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EFFECT OF LASER PEENING ON RESIDUAL STRESS AND STRESS CORROSION CRACKING FOR TYPE 304 STAINLESS STEEL

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ABSTRACT
A novel technique in which pulse laser irradiation is used to improve residual stress of material surface has been developed. When a material surface is irradiated by a high-energy pulse laser, the impulsive wave, which is generated by the high-pressure plasma, propagates into the material interior, thereby inducing high compressive stress on the material surface. We call the stress improvement technique using pulse laser irradiation "laser peening". The thickness of a compressive stress layer is much larger than that in the case of conventional peening techniques. The effects of processing parameters and material strength on the stress improvement of cold worked Type 304 stainless steel were investigated. The laser peening remarkably increases the stress corrosion cracking (SCC) resistance of thermal sensitized Type 304 stainless steel in corrosive high temperature water. It was confirmed that the laser peening was more effective than conventional peening techniques for improving the residual stress and the SCC resistance of Type 304 stainless steel.

KEY WORDS
Stress improvement, Pulse laser, Stress corrosion cracking, Compressive stress, Stainless steel

1. INTRODUCTION

The preventive maintenance techniques are becoming more important for enhancing the reliability of reactor internals in initial light water reactors. A residual stress improvement technique using pulse laser irradiation (laser peening) has been developed as a preventive maintenance technique to suppress stress corrosion cracking(SCC) susceptibility in core components. Recently, some stress improvement techniques have been examined with a view to applying them to in core components. For example, the water projection type shot peening system and remotely driven robots have been developed and successfully applied to weld lines of a practical core shroud[1][2]. Laser peening has some advantages in comparison with the other processes. For example, laser can be delivered for long distance with minimizing the attenuation during the delivery, and the laser irradiation head can be miniaturized to access the weld lines in narrow core region.

Surface improvement techniques using pulse laser irradiation have been investigated for the purpose of enhancing the fatigue strength of components in automobiles or aircraft[3][4]. When an intense pulse laser is irradiated against material surface under water, high pressure plasma is generated to induce the shock wave, which propagates into the material interior to form plastic deformation beneath the surface (Fig.1). The plastic deformation is restricted by elastic material around it, to form compressive stress at the material surface.

The applicability of laser peening to a stress improvement technique for neutron irradiated high strength Type 304 stainless steel was evaluated. The characteristics of the stress improvement, and its dependence on processing parameters and material strength were examined using cold worked Type 304 stainless steel. The susceptibility for stress corrosion cracking of the laser peened Type 304 stainless steel was also evaluated by creviced bent beam tests in corrosive high temperature water.

2. EXPERIMENTAL

2.1 Test pieces preparation

Test pieces (60×40×10t (mm)) were prepared from cold worked Type 304 stainless steel. The effects of processing parameters (Spot diameter(D_S), Pulse energy(E_P), Pulse number density(N_P)) on stress improvement were examined using 20% cold worked Type 304 stainless steel, which simulated the strength of neutron irradiated Type 304 stainless steel for long period in core region. The influences of material strength on the stress improvement were also evaluated using Type 304 stainless steels with and without cold working, of which the highest cold working rate was 30%. The processed surface of test pieces was ground in one direction parallel to the material rolling direction to form tensile stress on the surface(Fig.2).

The test pieces (10×50×2t (mm)) for SCC tests were prepared from Type 304 stainless steel with high carbon content (0.06 wt%) which was thermally sensitized (620℃×24 hours) followed by 20% cold working.

