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Laser Peening: A Novel Tool to Reduce SCC Susceptibility and Prolong Fatigue Life of Metallic Components

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Abstract : The effects of laser peening on metallic materials have been investigated with water-penetrable frequency-doubled Nd:YAG laser. Laser pulses of 200 mJ energy and 8 ns duration focused on samples underwater with 0.8 mm spot diameter. X-ray study showed that compressive residual stress was imparted on SKD61 from the surface to nearly 2 mm depth. Stress corrosion cracking (SCC) was prohibited for sensitized SUS304 even in a severely corrosive environment fatigue lives of SUS316L and SM490A welded samples were prolonged significantly in the high-cycle regime. Since 1999, laser peening has been applied to prevent SCC in operating nuclear power plants in Japan.

Key words : Laser peening, Surface technology, Residual stress, Nuclear power plants

1. Introduction

Advances in laser technology have yielded a multitude of innovative processes and applications in various industries. Laser peening is a typical example invented in the mid-1990s as a surface technology, which converted residual stress from tension to compression by just irradiating successive laser pulses to metallic materials under aqueous environment without any surface preparation [1]. Laser peening utilizes a Q-switched and frequency-doubled Nd: YAG laser emitting water-penetrable green light (λ = 532 nm). Recent studies have demonstrated that laser peening dramatically improved the stress corrosion cracking (SCC) resistivity [2] and fatigue strength of various metallic materials [3]. Taking advantage of the process without reacting force against laser irradiation, a remote operating system was developed to apply laser peening to nuclear power reactors as a preventive maintenance measure against SCC [4].

In this paper, the fundamental process, characteristics and the effects of laser peening are presented together with the application to nuclear power reactors.

2. Process and Characteristics of Laser Peening

The scheme of laser peening is illustrated in **Figure 1**. When an intense

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laser pulse is focused on the material, the thin surface layer evaporates instantaneously through ablative interaction between the laser pulse and the material. The evaporating material is confined by the inertia of the water film and immediately ionized to form plasma by inverse bremsstrahlung. The plasma absorbs subsequent laser energy and generates a heat-sustained shock wave, which impinges on the material with an intensity of several gigapascals, far exceeding the yield strength of the material.

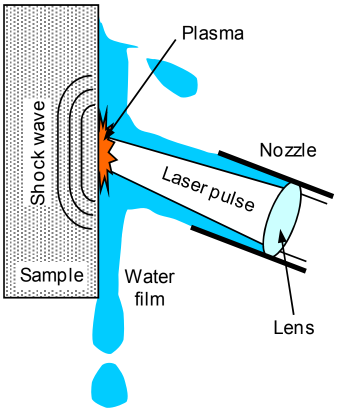

Figure 1: Basic scheme of laser peening

The shock wave loses energy as it propagates to create a permanent strain in the material. After the shock wave propagation, the surface is elastically constrained to form a compressive residual stress [1].

In our experiment, the duration of the laser pulse is less than 10 ns and the plasma disappears within several tens of nanosecond. Accordingly, the water film with thickness of 0.1 mm is enough to confine the plasma. Laser peening can be applied to water-immersed components as well, as shown in **Figure 2**, by utilizing water-penetrable laser such as frequency-doubled Nd:YAG laser (λ = 532 nm).

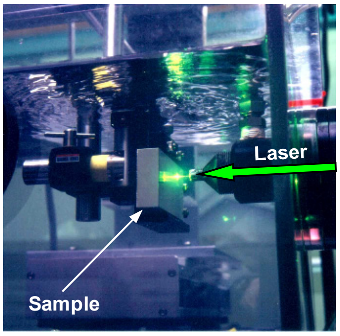

Figure 2: Underwater laser peening with water-penetrable laser

The major characteristics of laser peening are twofold: Firstly, the effect penetrates 1 mm or more from the surface and much deeper than that of shot peening. Secondly, the effect is highly reliable and reproducible since the objects are treated in the pre-determined manner, where the surface is sequentially irradiated by consecutive laser pulses under fully-controlled conditions.

