CAAP Quarterly Report

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Project Title: Laser peening for preventing pipe corrosion and failure

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Contact Information: Yongfeng Lu
Lott Distinguished Professor
Department of Electrical and Computer Engineering,
University of Nebraska-Lincoln,
209N Walter Scott Engineering Center,
Lincoln, NE 68588-0511
Phone: (402) 472-8323
E-mail: ylu2@unl.edu

For quarterly period ending: March 31, 2016

Business and Activity Section

(a) Status Update of Past Quarter Activities

1. Major goal of the project

The ultimate goal of this project is to investigate and develop laser peening of stainless and carbon steels used for pipeline construction to improve their corrosion resistance. The corrosion resistance of pipelines will be enhanced via the compressive residual stress created by laser-induced shock waves during laser peening. It is anticipated that using laser shock peening in the construction of a pipeline will highly improve the reliability, safety, and life span of the nation's pipeline transportation system. As stated in our proposal, the major goals of this project will be

achieved by organizing the project into four phases, each with specific objectives. Table 1 summarizes the current progress of each phase and its objectives during this reporting period.

Table 1. The completion rate for the objectives of each phase of the project.

Phases	Major Goals and Milestones	Starting Date (mm/dd/yy)	Ending Date (mm/dd/yy)	Completion Rate (%)
Phase 1	1) Develop experimental setup for laser cleaning.	10/01/2014	12/31/2014	100
	2) Establish cleaning mechanism and parameter windows.	01/01/2015	09/30/2016	70
	3) Develop real-time monitoring of cleaning process.	01/01/2015	09/30/2016	0
Phase 2	1) Develop laser peening system.	10/01/2014	12/31/2014	100
	2) Establish parameter windows for laser peening.	01/01/2015	09/30/2016	80
Phase 3	1) Study surface morphology of the laser-peened surfaces.	01/01/2015	09/30/2016	70
	2) Determine residual stress of pipeline steels after laser cleaning and peening.	01/01/2015	09/30/2016	80
	3) Study corrosion resistance of laser-peened surface.	01/01/2015	09/30/2016	40
Phase 4	Design a laser peening prototype system.	06/30/2016	09/30/2016	20

2. Specific objectives during this reporting period

During this reporting period (January 1, 2016, to March 31, 2016), the single spot and large area Nd:YAG laser peening experiments were performed using carbon steel samples and optimized for better peening effect. The samples were examined using surface morphology and residual stress measurement of the carbon steel surface. In addition, laser cleaning experiments were carried out using a pulsed Nd:YAG laser. The objectives are as follows:

(1) Parameter optimization of Nd:YAG laser peening.

(2) Surface morphology and residual stress measurement of the carbon steel.

(3) Laser cleaning experiments with a Nd:YAG laser to remove mixed paint, black tape, and resin.

3. *Significant results*

3.1. Experimental setup and procedure

3.1.1. Material preparation

During this reporting period, the samples tested were prepared from 1018 carbon steel (CS) and 5456 aluminum-magnesium (Al-Mg) alloy plates, which were cut into rectangular shapes with dimensions of 2 in. × 2 in. × 0.25 in. (length × width × thickness). Prior to the laser surface peening (LSP) treatment, mechanical polishing was performed using sandpapers of different grades (400-1200 grit) to obtain mirror-like sample surfaces. In addition, the electrochemical polishing was conducted by immersing the carbon steel into a specific polishing solution (ethanol solution with 10% perchloric acid ($HClO_4$)) and positively biased at 25 V for a certain time. The polishing was followed by ultrasonic cleaning, first with acetone and then deionized water, to degrease the sample surface. All samples were prepared shortly before the LSP/laser cleaning experiments.