2.2 Processing apparatus

The processing apparatus is schematically shown in Fig.3. A test piece was fixed on the holder under water, and it was driven along X and Y directions so as to irradiate the surface at the same intervals in order to obtain the irradiated area necessary for stress

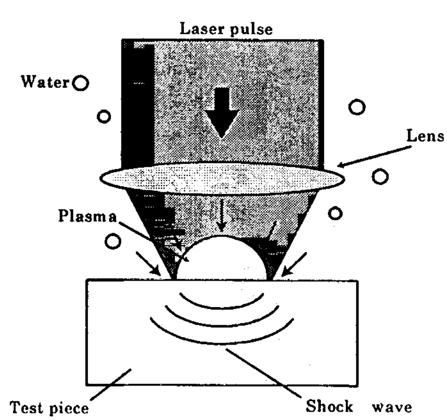

Fig. 1 Principle of stress improvement by pulse laser irradiation

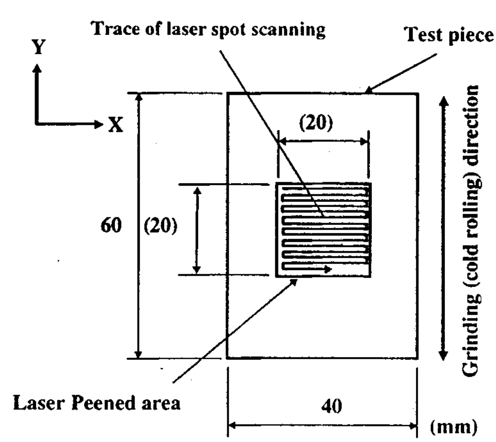

Fig. 2 Laser processing pattern for a test piece

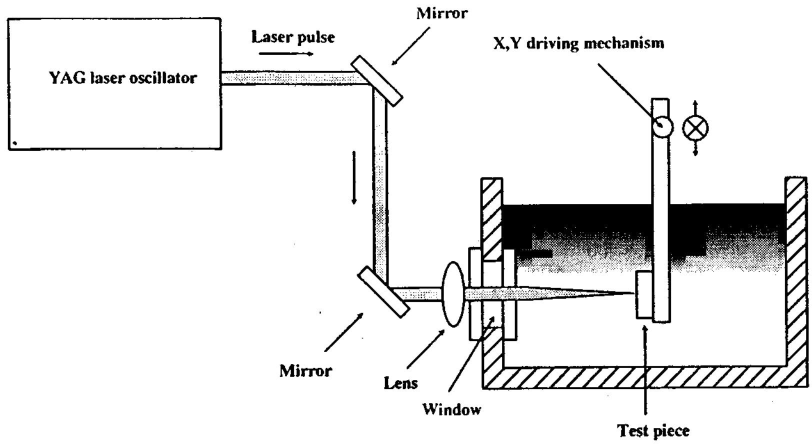

Fig. 3 Processing apparatus of pulse laser irradiation

measurement. The fundamental wave of a Q-switched Nd:YAG laser was frequency-doubled to the water-penetrable wave (λ =532 nm) by a second harmonic generator. The pulse laser traveled to a focusing lens using reflecting mirrors. The width of the pulse laser was 8 nm, the pulse frequency was 10 Hz.

2.3 Stress measurement

Surface residual stress was measured using the X-ray method. The X-ray source and diffraction plane were Mn-k α ray and γ phase (311) plane, respectively. Stress depth profiles were obtained in order to measure the residual stress on the electrochemical polished surface repeatedly. The direction parallel to the grinding (rolling) direction was defined as Y direction and the transversal direction was defined as Y direction.

2.4 Stress corrosion cracking test

The effectiveness of laser peening for the resistance for stress corrosion cracking (SCC) of Type 304 stainless steel was evaluated by creviced bent beam(CBB) type SCC test. Test pieces(10 × 50 × 2t (mm)) were prepared from the material which was subjected to thermal sensitization treatment (620℃ × 24 hours) followed by 20% cold working. Test pieces were bent to form 1% tensile strain on the surface using the holder with curvature, and then laser peened with the standard processing conditions without removing from the holder. Five test pieces with and without peening were respectively immersed in high temperature (288℃) water using a autoclave for 500 hours after making a crevice using graphite wool at the surface, which accelerates the corrosive environment. The surface of the test pieces was observed and each was cut into two pieces along the longitudinal direction in order to observe the cross section for the purpose of confirming whether it was cracked or not.

2.5 Evaluation of the material characteristics

Surface roughness after laser peening was measured using needle type roughness tester. Metallographical structure on the cross section of the processed surface was investigated using secondary electron microscopy (SEM) after electrochemical etching in oxalic acid, to examine the change by laser irradiation. Elemental concentration depth profiles from the processed surface to material interior were obtained by auger electron spectroscopy(AES) in order to examine elemental concentration change by laser irradiation.

