Laser Peening without Coating as a Surface Enhancement Technology

Yuji SANO[*], Koichi AKITA[**], Kiyotaka MASAKI[***], Yasuo OCHI[***]
Igor ALTENBERGER[****] and Berthold SCHOLTES[****]

[*]*Toshiba Corporation, 8 Shinsugita-cho, Isogo-ku, Yokohama 235-8523, Japan*
E-mail: Yuji.sano@toshiba.co.jp
[**]*Musashi Institute of Technology, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan*
[***]*University of Electro-Communications, Tokyo, 1-5-1 Chofugaoka, Chofu 182-8585, Japan*
[****]*University of Kassel, Mönchebergstr. 3, Kassel 34125, Germany*

Laser peening without coating (LPwC) is an innovative surface enhancement technology, which imparts compressive residual stress without any surface preparations. Materials were peened in aqueous environment with laser pulses of about 100 mJ from a Q-switched and frequency-doubled Nd:YAG laser. Surface roughness of the materials somewhat increased due to ablative interaction. Compressive residual stress nearly equal to the yield strength of the materials appeared at the surface after LPwC in spite of the possible heat effect by direct laser irradiation to the materials. The depth of the compression reaches 1 mm or more from the peened surface. High-cycle fatigue properties were evaluated through rotating-bending or push-pull type testing for an austenitic stainless steel (SUS316L), a titanium alloy (Ti-6Al-4V) and a cast aluminum alloy (AC4CH). LPwC significantly prolonged the fatigue lives despite the increase in surface roughness. Accelerating stress corrosion cracking (SCC) tests showed that LPwC completely eliminated SCC susceptibility of sensitized austenitic stainless steels, nickel-based alloys and their weld metals. LPwC has been utilized to prevent SCC in Japanese nuclear power reactors since 1999.

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1. Introduction

The advent of high performance lasers has yielded a multitude of innovative processes and applications in many industrial fields. Laser peening without coating (LPwC) was invented a decade ago, as a surface enhancement technology, which converted tensile residual stress to compressive by just irradiating successive laser pulses to metallic materials under aqueous environment [1]. LPwC utilizes a compact and commercially-available Nd:YAG laser and does not require any surface preparations or coating prior to laser irradiation. The initial investment and operating expense are significantly small compared to conventional laser peening system with Nd:glass laser.

Recent studies have revealed that LPwC dramatically improved the fatigue properties of steels [2], titanium alloys [3] and aluminum alloys [4-6], in spite of the increase in surface roughness. It was also confirmed that LPwC is effective to prevent the initiation and propagation of stress corrosion cracking (SCC) [7]. Taking advantage of the inertialess process of LPwC over mechanical treatment, a remote-controlled processing system has been developed and applied to nuclear power reactors as a preventive maintenance measure against SCC [8-10].

In the present paper, the authors outline the process and recent research outcome of LPwC.

2. Process and characteristics

2.1 Basic process

Laser peening with and without coating is illustrated in **Fig. 1**. When a laser pulse is focused on the material, the thin surface layer evaporates instantaneously through ablative interaction. The water confines the evaporating material and the vapor is 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. The shock wave loses energy as it propagates to create a permanent strain. After the shock wave propagation, the surface is elastically constrained to form a compressive residual stress [11-14].

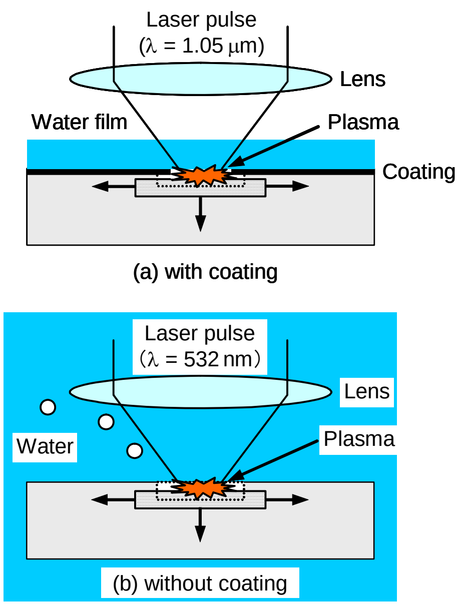

Fig. 1 Process of laser peening.