3.1.2. Nd:YAG laser peening setup and procedure

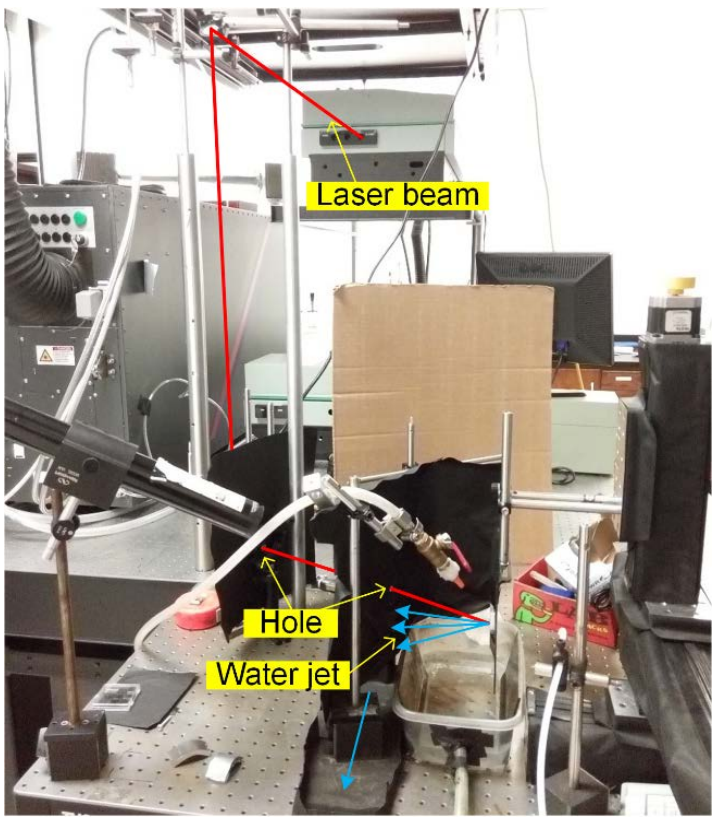

Fig. 1. Nd:YAG laser peening system.

With the incident Nd:YAG laser beam emitted perpendicular to the sample surface, serious contamination to the optical systems occurs from the water jet and particles generated during the

laser peening process, which shields subsequent laser pulse energy. Therefore, the optical setup was modified for higher effectiveness and convenience (Fig. 1). By introducing a small tilt angle to irradiate the laser beam and adding two fenders with small holes, contaminant particles and water jet spray were prevented from reaching the reflective mirrors, which were both generated during the laser peening process. This eliminated the need for protective glass and compressed air, thereby reducing the loss of laser energy and increasing/stabilizing the laser peening effect, which is also beneficial for compact laser peening system design. In addition, the laser repetition rate was reduced to 5 Hz to avoid the incident laser from being seriously disturbed by the water spray induced by previous laser impact. Moreover, the sacrificial layer for the Nd:YAG laser peening process was decreased to 100 μm of black tape to reduce the shock wave attenuation in the sacrificial layer and enhance the peening effect. The detailed parameters of the laser/confining layer/sacrificial layer are shown in Table 2. The sample position was carefully optimized by comparing morphology changes on the carbon steel sample surface after laser peening. Surface residual stress measurements were conducted by X-ray diffraction (XRD) equipment.

Table 2. Processing parameters used in the LSP experiment.

Laser system	Continuum Nd:YAG PR II 8010 laser; Wavelength: 1064 nm; Pulse energy: 850 mJ; Pulse duration: 6-8 ns; Frequency: 1-10 Hz; Beam size: ~1 mm
Confining layer	Water jet with layer thickness of approximately 1 mm
Sacrificial coating	Black tape (~100 μm)

3.1.3. Nd:YAG laser cleaning setup and procedure

The Nd:YAG laser cleaning system was set up using a Continuum Q-switched Nd:YAG PR II 8010 laser (the same one used for the Nd:YAG laser peening experiments described in Table 2). The laser was directed to the contaminated sample surface by specifically coated mirrors. No lens was used to clean off the mixed paint; and the original spot diameter was 12 mm. A 500 mm focusing lens was used to focus the spot size to ~4 mm and ~1.5 mm to remove the black tape and transparent resin, respectively. A 3D linear stage was used to move the samples for laser scanning on the sample surface. After laser cleaning, the sample surface was examined by 3D profile meter. The sample selected for fiber laser cleaning experiments was an Al-Mg alloy plate.