3. RESULTS AND DISCUSSION

3.1 Processing parameter dependence

The processing parameters should be optimized to obtain enough stress improvement against the neutron irradiated Type 304 stainless steel. Laser spot diameter(Ds), pulse energy(Ep) and pulse number density(Np) were selected as the dominant parameters for stress improvement from previous experimental results, which examined the effects of the other processing parameters such as pulse frequency, pulse width, and irradiation angle to the processed surface.

Surface residual stress distribution is shown in Fig.4. The surface stresses were measured at 15 degree intervals from the X direction. Though laser peening could induce high compressive stress toward all directions, the compressive stress value along the X direction was lower than that along Y direction. The anisotropic stress improvement depending on the laser spot scanning pattern is one of the characteristics of laser peening.

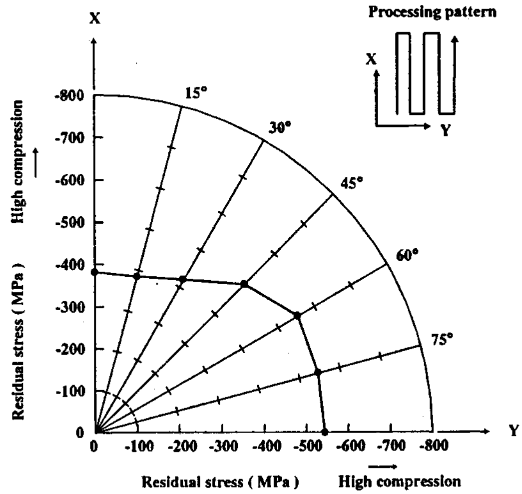

Fig. 4 Surface residual stress distribution(20% cold worked Type 304 stainless steel) (0.8mm／200mJ／3600pulse/cm^2)

Processing parameter dependence of stress improvement is shown in Fig.5 ~10. Effects of laser spot diameter (Ds) on residual stress at the surface and material interior are shown in Fig.5 and 6. Although the highest compressive stress was formed at the surface in the case of laser spot diameter of 0.8mm, the compressive stress increased with increasing laser spot diameter in material interior. Effects of pulse energy (Ep) at the surface and material interior are also shown in Fig.7 and 8. Although the highest compressive stress was formed at the surface in the case of laser pulse energy of 200mJ, the compressive stress increased with increasing pulse energy in material interior. And effects of pulse number density (Np) at the surface and material interior are shown in Fig.9 and 10. Although compressive stress at the surface increased with increasing pulse number density, the compressive stress in material interior did not depend on the pulse number density.

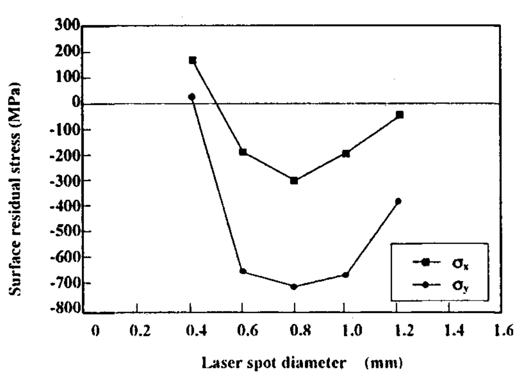

Fig. 5 Effects of laser spot diameters on the residual stress at the surface (200mJ／3600pulse/cm^2)

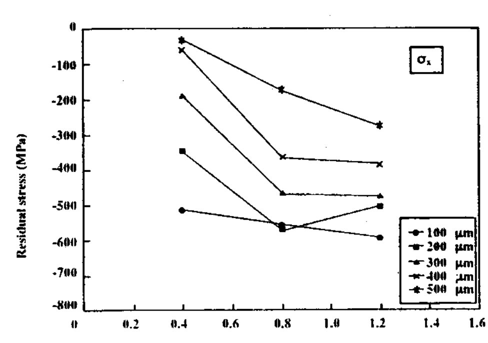

Fig. 6 Effects of laser spot diameters on the residual stress under the processed surface (200mJ／3600pulse/cm^2)