The major characteristics of both processes with and without coating are summarized in **Table 1**.

Table 1 Laser peening with and without coating.

	with coating	without coating
Laser oscillator	Nd:glass (1.05 μm)	Nd:YAG (532 nm)
Pulse duration	< 100 ns	< 10 ns
Pulse energy	≤ 100 J	40 ~ 250 mJ
Spot size	≤ 10 mmϕ	≤ 1.2 mmϕ
Delivery system	Mirror	Fiber or mirror
Developed in	USA, France	Japan

2.2 Laser peening with coating

The conventional type of laser peening has utilized the coating (sacrificial overlay) and the Nd:glass laser with near infrared wavelength of 1.05 μm [15-20]. The coating enhances laser absorption and prevents the surface from melting or being damaged [21-23]. The coating is usually formed from black paint prior to laser irradiation and the remaining paint is removed after the treatment.

2.3 Laser peening without coating (LPwC)

The new process without coating (LPwC) employs a Q-switched Nd:YAG laser. The wavelength is halved to water- penetrable 532 nm, which necessarily decreases the laser pulse energy to around 100mJ from several tens of joules in the conventional process. In the new process, the surface residual stress becomes compressive by increasing the density of irradiating laser pulses [1,24].

In 1995, the authors reported the successful results of LPwC for the first time in the world [1]. This achievement constitutes a major breakthrough in the underwater maintenance for nuclear power plants since the process requires neither surface preparation under radiation environment nor drainage work of water in a reactor vessel.

2.4 Characteristics of the new process

The main characteristics of LPwC are as follows:

(1) LPwC does not require any coatings that protect the material surface from melting or being damaged,
(2) employs Q-switched and frequency-doubled Nd:YAG lasers, which are compact and commercially-available,
(3) can deliver laser pulses through a flexible optical fiber,
(4) can irradiate laser pulses to water-immersed objects without the restrictions of transmitting length because of the water-penetrable wavelength, and
(5) requires a less complicated apparatus to access objects because of no reactive force against laser irradiation.

Thanks to the above characteristics, LPwC is practical not only in nuclear facilities but in other extreme environments necessitating a full-remote operation.

3. Effect of LPwC on residual stress

3.1 Residual stress depth profile

The effect of laser peening without coating (LPwC) on residual stress was examined. A sample prepared from a tool steel (JIS SKD61) was fixed on a holder and driven two-dimensionally underwater. Laser pulses of 200 mJ and 8 ns duration were incident on the sample with a focal spot diameter of 0.8 mm and a pulse density of 100 pulses/mm^2. The corresponding peak power density was 50 TW/m^2. Residual stress was measured with X-ray diffraction ($\sin^2\psi$ method) and the depth profile was obtained by repeating the measurement and electrolytic polishing, alternately.

The depth profiles are shown in **Fig. 2** for the sample after LPwC and unpeened sample. LPwC imparts compression on the surface and has an advantage over shot peening in terms of the affected depth. The overall profile can be reproduced by time-dependent elasto-plastic analysis with a finite element program [13,14]. In most cases, the magnitude of the residual stress after LPwC in y-direction (σ_y) is larger than that in x-direction (σ_x) in the surface region, which is an open question.

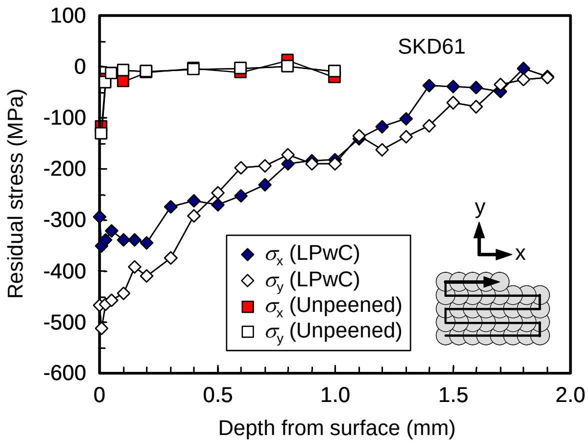

Fig. 2 Residual stress depth profile of SKD61.

3.2 Constant penetration depth (CPD) method

In the previous section, we have demonstrated that LPwC can introduce the compression up to 1 mm or more from the surface. In this section, we precisely discuss the experimental results on the residual stress state and thermal stability in the top surface of material after LPwC [25].