3. Effects of Laser Peening on Residual Stress

The effect of laser peening on residual stress was examined. A sample prepared from a tool steel (SKD61) was fixed on a holder and driven two-dimensionally underwater as shown in **Figure 2**. The chemical compositions of SKD61 are summarized in **Table 1**. Laser pulses of 200 mJ energy and 8 ns duration from a Q-switched and frequency-doubled Nd:YAG laser impinged on the sample with a focal spot diameter of 0.8 mm and an irradiation density of 100 pulses/mm^2. The corresponding peak power density was 50 TW/m^2, which generated plasma with peak pressure of about 3.2 GPa. Residual stress was measured by X-ray diffraction (sin$^2\psi$ method) and the depth profile was obtained by repeating the diffraction measurement and electrolytic polishing, alternately.

Table 1: Chemical compositions of SKD61 (mass %)

C	Si	Mn	P	S	Cu
0.37	0.95	0.42	0.020	0.003	0.07
Ni	Cr	Mo	V	Fe	
0.14	5.34	1.20	0.80	Bal.	

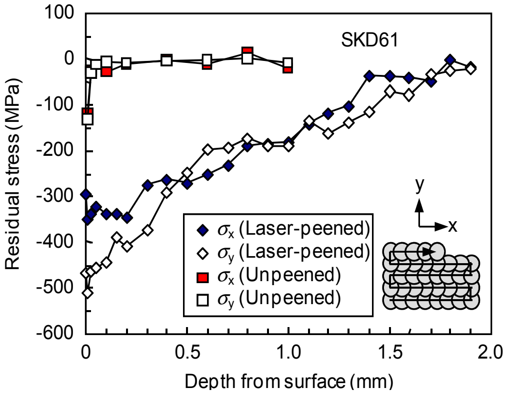

Figure 3: Residual stress depth profile of SKD61

The depth profiles of the residual stress are shown in **Figure 3** for an unpeened and the laser-peened sample. Laser peening imparts compression on the surface and has an advantage over shot peening in terms of the affected depth. The driving power for imparting the compression originates in the laser pulse energy, namely 200 mJ in this case. Meanwhile the kinetic energy of each steel shot with diameter of 0.6 mm and impinging velocity of 70 m/s is only 2 mJ, for example. The huge difference in the driving power is one of the reasons why the affected depth in laser peening is much deeper than that in shot peening. The residual stress depth profile after laser peening can be reproduced by time-dependent elasto-plastic calculations with a finite element program[5].

4. Effects of Laser Peening on SCC Susceptibility

4.1 Experimental Procedure and Results

The effect of laser peening on SCC susceptibility was evaluated for SUS304 through creviced bent beam (CBB) type testing[3]. The chemical compositions and the mechanical properties of the tested material are shown in **Table 2** and **3**, respectively. Samples of 10 mm × 50 mm and the thickness of 2 mm were prepared from an SUS304 plate sensitized at 893 K for 8.64 × 10^{4}s (24hours) followed by 20% cold working. Each sample was bent to produce uniform tensile strain of 1% on the surface with a curved holder, and then laser-peened. Graphite wool was set on the sample to simulate a crevice with

Table 2: Chemical compositions of SUS304 (mass %)

C	Si	Mn	P
0.06	0.41	0.90	0.032
S	Ni	Cr	Fe
0.001	8.47	19.07	Balance

Table 3: Mechanical properties of 20% cold-worked SUS304

0.2% yield strength (MPa)	725
Tensile strength (MPa)	946

stagnant water accelerating SCC. Samples were held in high-temperature water (561K) with dissolved oxygen of 8ppm and the conductivity of 10^{-4}S/m for 1.8 × 10^{6}s (500 hours) in an autoclave. Then, the surface of the test samples was observed and each sample was cut into two pieces along the longitudinal direction to observe the cross section.