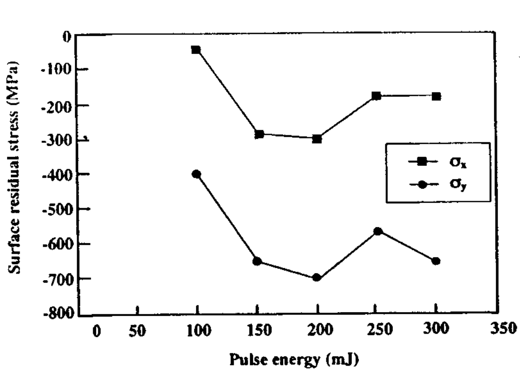

Fig. 7 Effects of laser pulse energy on the residual stress at the surface
(0.8mm/3600pulse/cm^2)

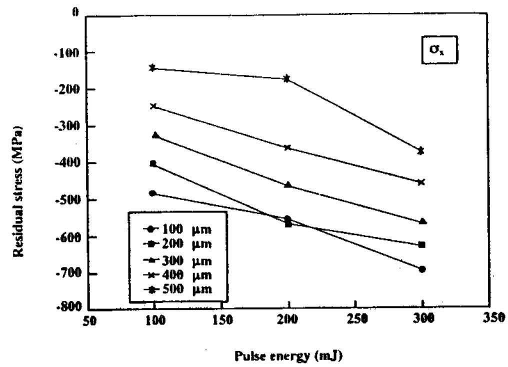

Fig. 8 Effects of laser pulse energy on the residual stress under the processed surface
(0.8mm/3600pulse/cm^2)

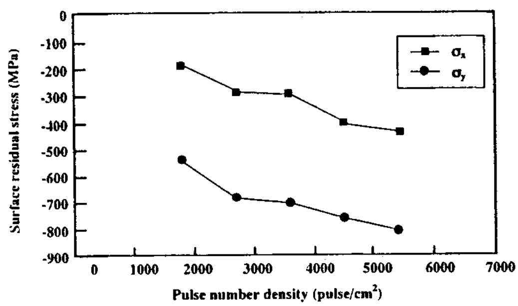

Fig. 9 Effects of laser pulse number density on the residual stress at the surface
(0.8mm/200mJ)

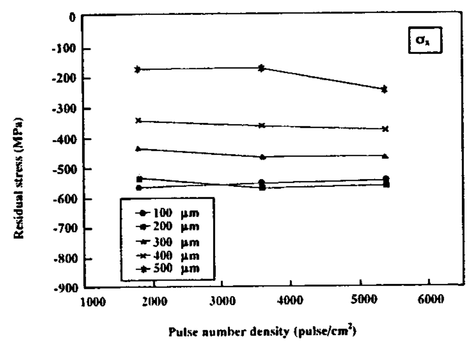

Fig. 10 Effects of laser pulse number density on the residual stress under the processed surface
(0.8mm/200mJ)

The different processing parameter dependence between at the surface and in the material interior was obtained. Two different factors due to pulse laser irradiation affect the thin surface layer, one is heating, which is very little quantity and extremely short duration, and the other is plastic deformation. The heating tends to form tensile residual stress by thermal expansion, and the plastic deformation induces compressive stress simultaneously to the layer. The surface residual stress is determined by the complementary roles of the two factors. The thickness of the layer is below 20 μ m from the detailed measurement of the stress depth profile immediately under the processed surface. On the other hand, the compressive stress value in the material interior is determined by the degree of plastic deformation, which is induced by impulsive shock wave. Therefore stress improvement of laser peening tends to be more effective under the processing conditions with larger spot size and higher pulse energy.

3.2 Residual stress depth distribution

Fig.11 shows residual stress depth profiles of the test piece which was laser peened under the standard processing conditions(Ds:0.8mm, Ep:200mJ, Np:3600 pulses/cm^2) selected from the parameter survey. Compressive stress layer of over 1mm was formed. Laser peening could form thicker compressive stress layer compared with conventional peening techniques.

