LASER PEENING WITHOUT COATING: PROCESS, EFFECTS AND APPLICATIONS

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ABSTRACT

This paper reviews the current status of research, development and application on laser peening without coating (LPwC). LPwC imparts compressive residual stress on material by irradiating laser pulses under aqueous environment without any surface preparation. LPwC can be operated without restriction on absorption by water, using water-penetrable green lasers. The effect penetrates 1mm or more, much deeper than that of conventional surface treatment such as shot peening. Accelerating stress corrosion cracking (SCC) tests showed that LPwC effectively prevented the initiation of SCC in sensitized austenitic stainless steels, nickel-based alloys and their weld metals. LPwC remarkably improved high-cycle fatigue properties of steels, aluminum alloys, titanium alloys. Retardation of crack propagation due to stress corrosion and fatigue was also confirmed. LPwC has been utilized to prevent SCC in Japanese nuclear power plants (NPPs) since 1999.

KEY WORDS

Laser peening, Residual stress, Stress corrosion cracking, Fatigue

INTRODUCTION

Recent advances in laser material processing have yielded a multitude of innovative processes and applications in various fields. Laser peening without coating (LPwC) is a typical example and blazed a trail in preventive maintenance for SCC in operating nuclear power plants (NPPs), taking full advantage of the inertia-less process over mechanical treatment (Sano, 2000a).

LPwC was invented about a decade ago as a surface enhancement technology to introduce compressive residual stress on materials, while exploring new applications of copper vapor lasers (Konagai, 1995). Through the optimization, the laser was replaced with a Q-switched and frequency-doubled Nd:YAG laser, which is much more compact and commercially-available.

Since the spring of 1999, LPwC has been used for preventive maintenance against SCC in Japanese NPPs (Sano, 2000a; Yoda, 2006). In 2002, a fiber delivery system for transmitting 20MW laser pulses through an optical fiber was completed (Yoda, 2000) and incorporated into the system for NPPs (Mukai, 2005; Yoda, 2006), which significantly extended the applicability of LPwC.

Meanwhile, laser peening with surface coating has been applied to prolong the fatigue life of turbine fan blades in the U.S. (See, 2002; Sokol, 2004). Following this achievement, the authors initiated studies on the applicability of LPwC for enhancing the fatigue strength of materials (Ochi, 2004). Recent experiments revealed that LPwC significantly enhanced the fatigue strength of steels, aluminum alloys and titanium alloys, in spite of the increase in surface roughness due to direct irradiation of laser pulses to the material without coating (Sano, 2006a).

PROCESS AND CHARACTERISTICS

Basic process of laser peening

The basic process of laser peening is illustrated in **Fig.1**. When a laser pulse with duration ranging from several to tens of nanoseconds is focused on an object, the surface evaporates instantaneously through the ablative interaction. The water confines the evaporating material and the resulting high-density vapor is immediately ionized to form metal plasma by inverse bremsstrahlung (Sano, 1997). Subsequent laser absorption in the plasma generates a heat-sustained shock wave, which impinges on the object with an intensity of several GPa, far exceeding the yield strength of metal material. The shock wave propagates and loses energy as it propagates to create a permanent strain. After the passage of the shock wave, the surrounding material elastically constrains the strained region, and thus forms a compressive residual stress on the surface (Sano, 2000b).

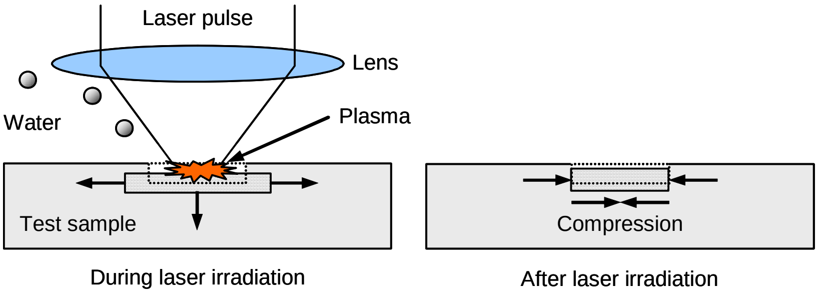

Fig.1 Basic process of laser peening

Laser peening with coating

The conventional type of laser peening has used an Nd:glass laser with near infrared wavelength (λ=1.05μm) and a protective coating (sacrificial overlay) on material (Fairand, 1972; Fabbro, 1998). The coating increases laser absorption efficiency and prevents the surface from melting or being damaged. The coating is usually formed from black paint prior to laser irradiation and the remaining paint is removed after the treatment.