3.1.4. Characterization methods

A 3D profile meter (New View 8000, Zygo Corporation) was used to characterize the sample morphologies after laser peening to optimize the single spot and large area laser peening

parameters. Surface residual stress measurements were conducted by XRD equipment (Smartlab, Rigaku) with copper (Cu) as the anode target and a monochromator for signal acquirement.

3.2. Results and discussion

3.2.1. Nd:YAG laser peening experiments with low carbon steel

Our previous laser peening experiments proved the applicability of using a pulsed Nd:YAG laser to improve the anticorrosion property of pipeline steels, including stainless steel and carbon steel, in which laser-peening-induced compressive residual stress was investigated and considered to be the most important factor in preventing stress corrosion cracking. During this reporting period, single spot and large-area laser peening parameters were further optimized specifically with low carbon steel to achieve higher residual stress.

As shown in Fig. 2, the laser peening dent depth was measured on the 1018 carbon steel surface after Nd:YAG laser peening at different sample positions. Five repeated spots were measured and averaged for each sample position. The zero point was an arbitrary position. One laser impact with a pulse energy of 850 mJ was used with 100 µm of black tape as a sacrificial layer. As we can see, the single spot dent depth varied from 3.5 to 5.4 µm, while the second-order fit curve peaked at the -10 mm sample position. The dent depth on low carbon steel samples increased compared to previous results (~3 µm).

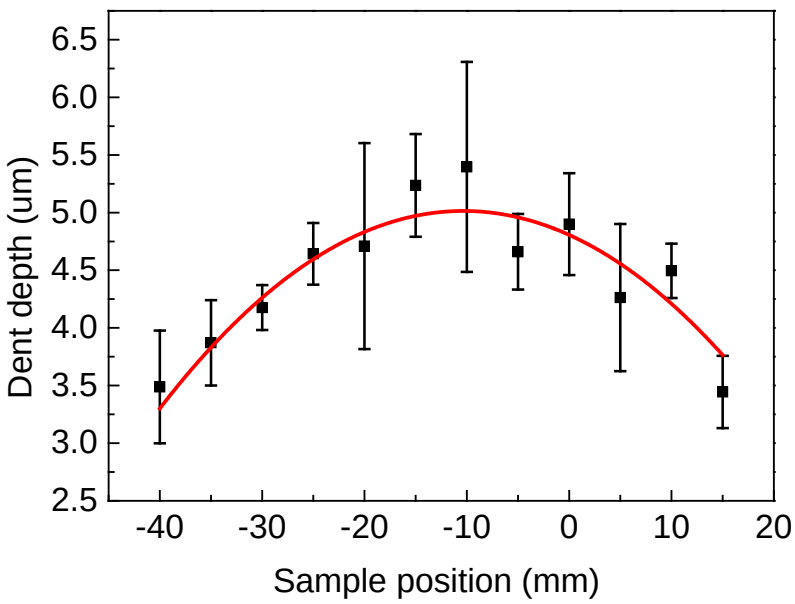

Fig. 2. The dent depth on 1018 carbon steel surfaces after laser peening at different sample positions.

For the large-area laser shock peening, two sample positions were selected: 0 and -10 mm. Two of the 1018 carbon steel samples were processed successively by: 1) mechanical polishing, 2) electrochemical polishing, and 3) laser shock peening at 0 and -10 mm, respectively. After each

step, the residual stress on the processed surface was measured by X-ray diffraction. The aim of the mechanical polishing was to decrease the surface roughness for an accurate XRD test. After that, the residual stress introduced by both the manufacturer and the mechanical polishing could be removed by electrochemical polishing to generate a surface without stress or with tensile stress. After E-polishing, the influence of the laser peening could be easily observed. The laser shock peening parameters were: 850 mJ, 5 Hz, 1 impact, 50% overlap, and 100 µm of black tape as the sacrificial layer.