3.3 Material strength dependence

Fig.12 shows residual depth profiles obtained from the cold worked Type 304 stainless steel, which the cold working rate ranged from 0 % to 30%. The 0.2% yield stress of the 30% cold worked Type 304 stainless steel was 945 MPa, which is over three times that of the material without cold working. Almost the same stress distributions were obtained from surface to 500 μ m independent of the material strength. The high pressure plasma , which its pressure was estimated to be over 2 GPa for an instant, induced high intensity shock wave which could give the plastic deformation to the high strength materials used in this experiments. Therefore the stress improvement of the laser peening is not sensitive to the processed material strength, and suited to the neutron irradiated high strength Type 304 stainless steel which has different strength depending on the neutron fluence in core region.

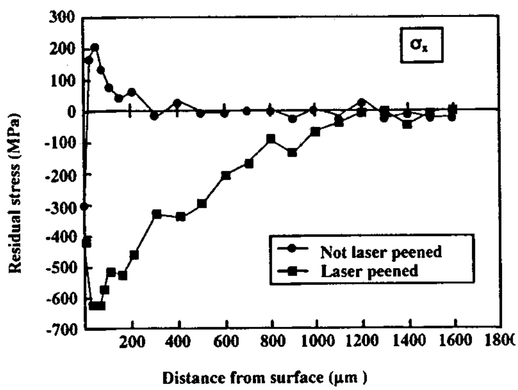

Fig. 11 Residual stress depth profiles for 20% cold worked Type 304 stainless steel (0.8mm/200mJ/3600pulse/cm^2)

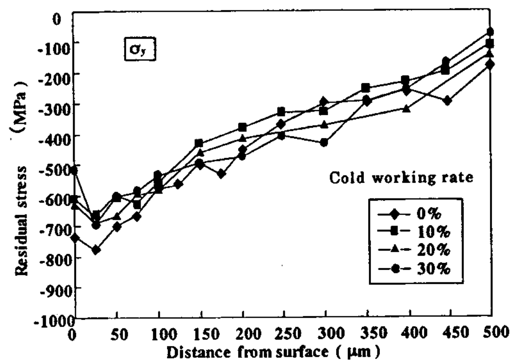

Fig. 12 Material strength (cold working rate) dependence of residual stress depth profiles (0.8mm/200mJ/3600pulse/cm^2)

3.4 Material characteristics of laser peened material

The microstructure on the cross section of the laser peened test piece is shown in Fig.13. No indications for solidification and thermal sensitization beneath the surface were observed, and therefore the heat input to the processed surface was thought to be negligible. Fig.14 shows the elemental concentration profiles from the processed surface to material interior, Oxygen diffuses into material from the surface to form the oxide layer with about 1 μ m thickness. It is supposed that the remarkably thin oxide layer was formed by which the activated oxygen due to the plasma generated by pulse laser irradiation reacted with the base metals such as Fe, Cr. Therefore the thermal effects on the processed material was very little because the average heat input was extremely low level due to the short pulse duration(8×10^{-9} seconds).

The average roughness of the processed surface were from 1.2 μ m to 1.3 μ m independent of measured directions, which was relatively smooth in comparison with that of shot peened surface.

3.5 Stress corrosion cracking susceptibility

Fig.15 shows the microstructures on the cross section of the test pieces with and without laser peening after immersion in 500 hours in high temperature water. The typical stress corrosion cracking occurred in all test pieces without laser peening according to the high tensile stress on the test pieces introduced by bending, whereas there were no cracks in all test pieces with laser peening. Therefore it is expected that the stress improvement by the laser peening can suppress the stress corrosion cracking susceptibility of thermally sensitized Type 304 stainless steel in corrosive high temperature water.