Laser peening without coating (LPwC)

The new process (LPwC) employs a compact Q-switched Nd:YAG laser. The original wavelength (1.06μm) is halved to water-penetrable green (532nm), which necessarily decreased laser pulse energy to around 100mJ from several tens of Joules in the conventional process with the Nd:glass laser. In LPwC, the surface residual stress becomes compressive by increasing the number of irradiating laser pulses per unit area, in spite of possible heat effect of direct laser irradiation to material.

In 1995, the authors reported the successful results of the new process without any surface preparations for the first time in the world (Mukai, 1995). This achievement constitutes a major breakthrough in underwater maintenance for NPPs because the process requires neither surface preparation under severe radiation environment nor drainage work of water for radiation shielding.

Characteristics of LPwC

The major characteristics of LPwC are as follows:

(1) LPwC does not require any surface preparation nor coatings that would protect the material from melting or being damaged,

(2) employs Q-switched and frequency-doubled Nd:YAG lasers, which are compact, commercially available and easy-handled,

(3) can deliver laser pulses through a flexible optical fiber up to 50m,

(4) can irradiate laser pulses to water-immersed objects without the restrictions of transmitting length because of the water-penetrable wavelength, and
(5) requires less complicated handling system to access objects because of no reactive force against laser irradiation.

Thanks to the above characteristics, LPwC is practical in field applications not only in NPPs but also in other facilities under harsh environment necessitating a full-remote operation.

EFFECT ON RESIDUAL STRESS

The effect of LPwC on residual stress was examined. A test sample was fixed on a holder and driven two-dimensionally in a water jacket during consecutive laser pulse irradiation, as shown in **Fig.2**. Test samples were prepared from 20% cold-worked type 304 austenitic stainless steel (SUS304) plates. The samples were ground parallel to the material rolling direction to make a tensile stress on the surface prior to LPwC. Surface residual stress was measured by X-ray diffraction ($\sin^2\psi$ method) and the depth profile was obtained by repeating the stress measurement and electrolytic polishing, alternately.

The residual stress depth profiles of the samples with and without LPwC are shown in **Fig.3**, together with profiles predicted by finite element simulation (Sano, 2000b). Laser pulses of 200mJ and 8ns duration were incident on the sample with a focal spot diameter of 0.8mm and a pulse density of 36pulses/mm^2. It is evident that LPwC remarkably improves the residual stress from tensile to compressive and has an advantage over shot peening in terms of the affected depth.

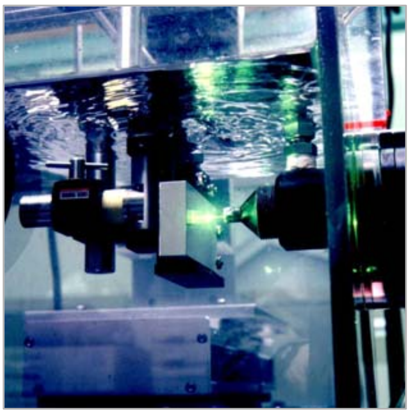

Fig.2 Experiment of laser peening without coating (LPwC)

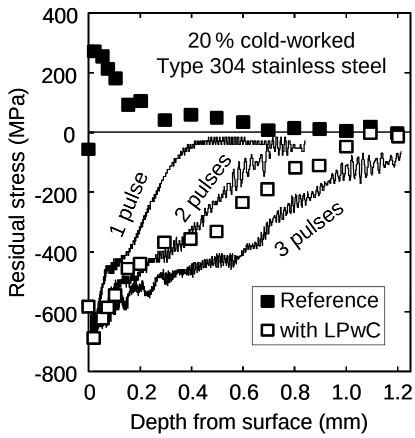

Fig.3 Residual stress depth profiles of SUS304 with/without LPwC

PREVENTION OF STRESS CORROSION CRACKING

Experimental procedure and results

The effect of LPwC on stress corrosion cracking (SCC) susceptibility was evaluated through creviced bent beam (CBB) type accelerating SCC testing (Obata, 1999). Samples with a thickness of 2mm were prepared from an SUS304 plate subjected to thermal sensitization (893K, 8.64×10^4s) followed by 20% cold working. Each sample was bent to produce uniform tensile strain of 1% on the surface with a curved holder, and peened by laser. A crevice was made on the sample surface using graphite wool to accelerate environmental SCC. The samples were immersed in high-temperature water (561K) with dissolved oxygen of 8ppm and the conductivity of 10^{-4}S/m for 1.8×10^6s using an autoclave.