Figure 3 shows the configuration of X-ray diffraction experiment in SPring-8. The energy of X-ray was adjusted to be 25 keV with a silicon monochromator. Then, the X-ray was collimated by a four-quadrant slit and irradiated to a sample placed on a four-circle goniometer. The sample material investigated was an austenitic stainless steel (JIS SUS304). Diffracted X-ray from a γ-Fe 422 plane was detected by a scintillation counter via a solar slit. The scattering angle (2θ) was around 39.4 deg. The penetration depth of X-ray was 15.7 μm at $\psi = 0$ in this geometry.

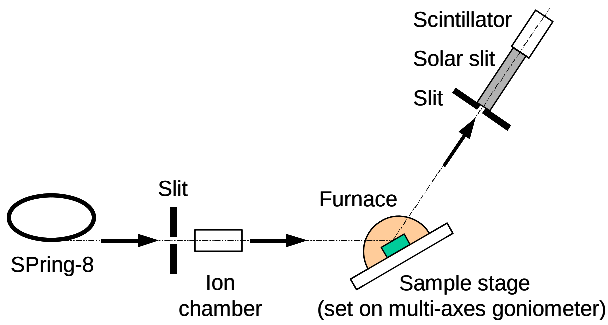

Fig. 3 Configuration of X-ray diffraction in SPring-8.

The constant penetration depth (CPD) method [26] was applied, which provides relevant information on the surface residual stress, because the method strictly controls the X-ray penetration depth constant during the series of exposure with various ψ angles. Using this method with high energy and high brilliance X-ray of SPring-8, the residual stress depth profile in the top surface can be precisely evaluated in a non-destructive manner.

3.3 Residual stress in top surface

The CPD method was used to measure the residual stress depth profile of 20 % cold-worked SUS304. The sample was processed by LPwC with the condition of 60 mJ pulse energy, 8 ns pulse duration, 0.7 mm spot diameter and 70 pulses/mm^2 irradiation density. The profile was measured before, during and after heating. To attain thermal equilibrium in elevated temperatures (562 K and 673 K), the sample was covered with a Kapton (polyimide) dome and held for one hour at each temperature.

The measured profiles are shown in **Fig. 4**. It is evident that the residual stress in the top surface is compressive despite the direct irradiation of laser pulses to the sample without coating. The thermal loading up to 673 K somewhat reduced the residual stress; however, the overall distribution was quite stable. This kind of measurement using the same sample could not be realized without the CPD method combined with high energy X-ray of SPring-8.

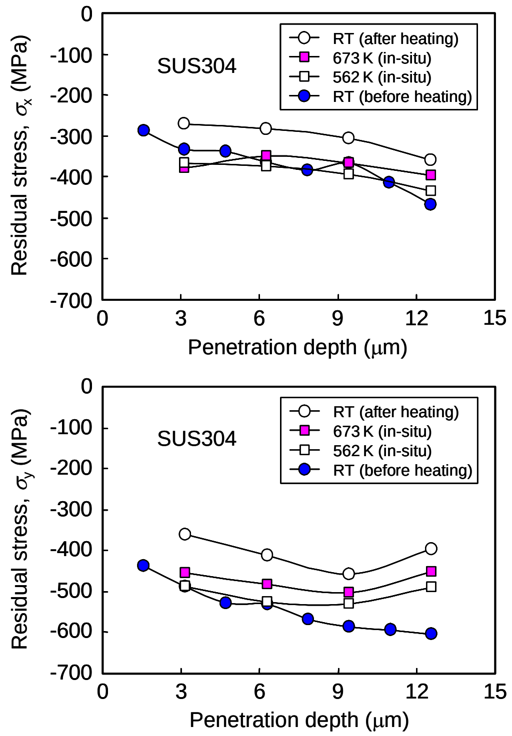

Fig. 4 Residual stress depth profile of 20 % cold-worked SUS304 processed by LPwC.

4. Effect of LPwC on fatigue properties

The effect of laser peening without coating (LPwC) on high-cycle fatigue property was examined for austenitic stainless steels (SUS304 and SUS316L), titanium alloys (Ti-6Al-4V and Timetal LCB), aluminum alloys (AC4CH and 7075-T7351), etc [2-7]. Typical examples are presented in the following sections.