The residual stress of the sample peened at the -10 mm sample position is shown in Fig. 3. After mechanical polishing, the residual stress was -907 MPa due to the surface compression and deformation layer. The electrochemical polishing that followed removed the thin layer of deformation and changed the residual stress to tensile: 218 MPa. On the tensile surface, laser peening impacted the sample surface and changed the residual stress back to -206 MPa. Fig. 4 shows the residual stress of the sample peened at the 0 mm sample position. After mechanical polishing, the residual stress was -744 MPa. The electrochemical polishing that followed changed the residual stress to 46 MPa. After that, laser peening processed the sample surface and changed the residual stress back to -517 MPa. Obviously, large area laser peening has a better peening effect at the sample position of 0 mm, which caused the larger residual stress on the carbon steel surface. The low residual stress at -10 mm of -207 MPa was mainly attributed to the large tensile stress before laser peening. It also indicated that the best dent depth may not result in the largest residual stress, which may be due to the spot size change and the spot-to-spot interaction. According to our last report, the in-depth residual stress should also extend to depth, which will be examined later.

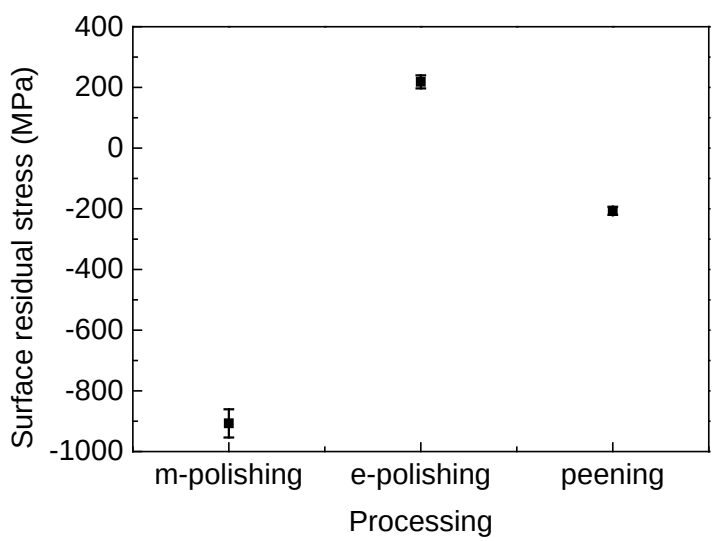

Fig. 3. Surface residual stress of 1018 carbon steel after successive mechanical polishing, electrochemical polishing, and Nd:YAG laser peening (850 mJ, 1 time, 50% overlap, -10 mm sample position, 100 µm of black tape).

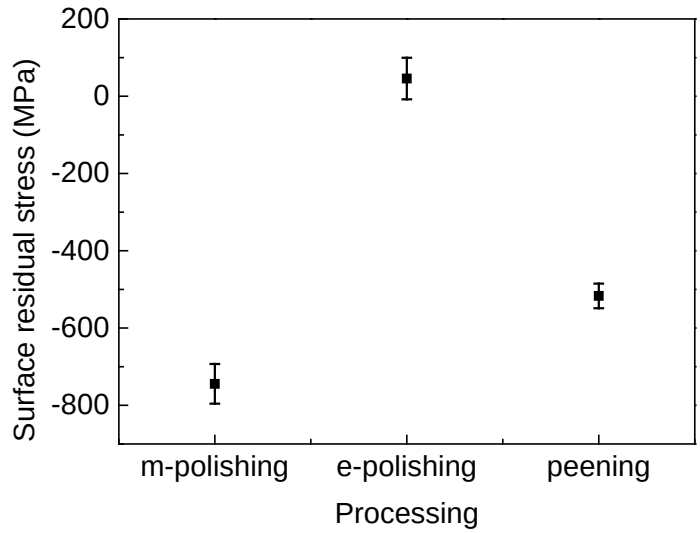

Fig. 4. Surface residual stress of 1018 carbon steel after successive mechanical polishing, electrochemical polishing, and Nd:YAG laser peening (850 mJ, 1 time, 50% overlap, 0 mm position, 100 μm of black tape).