After the immersion, 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.

SCC occurred in every sample without LPwC, whereas there were no cracks in samples with LPwC, as shown in **Fig.4**. The effect of LPwC to prevent SCC was confirmed on austenitic stainless steel, nickel-based alloy and their weld metals, as well.

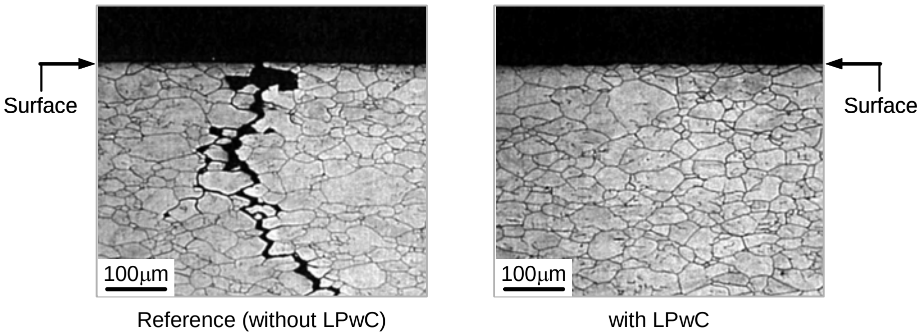

Fig.4 Stress corrosion cracking (SCC) test results of SUS304

Application to nuclear power plants

The concept for applying LPwC to a core shroud of boiling water reactors (BWRs) is illustrated in **Fig.5** (Mukai, 2005). The LPwC system is composed of laser oscillators, a beam delivery system, a laser irradiation head, remote handling equipment and a monitor/control system. **Figure 6** shows an example of the application to the inside wall of small diameter nozzles in pressurized water reactors (PWRs) (Yoda, 2006).

A fiber delivery system of laser pulses was developed to access complicated objects in narrow space, which extended the applicability of LPwC (Yoda, 2000). The intense laser pulse causes damage on the coupling surface of optical fiber and, if not, the incoming laser pulse tends to focus and leads to damage in the optical fiber due to the non-linear effect of refractive index. To cope with this issue, the authors introduced a novel input 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. Thus, the stable delivery of laser pulses with peak power of 20MW (pulse energy of 100mJ and pulse duration of 5ns) was attained with a single optical fiber. This enables us to use the fiber-delivered LPwC system, which drastically improved the accessibility to more complicated objects together with a miniaturized irradiation head.