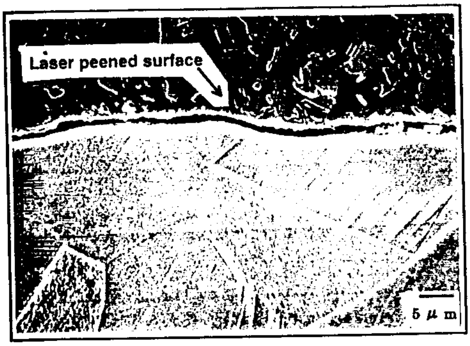

Fig. 13 Microstructure on the cross section of the laser peened Type 304 stainless steel (0.8mm／200mJ／3600pulse/cm^2)

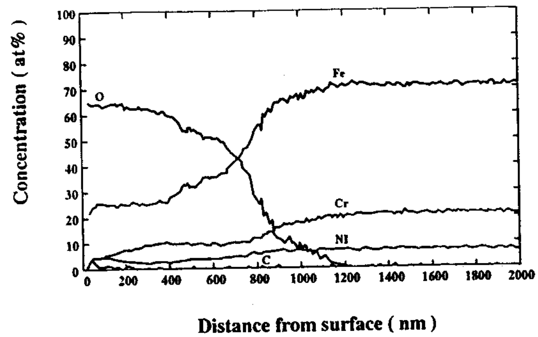

Fig.14 Concentration depth profiles obtained by auger electron spectroscopy (AES) (0.8mm／200mJ／3600pulse/cm^2)

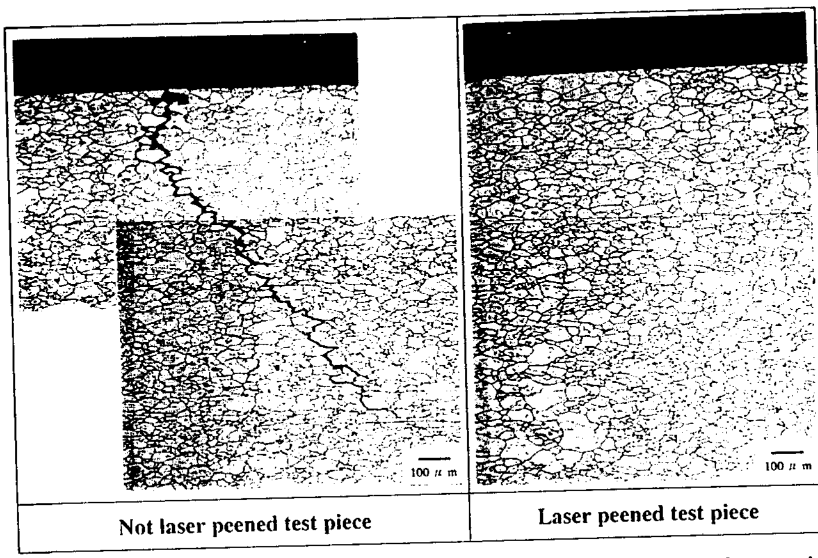

Fig.15 Microstructures on the cross section of the test pieces after stress corrosion cracking tests (0.8mm／200mJ／3600pulse/cm^2)

4. CONCLUSIONS

The effects of residual stress and the material characteristics of laser peening for Type 304 stainless steel were evaluated. The obtained results are as follows.

a. Processing parameters(spot diameter, pulse energy, pulse number density) were optimized by evaluating compressive stress at the surface and in the material interior. The standard processing conditions were selected as follows.
   Spot diameter (Ds) : 0.8 mm
   Pulse energy(Ep) : 200mJ
   Pulse number density(Np) : 3600 pulse/cm^2
b. Remarkable stress improvement for 20% cold worked Type 304 stainless steel was obtained. In particular, compressive stress layer of over 1mm could be formed, which stress improvement reached deeper into the material interior than in the case of using

the other conventional peening techniques.

c. Compressive stress depth profiles were independent of the material strength (cold working rate), and therefore laser peening is suited for stress improvement of neutron irradiated high strength Type 304 stainless steel.

d. The thermal effects on the material due to pulse laser irradiation were extremely small, and therefore there was no change of the metallurgical structure of the laser peened material, and the oxide film thickness on the processed surface was about 1 μm.

e. The stress improvement by laser peening could mitigate the stress corrosion cracking occurrence in corrosive high temperature water.

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