3.2.2. Nd:YAG laser cleaning experiments

During this period, the laser cleaning experiments were implemented using a Nd:YAG laser. Three different kinds of contamination layers were used: 1) mixed coatings (mixture of rubber, paint, and high-temperature-resistant coating), 2) black tape, and 3) transparent resin.

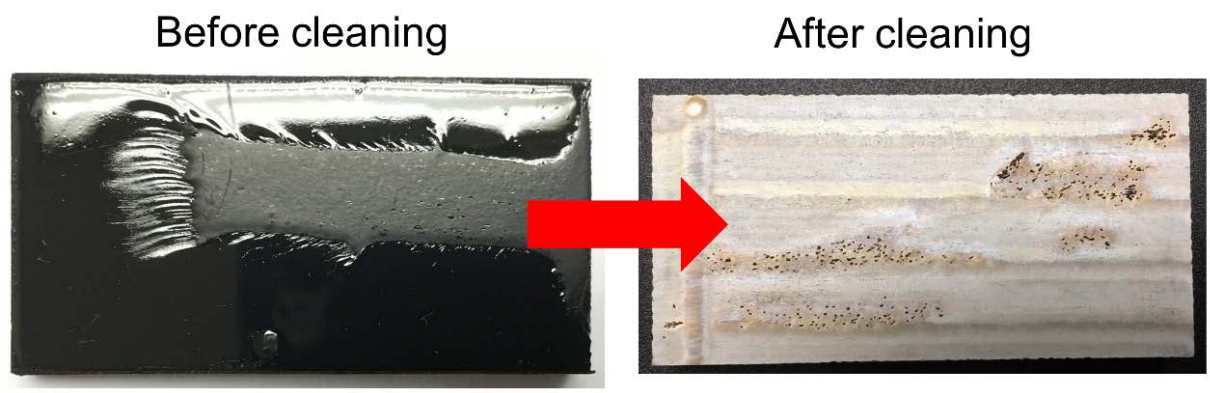

Fig. 5. Nd:YAG laser cleaning of mixed coating (mixture of rubber, paint, and high-temperature-resistant coating, uneven, 50~100 μm thickness; 850 mJ laser energy, 6~8 ns, 12 mm spot size, 10 Hz, 5 mm/s).

As shown in Fig. 5, after laser scanning once without focusing (850 mJ laser energy, 6~8 ns,12 mm spot size, 10 Hz, 5 mm/s), most of the paint was removed. Some residuals were observed at places with thick coatings before laser cleaning, which could be removed by increasing the laser scanning times. Surface morphology was measured on the surface before/after laser cleaning (Fig. 6.) and showed unchanged or even decreased surface roughness, indicating the Al alloy surface was not damaged. The decrease in surface roughness might have been caused by the removal of the original surface contamination on the sample surface. The mechanism for this

type of laser cleaning should be rapid burning of the contamination material due to the fast energy input by the pulsed laser.