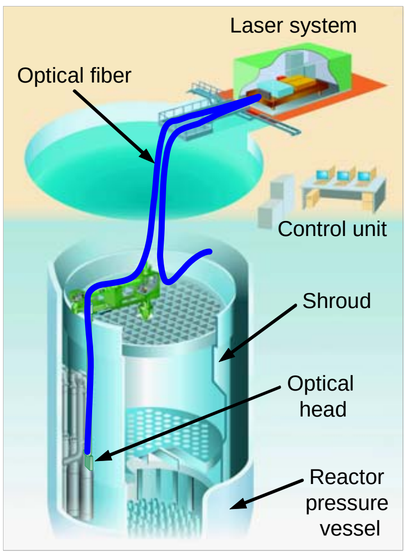

Fig.5 Laser peening system for preventive maintenance of BWR core shroud

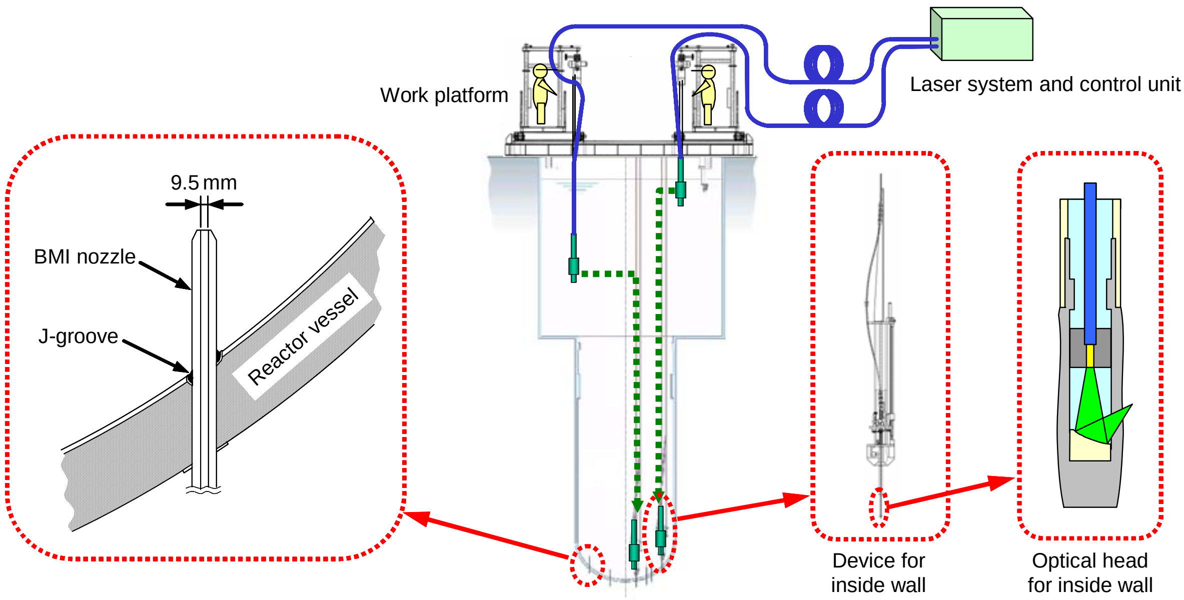

Fig.6 Application to inside wall of small diameter nozzles in PWR

EFFECT ON FATIGUE PROPERTY

Experimental procedure and results

The effect of LPwC on high-cycle fatigue properties was examined. Samples of low carbon type austenitic stainless steel (SUS316L) were prepared for fatigue testing. Before testing, two types of heat treatments are applied; one is full heat treatment (FH; 1373K, 3600s in vacuum) and another is stress relieving (SR; 1173K, 3600s). High-cycle fatigue tests by rotating bending with a frequency of 47Hz (2820rpm) were carried out. The samples were cooled by circulating distilled water during loading. **Figure 7** shows the results (Ochi, 2004). The fatigue strength of FH and SR material with LPwC were 300MPa and 340MPa at 10^8 cycles, respectively, which were 1.7 and 1.4 times as great as that of the materials without LPwC. Fatigue testing was also made for SUS304, aluminum alloys (Masaki, 2007), titanium alloys (Altenberger, 2006), etc. and showed that LPwC significantly enhanced the fatigue strengths of the materials.

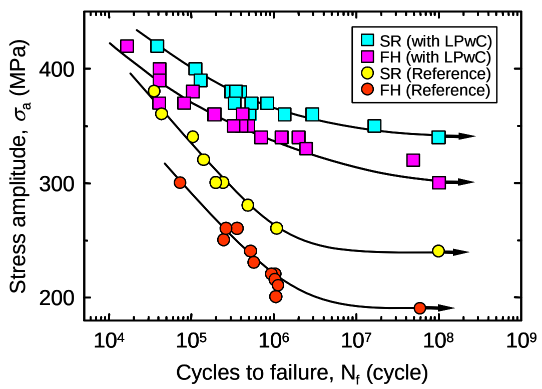

Fig.7 Fatigue test results of SUS316L with and without LPwC

Application to aeronautical and automotive parts

Applicability of LPwC to aeronautical and automotive components has been studied. Coupon tests for 7000 series aluminum alloys showed significant effects of LPwC prolonging the fatigue lives (Adachi, 2008). The effects were more prominent for stress-concentrating area such as fastener holes. Realistic testing with a mockup of a dynamic component of rotorcrafts showed that LPwC had an effect to increase the fatigue life. Rough estimation indicated that the overall cost would be reduced by implementing LPwC, which could extend the lifetime of the components.

LPwC to motor rotors of hybrid electric vehicles (HEV) and fuel cell vehicles (FCV) was studied to reinforce electrical steel sheets in rotors (Shimada, 2006). A rotor with LPwC withstood a higher centrifugal force of faster revolution.

CONCLUDING REMARKS

The process, effect and application of laser peening without coating (LPwC) were reviewed. The experimental results clearly show that LPwC prevents stress corrosion cracking (SCC) and prolongs fatigue lives due to the impartment of compressive residual stress on material surface. Featuring the characteristics of LPwC, such as the simpler process, better accessibility and deeper effect, it will necessarily extend the territory in many industrial fields in future.

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