4.1 SUS316L

A low carbon type austenitic stainless steel (JIS SUS316L) was machined to make rotating bending test samples shown in **Fig. 5**. Two kinds of heat treatments are applied to the samples; one is full heat treatment (FH; 1373 K, 3600 s in vacuum) and the other is stress relieving treatment (SR; 1173 K, 3600 s in vacuum).

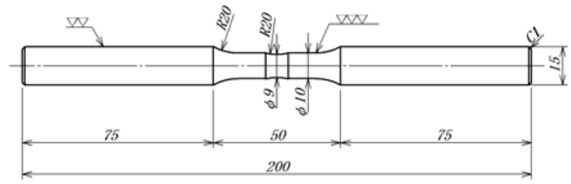

Fig. 5 Shape and dimensions of SUS316L samples.

After the heat treatments, each sample was subjected to LPwC with a condition of 200 mJ pulse energy, 8 ns pulse duration, 0.8 mm spot diameter and 36 pulses/mm^2 irradiation density. Laser pulses were irradiated on the sample surface spirally using a rotating stage. The average surface roughness (R_a) increased from 0.3 μm to 2 μm by LPwC. Measurements of the micro-vickers hardness (H_v) revealed that the hardened layer was about 0.6 mm thick from the surface. The hardness of FH and SR materials after LPwC 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 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. The depth profiles showed the maximum of about -600 MPa (σ_z) and -400 MPa (σ_θ) at 60~100 μm from the surface.

High-cycle fatigue tests were carried out by rotating-bending with a frequency of 2820 rpm, where the sample was cooled by circulating distilled water. **Figure 6** shows the fatigue test results. 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 with LPwC 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. The symbol with asterisk (*) stands for the sample with a crack developing in the axial direction [2]. Similar cracks were observed in hard-shot peened SUS316L [27].

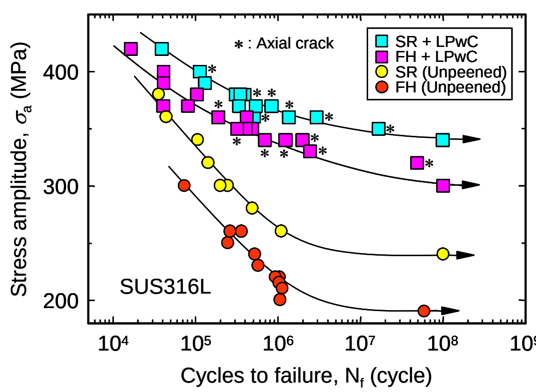

Fig. 6 Rotating-bending fatigue test results of SUS316L.

4.2 Ti-6Al-4V

The material investigated is an α-β-titanium alloy, Ti-6Al-4V, which is characterized by a bimodal or solution heat treated and over-aged microstructure with a primary α-content of 64 % and an average grain size of 20 µm. Further details regarding the heat treatment and mechanical properties are summarized in the literature [28].

The shape and dimensions of the samples are shown in Fig. 7. The diameter of the gage volume is 7 mm. LPwC was performed with a condition of 200 mJ pulse energy, 8 ns pulse duration, 0.8 mm spot diameter and 36 pulses/mm^2 irradiation density, the same condition as SUS316L in the previous section.

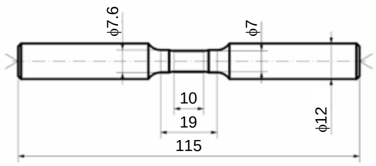

Fig. 7 Shape and dimensions of Ti-6Al-4V samples.

Push-pull type fatigue tests were conducted at a frequency of 5 Hz with an R-ratio of -1 under stress control. Figure 8 exhibits the S/N-behavior of samples with LPwC in ambient temperature compared to the unpeened samples.

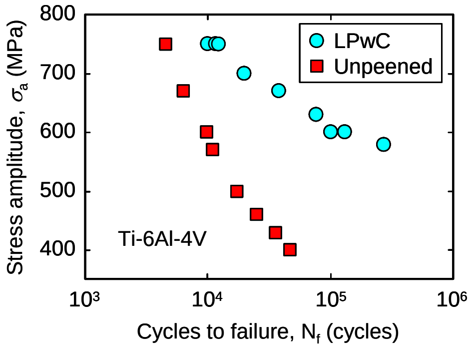

Fig. 8 Push-pull fatigue test results of Ti-6Al-4V.