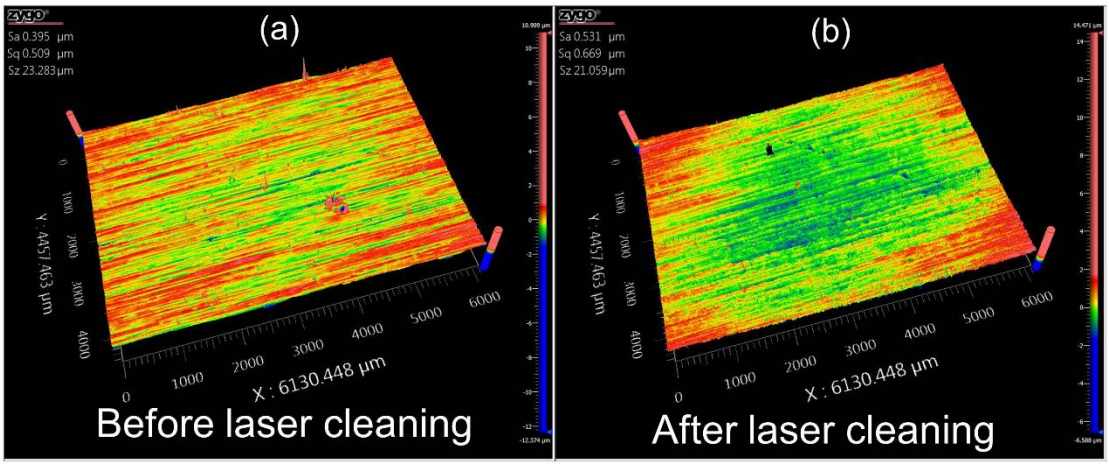

Fig. 6. The Al-Mg alloy surface morphology before/after Nd:YAG laser cleaning (mixed paint).

As shown in Fig. 7, after laser scanning once with a 500 mm focusing lens (850 mJ laser energy, 6~8 ns, 4 mm spot size, 10 Hz, 5 mm/s), the black tape was removed along the scanning line. Some color change was observed after scanning the sample surface. In addition, the surface morphology after laser cleaning (Fig. 8.) showed increased roughness of approximately 2 µm, indicating slight ablation damage on the Al-Mg alloy surface, which may also be acceptable. The mechanism of this type of laser cleaning might also be induced by rapid burning and ablation.

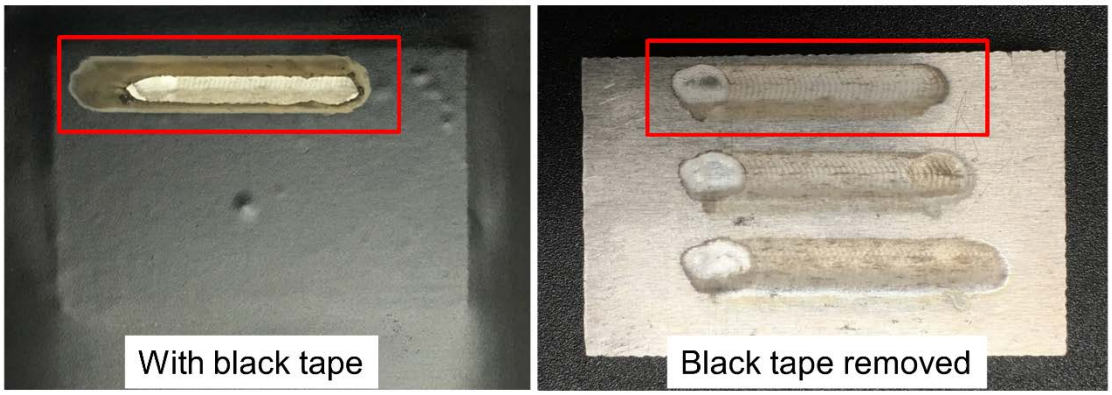

Fig. 7. Nd:YAG laser cleaning of black tape (100 µm thickness; 850 mJ laser energy, 6~8 ns, 4 mm spot size, 10 Hz, 5 mm/s).