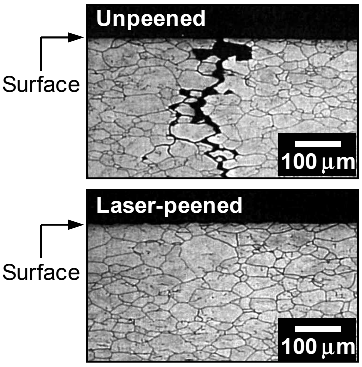

Figure 4: Accelerating SCC test results on sensitized SUS304

Typical SCC occurred in all reference samples without peening, whereas there were no cracks in samples after laser peening, as shown in **Figure 4**. The effect to prevent SCC was also confirmed on nickel-based alloy and their weld metals [2]. These effects to reduce SCC susceptibility on laser-peened materials would be due to the compressive residual stress imparted on the surface.

4.2 Application to Nuclear Power Plants

The concept for applying laser peening to a reactor core shroud in a boiling water reactor (BWR) is illustrated in **Figure 5**. The laser peening system is composed of a laser system, a beam delivery system with optical fiber cables, laser irradiation heads, remote handling equipment and a controlling system. The fiber-delivery of laser pulses from a Q-switched Nd:YAG laser is not straightforward due to dielectric break down which induces damage on the coupling surface of optical fiber; besides, the incoming laser pulse tends to focus and leads to damage in the optical fiber because of the non-linear effect of refractive index of fiber material (pure silica). The authors introduced unique coupling optics with a beam homogenizer comprised of micro lens arrays which averaged the spatial distribution of laser power density and eliminated the possible hot spots due to the non-linear effect [6].

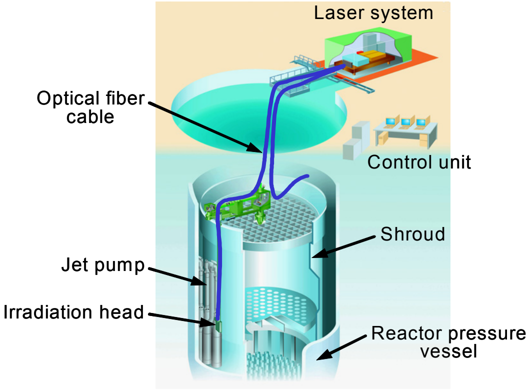

Figure 5: Laser peening system for preventive maintenance against SCC of BWR core shroud

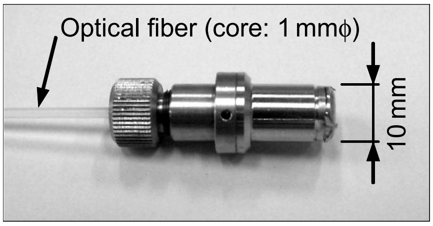

Figure 6: Miniaturized head with optical fiber

A miniature laser irradiation head with diameter of about 10 mm was also developed as shown in **Figure 6**, together with an automated focusing system that adjusts the focal position on the surface of curved objects with enough accuracy and response [4]. In this way, stable delivery of 20 MW laser pulses through a single optical fiber was established and incorporated into the laser peening system, which drastically improved the accessibility to complicated objects in a limited space.

Since 1999, laser peening has been applied to reactor core shrouds or nozzles of ten nuclear power plants of both BWR and PWR types as preventive maintenance against SCC, which covers nearly one fifth of existing nuclear power reactors in Japan [4].

5. Effects of Laser Peening on Fatigue Properties

5.1 Fatigue Properties of Base-metal Samples

A low carbon type austenitic stainless steel (SUS316L) was machined to make samples with a minimum diameter of 9 mm for rotating-bending fatigue testing [3]. Two kinds of heat treatments are applied to the samples prior to fatigue testing; one is full heat treatment (FH; 1373K, 3600s in vacuum) and the other is stress relieving treatment (SR; 1173K, 3600s in vacuum). The chemical compositions and mechanical properties of the materials are summarized in **Table 4** and **5**. After the heat treatments, each sample was subjected to laser peening with a condition of 200 mJ pulse energy, 8 ns pulse duration, 0.8 mm focal spot diameter and 36 pulses/mm^2 irradiation density. Here, laser pulses were irradiated on the sample surface spirally using a rotating and a linear stage.