Some samples were tested in elevated temperatures using halogen radiant heating. The fatigue life dropped systematically by increasing the temperature. However, the samples after LPwC still have longer lives than the unpeened material at temperatures up to 723 K (450 °C) as shown in Fig. 9. Even at 723 K, LPwC enhanced the lifetime by a factor of two at the stress amplitude investigated (460 MPa).

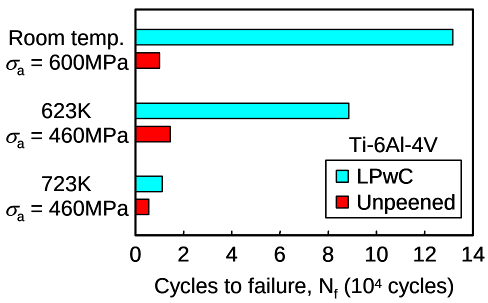

Fig. 9 Push-pull fatigue test results of Ti-6Al-4V at elevated temperatures.

At this high-temperature and stress amplitude, the fatigue is clearly within the low-cycle fatigue regime and the high-cyclic plasticity and temperature leads to a complete relaxation of compressive residual stresses in near-surface regions [3]. Nevertheless the fatigue life is considerably improved by LPwC. This is due to stable work hardening and near-surface microstructures that inhibit fatigue crack initiation [28]. Evidence for the stability appeared in X-ray peak broadening and in the direct observation of fatigued near-surface regions by transmission electron microscopy (TEM) [3].

4.3 AC4CH

Fatigue samples were prepared from cast blocks of an aluminum-silicon-magnesium alloy (JIS AC4CH). Defects and impurities in the material were reduced by degassing in the casting process [4]. T6 heat treatment was applied to the blocks before machining. The microstructure is a typical dendrite structure with aluminum matrix and eutectoid silicon particles.

The shape of the test samples is similar to that of SUS316L, however, the size is smaller and the minimum diameter of the gage volume is 7 mm in AC4CH samples. LPwC was performed with a condition of 100 mJ pulse energy, 8 ns pulse duration, 0.6 mm spot diameter and 27.3 pulses/mm^2 irradiation density. Rotating-bending fatigue testing was conducted at a frequency of 2760 rpm in air at room temperature. The surface crack behavior was observed using the replication technique. Fracture surface was observed by a field emission type scanning electron microscope (FE-SEM) in order to specify the crack initiation sites [5].

The S/N diagrams of AC4CH showed that the samples after LPwC had higher fatigue strengths than those of the unpeened reference materials, i.e., 150~160 MPa for samples after LPwC and 130 MPa for the reference at 10^7 cycles. It is clear that LPwC is effective for improving the fatigue strength of AC4CH, which should be ascribed to the decelerating effects of the surface crack growth rate due to the hardness increase and the compressive residual stress in the surface layer induced by LPwC.

Figure 10 shows the typical propagation behavior of main surface cracks at the stress amplitude of 200 MPa [4]. The crack initiation lives of both materials were almost identical. After the crack initiation, the crack propagated rapidly in the unpeened material. However, the cracks propagated slowly during a certain period until the crack length reached 100 µm in the material after LPwC.

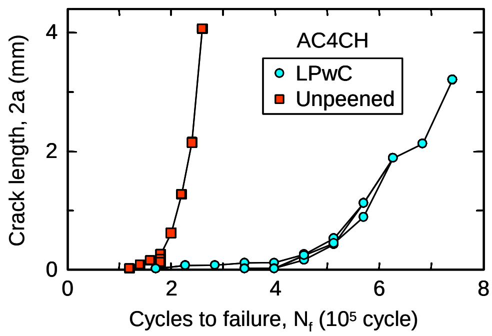

Fig. 10 Fatigue crack propagation behavior in AC4CH.

5. Effect of LPwC on stress corrosion cracking (SCC)

It is well known that the compression at surface has a tremendous effect to reduce stress corrosion cracking (SCC) susceptibility of metallic materials even under severely corrosive environments. In this chapter, the effect of LPwC to prevent SCC and a system for applying operating nuclear power plants are described.