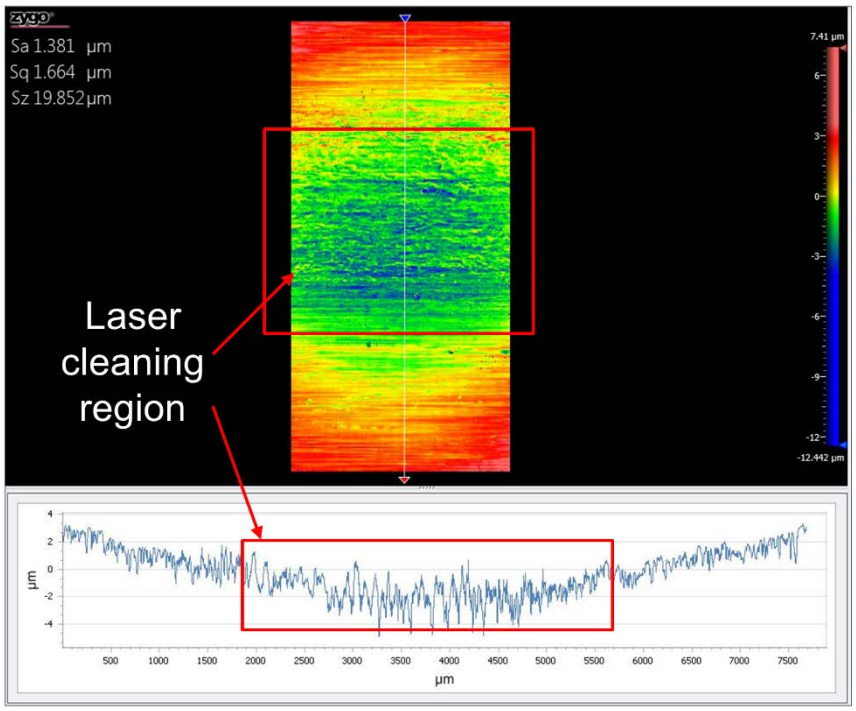

Fig. 8. The Al-Mg alloy surface morphology before/after Nd:YAG laser cleaning (black tape).

After laser cleaning once with a 500 mm focusing lens (850 mJ laser energy, 6~8 ns, 10 Hz, 1.5 mm spot size), as shown in Fig. 9, the ~2 mm transparent resin was removed completely if the spot-to-spot distance was 2.5 mm (red dashed rectangle). According to the shape of the resin after single point cleaning (yellow dashed rectangle), the cleaning mechanism for resin removal should be different from that in the previous experiments, which was laser ablation and material burn. Since the resin was transparent, the laser went through it and ablated the sample surface to generate plasma, which expanded rapidly, crushed the resin into pieces, and detached it from the sample surface. In this process, shock wave may also have played an important role. The surface morphology after laser cleaning (Fig. 10) showed clear dents and increased roughness, of approximately 10 µm, which might have been induced mainly by the laser-induced shock wave (laser peening process).

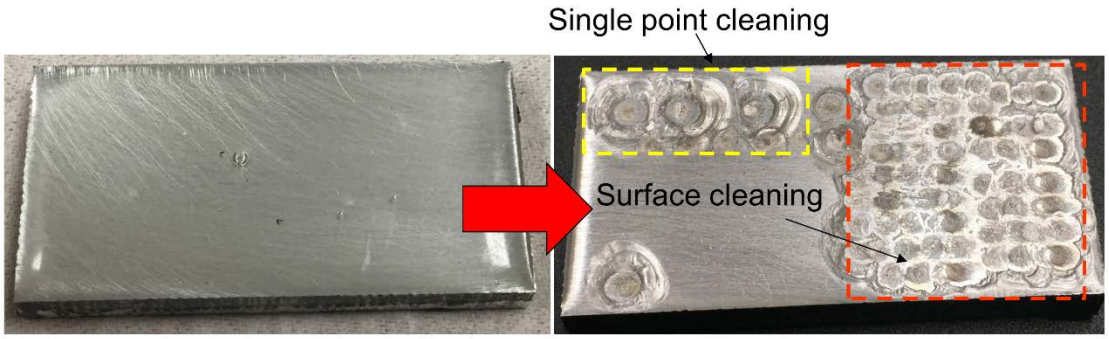

Fig. 9. Nd:YAG laser cleaning of transparent resin (~2 mm thickness; 850 mJ laser energy, 6~8 ns, 10 Hz, 1.5 mm spot size).

