJP covering the metal surface) is less than 100%, it is indicating that the plastic dent has not spread all over (uniformly) the surface. It is considered that the change in slit width gets reduced when the plastic dent covers the surface thoroughly (100%).

Effect of peening conditions on the residual stress: Figure 6(a) shows the distribution of residual stress in the direction of test pipe depth carried out with atmospheric pressure 0.15MPa and pump pressure 120MPa by varying the peening time. The horizontal axis in the figure indicates the depth from the inner surface of the test pipe. The residual stress on the test pipe surface is almost constant, irrespective of the peening time. On the other hand, when the peening time increases, the depth of compressive residual stress increases, with the compressive stress reaching approximately 0.7mm at the peening time 133min/m (per axis length). The relation between slit width change and residual stress is given in Figure 6(b), with the residual stress on the inner surface and the residual stress at the depth 0.3mm from the inner surface plotted in the figure. The horizontal axis shows the slit width change of thin pipes (SUS316) and the vertical axis shows the residual stress at the depth 0.3mm of thick pipes (NCF600). The results of slit thin pipes and thick pipes on the same WJP condition are plotted in this figure.



(a) Peening time vs. residual stress *(b) Relation between slit width and residual stress*

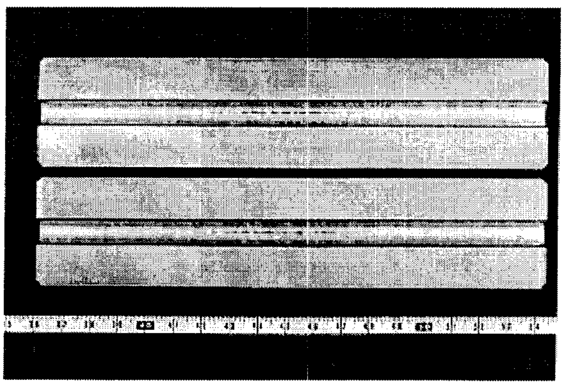
Figure 6. Residual stress improvement effect due to WJP

As shown in Figure 6(a), the residual stress on the surface is hardly affected by the WJP conditions, while the residual stress at the depth 0.3mm is found to have the correlation with the slit width change .Supposing the atmospheric pressure and the pump pressure (cavitation number) to be constant, it is obviously possible to estimate the depth from to reduce the residual stress. The cavitation number can be obtained from eq. (1).

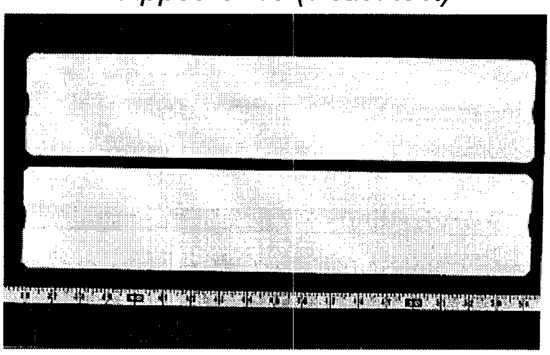
$$= (P_2 - P_V) / (P_1 - P_2) \quad (1)$$

where, P_1: discharge pressure of jet flow, P_2: atmospheric pressure, P_V: saturated vapor pressure.

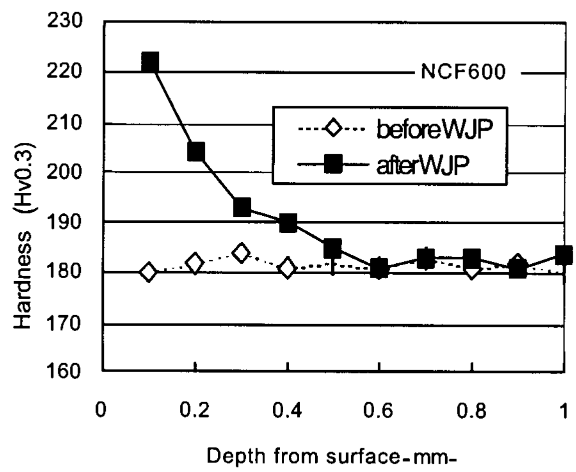
Observation of surface after WJP; The appearance photograph and liquid penetrant inspection result of the inner surface of the test pipe subjected to WJP in a pressurized tank with atmospheric pressure 0.15MPa under the pump pressure 120MPa at peening time 133 min/m(per axis length) are shown in Figure 7(a). Although extremely small dent is seen on the surface, no defects (cracks, etc. caused by plastic deformation) are found and the peened zone is apparently sound and wholesome. Further, the measurement of the surface roughness after WJP shows the smooth dent of depth less than 0.01mm over the width of 0.2-0.5mm of the inner surface of the test pipe. The smooth plastic dent caused by WJP suggests that the shock pressure at the collapse of cavitation bubbles is high and wide in range. Figure 6(b) shows the hardness measured near the surface of the site of peening, indicating that the hardening is confined to approximately 0.4mm from the surface. This clearly indicates that the depth of plastic strain is extremely large, about 40 times the depth of the dent=0.01mm.



Appearance (visual test)



Liquid penetrant inspection



(b) Measured hardness of section near surface after WJP

(a) Appearance and PT results after WJP

Figure 7. Surface condition after WJP (example of NCF600)

According to Al-Hassani, the depth h_P of the plastic region generated when a single hard ball is pressed statically on metal surface, the hard ball radius R and the dent depth Z are related to each other as shown in eq. (2) [7].

$$h_p / R = k (Z / R)^{1/2} \quad (2)$$

Where, k is constant (normally k=3 for the hard ball used for shot peening). Supposing k=3 at WJP, R comes to be approximately 2mm. The result corresponds with the result of measured surface roughness, indicating that the shock pressure generated at the collapse of cavitation bubbles has effect over an extremely deep region and causes deformation of the metal. When R is supposed to be 2mm, the depth geometrically comes to be 0.015mm at dent width 0.5mm and 0.02mm at dent width 0.2mm, showing almost a thorough correspondence at dent width 0.5mm.

CONCLUSIONS

The residual stress improvement method by WJP of the small-diameter pipe was studied as a preventive measure against SCC, and the following facts were learned.

(1) A bright prospect was obtained to improve the residual stress on the inner surface of a small-diameter pipe (inner diameter 15mm) into the compressive residual stress.

(2) There is not much difference in the compressive residual stress on the inner surface of the test pipe according to the WJP time, but the difference is found in the depth where the compressive residual stress is applied.

(3) It was confirmed that the depth for reducing the residual stress near surface could be estimated by measuring the slit width change at a slit thin pipe. Further, it was also learned that the change in slit width could be used as an index of peening strength to confirm peening conditions.

(4) The investigation of the peening section revealed that the inner surface of the pipe did have smooth plastic dent (width: 0.2-0.5mm, depth: 0.01mm), but no other conspicuous structural changes or damages could be seen.

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