5.1 Procedure and results of SCC experiments

The effect on SCC susceptibility of SUS304 was evaluated through creviced bent beam (CBB) type testing [7,14,29]. Samples of 10 mm × 50 mm and the thickness of 2 mm were prepared from a sensitized SUS304 plate (893 K, 8.64×10^4 s) followed by 20 % cold working. Each sample was bent to produce uniform tensile strain of 1 % on the surface with a curved holder, and processed by LPwC. A crevice was made on the sample using graphite wool to accelerate environmental SCC. Samples were immersed in high-temperature water (561 K) with dissolved oxygen of 8 ppm and the conductivity of 10^{-4} S/m for 1.8×10^6 s in an autoclave.

After the immersion, the surface of the test samples was carefully observed and each sample was cut into two pieces along the longitudinal direction to observe the cross section. SCC occurred in all reference samples without peening, whereas there were no cracks in samples after LPwC, as shown in **Fig. 11**. The effect of LPwC to prevent SCC was confirmed on austenitic stainless steel, nickel-based alloy and their weld metals, as well [7,29,30].

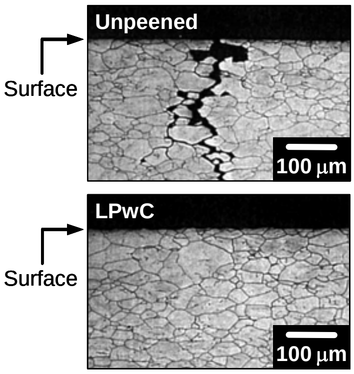

Fig. 11 SCC test results on SUS304.

5.2 Application to nuclear power plants

The concept for applying LPwC to a core shroud in a boiling water reactor (BWR) is illustrated in **Fig. 12**. The system is composed of a laser system, a beam delivery system with optical fiber cables, a laser irradiation head, 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 breakdown inducing 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.

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 [9,31-34].

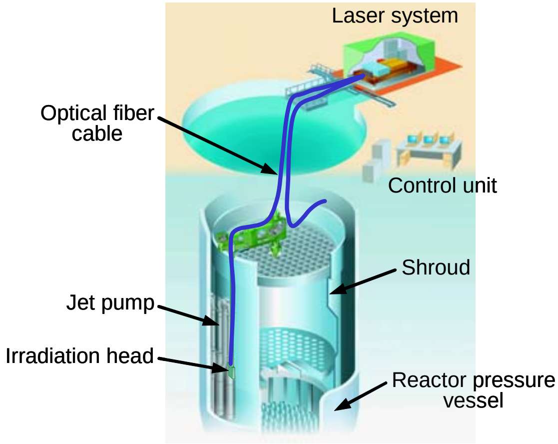

Fig. 12 LPwC system for preventive maintenance against SCC of BWR core shroud.

A miniature irradiation head with diameter of about 10 mm was also developed as shown in **Fig. 13**, together with an automated focusing function that adjusts the focal position to the surface of curved objects with enough accuracy and response [9,34]. In this way, stable delivery of 20 MW laser pulses through a single optical fiber was established and incorporated into the LPwC system, which drastically improved the accessibility to more complicated objects in a limited space.

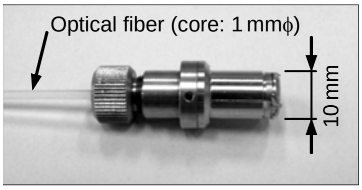

Fig. 13 Miniaturized head with optical fiber.

Since 1999, laser peening has been applied to core shrouds or nozzle welds of ten nuclear power reactors of both BWR and PWR types, which covers nearly one fifth of existing reactors in Japan [8-10].

6. Conclusion

The process, effects and applications of laser peening without coating (LPwC) were described. The experimental results clearly showed that LPwC prolongs fatigue life and prevents stress corrosion cracking (SCC) of various metallic materials due to the impartment of compressive residual stress and work hardening on material surface. The effects have been actually confirmed through the consequence of field applications. However, the mechanism to improve fatigue properties is not fully identified yet, since the underlying physical process involves many interconnecting scientific fields. Investigations to elucidate the fatigue properties are indispensable to optimize the process parameters and extend the territory of LPwC. Development of compact and low-cost lasers with high-repetition rate is highly expected to boost the process capabilities and promote the further applications of LPwC.

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