Table 4: Chemical compositions of SUS316L (mass %)

C	Si	Mn	P	S
0.017	0.39	0.8	0.029	0.014
Ni	Cr	Mo	Fe	
12.17	16.31	2.06	Bal.	

Table 5: Mechanical properties of SUS316L

Preparation	0.2% yield strength (MPa)	Tensile strength (MPa)
Mill annealed	258	560
Full heat treated	178	549
Stress relieved	218	582

The average surface roughness (R_a) increased from 0.3 mm to 2 mm by laser peening. A hardened layer of about 0.6 mm thick was formed from the surface. The hardness of FH and SR materials after laser peening reaches about 300 H_v just below the surface and increased by about 140 H_v compared to the unpeened materials. The residual stress depth profiles showed large anisotropy between longitudinal (z) and circumferential (θ) directions. In both materials, σ_z and σ_θ on the surface were about -400 MPa and -200 MPa, respectively, and the maximum of about -600 MPa (σ_z) and -400 MPa (σ_θ) appeared at 60~100 μm from the surface.

High-cycle fatigue tests were carried out by rotating-bending with a frequency of 47 Hz (2820 rpm), where the sample was cooled by circulating distilled water. **Figure 7** shows the fatigue test results.

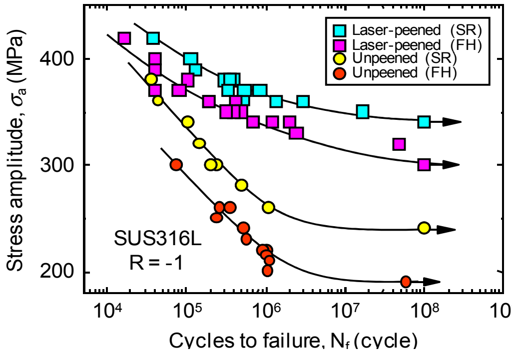

Figure 7: Rotating-bending fatigue test results on SUS316L

The vertical axis means the stress amplitude (σ_a) applied to the samples, whereas, the horizontal axis shows the number of loading cycles to failure (N_f). The fatigue strength of FH and SR materials after laser peening were 300 MPa and 340 MPa at 10^8 cycles, respectively, which were 1.7 and 1.4 times as great as that of the unpeened materials [3].

The reason for prolonging the fatigue lives must be the compressive residual stress on the samples due to laser peening, which effectively decreases tensile stress on the surface by fatigue loading.

5.2 Fatigue Properties of Welded Samples

Fillet-welded rib-plate samples of SM490A mild steel were prepared by welding a 9 mm thick rib to a 12 mm thick plate with a length of 450 mm and a width of 98 mm [7]. Carbon-dioxide (CO_2) gas shield welding was used with a JIS Z 3312 YGW11 filler wire. The chemical compositions and mechanical properties of SM490A are summarized in **Table 6** and **7**. Laser peening was performed to cover an area of 20 mm × 30 mm around the weld toe where stress concentration was evident. The conditions of laser peening were the same as those in SUS316L, namely, 200 mJ pulse energy, 8 ns pulse duration, 0.8 mm focal spot diameter and 36 pulse/mm^2 irradiation density.

High-cycle fatigue properties were studied through a series of fatigue tests under pulsating loading (R = 0) for the samples with and without laser peening. The external appearance of typical samples after fatigue tests are shown in **Figure 8**. The initiation of fatigue cracks occurred around the most expecting point (toe) for all unpeened samples. On the other hand, cracks started from an unexpected point for samples with laser peening, even though the stress amplitude and stress concentration at the toe is much larger than those at the crack-initiation point.