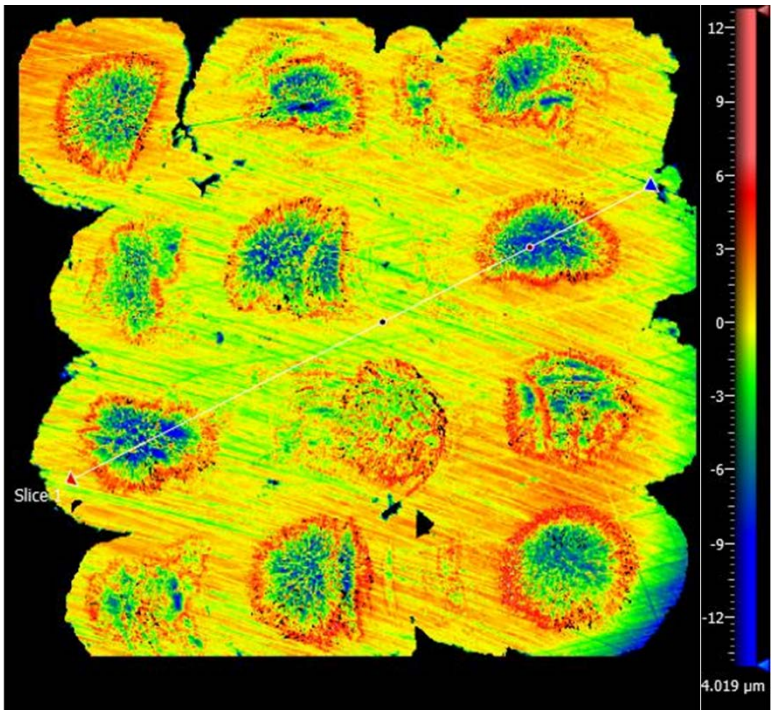

Fig. 10. The Al-Mg alloy surface morphology before/after Nd:YAG laser cleaning (transparent resin).

The Nd:YAG laser cleaning experiments showed not only the ability to remove colored paint/polymer tape but also solidified transparent resin, while the same laser could also be used for laser peening surface enhancement. Therefore, the laser peening and cleaning could be integrated into one piece of equipment.

4. Key outcomes

During this reporting period, the Nd:YAG laser peening was optimized by a single spot/large area experiment and examined by surface morphology and residual stress. Laser cleaning experiments were performed by Nd:YAG laser to remove different types of contamination layers. Some important conclusions are summarized as follows:

(1) Single spot laser peening experiments showed that the deepest dent was obtained at the sample position of -10 mm. However, large area laser peening indicated that the largest surface residual stress was obtained at a sample position of 0 mm with a lower single spot dent depth, where -517 MPa surface residual stress could be obtained from a tensile surface of 45 MPa residual stress.

(2) Nd:YAG laser cleaning experiments were also carried out. The paint was removed by using an unfocused laser beam (12 mm diameter), without damaging the Al-Mg alloy surface. The black tape was removed by using a focused laser beam (4 mm diameter), resulting in slight surface damage of ~2 µm. The

transparent resin was removed by focused laser beam (1.5 mm diameter) due to laser-induced plasma expansion and shock wave impact, which caused an increase in dents and roughness on the Al-Mg alloy surface.

(b) Description of Any Problems/Challenges

No problems were experienced during this reporting period.

(c) Planned Activities for the Next Quarter

The specifically planned objectives and activities to be accomplished during the next period (April 1, 2016 to June 31, 2016) are listed as follows.

Table 3. The planned objectives and activities in the next quarter.

Objectives	Activities
(a) Final optimization of the laser peening process.	(1) Selection of portable Nd:YAG laser, optical fiber, and relevant accessories. (2) Experimental comparison of laser peening using an optical fiber/metal tube to deliver the laser. (3) Optimization of Nd:YAG laser peening parameters for industrial application.
(b) Final verification of peening effects using a portable Nd:YAG laser.	(1) Residual stress measurement of laser-peened stainless and carbon steel on the surface and along the depth. (2) Verification of the corrosion resistance of laser-peened stainless steel and carbon steel. (3) Further investigation of the corrosion resistance mechanism of peened stainless and carbon steel using electron microscopy observation.
(c) Final optimization of the laser cleaning process.	(1) Laser cleaning experiment using portable Nd:YAG laser. (2) Further optimization of the laser cleaning process. (3) Portable laser cleaning head design and integration.