Table 6: Chemical compositions of SM490A (mass %)

	Base plate (12 mmt)	Rib (9 mmt)
C	0.16	0.13
Si	0.50	0.24
Mn	1.46	1.18
P	0.015	0.021
S	0.013	0.006
Fe	Balance	Balance

Table 7: Mechanical properties of SM490A

	0.2% yield strength (MPa)	Tensile strength (MPa)
Base plate (12 mmt)	382	548
Rib (9 mmt)	419	541

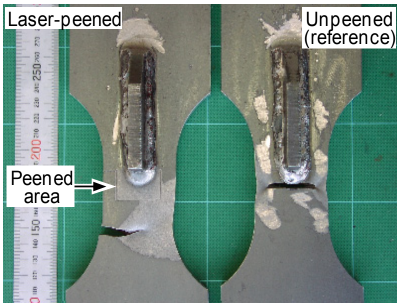

Figure 8: SM490A welded samples after fatigue test

Figure 9 illustrated the fatigue test results for stress ranges of 250, 300, 350 and 400 MPa considering the stress concentration due to the narrowed width of the base plates. The vertical axes are normalized so that the average fatigue lives of two unpeened samples would be unity for each stress amplitude. In the present experiment, so far, the fatigue strength or life of samples with laser peening could not be properly deduced, since some samples still survived after available fatigue cycles and cracks broke out from areas other than the toe for some samples. However, the overall results showed that laser peening significantly prolonged the fatigue lives of the fillet-welded rib-plate samples[7]. The external loading with the stress range of 400 MPa (R = 0) must introduce permanent strain on the material since the yield strength of the base plates is 382 MPa as shown in **Table 7**, which results in the relaxation of the residual stress due to laser peening and the reduction of the favorable effect on the fatigue life.

6. Conclusions

The process, effects and applications of laser peening were described. The

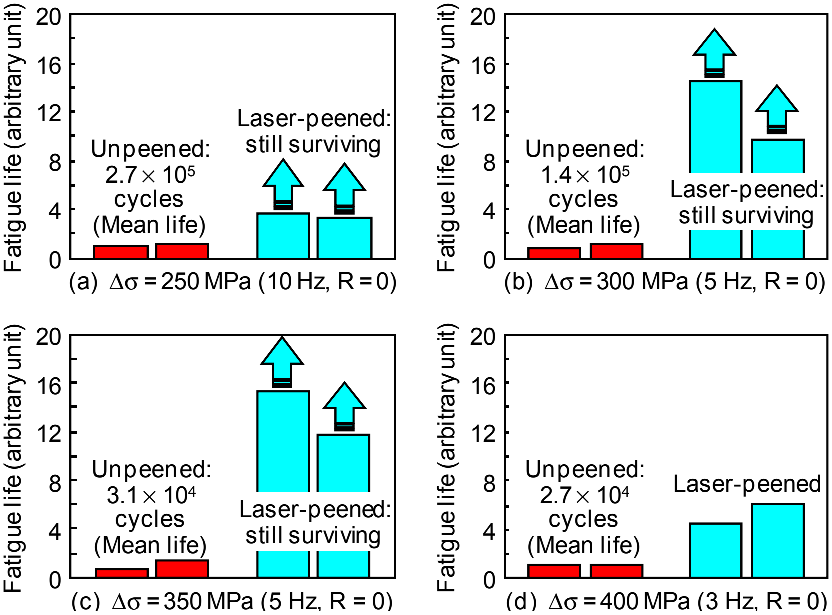

Figure 9: Fatigue test results of SM490A welded samples with and without laser peening

experimental results clearly showed that laser peening reduces stress corrosion cracking (SCC) susceptibility and prolongs fatigue life of metallic materials due to the impartment of compressive residual stress. The effects have been actually confirmed through the consequence of field applications. However, the mechanism to enhance SCC resistivity and fatigue properties is not fully identified yet, since the underlying physical process involves many interconnecting scientific aspects. Investigations to elucidate the mechanism are indispensable to optimize the process parameters and expand the territory of laser peening. Development of compact and low-cost lasers with high-repetition rate is highly expected to maximize the process capabilities and promote the further applications of laser peening.

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