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Closed-Loop Laser Ablation for Navy Maintenance Applications

ABSTRACT

In recent years, laser ablation has emerged as a practical alternative solution for many types of shipyard surface preparation applications. The development of reliable, solid state lasers with closed-loop beam delivery systems enables the use of laser energy for selective and controlled removal of corrosion products and coating materials without damage to the underlying substrate material. The energy absorption characteristics of metal-oxide compounds make the laser exceptionally effective in removing corrosion products such as rust. When operated with appropriate process parameters, the laser “photoablation” (photon-induced ablation) process converts coating materials and corrosion products into gaseous-phase and particulate waste that is readily captured and sequestered in a vacuum/filtration system.

The operating characteristics of the laser make it suitable for a wide range of shipyard maintenance applications, including coating removal, corrosion product removal, surface preparation for coatings application, and surface preparation for nondestructive inspection (NDI). Closed-loop laser technology has demonstrated significant improvements in productivity and environmental process metrics versus the conventional surface preparation techniques currently employed in Navy maintenance applications. This paper discusses the fundamentals of closed-loop laser technology and its potential cost benefits for Navy shipyard applications.

INTRODUCTION

The operational environment of Navy ships and submarines inherently requires substantial attention to programmed maintenance and corrosion prevention during the life of a vessel. Shipyard maintenance and overhaul cycles typically entail extensive use of labor-intensive corrosion removal and surface preparation processes in order to recondition the surfaces of the ship structure and to facilitate the refurbishment of preservation coatings. These surface preparation processes represent a significant element in the total cost of ship maintenance and overhaul.

Current surface preparation processes employing chemical stripping, blast media and high-pressure water techniques generate large waste streams that entail nonrecurring shipyard/drydock site preparation costs for waste containment as well as recurring waste management costs for collection and disposal. In many cases, the total waste stream generated by conventional blast processes is approximately four to over one-hundred times the mass of the actual corrosion products or coating materials that are removed from the ship structure¹.

Another important limitation of these processes is that they are difficult to perform inside of tanks, bilge spaces, and confined interior compartments. Visibility constraints, personnel exposure to waste products, process quality metrics, and waste disposal are fundamental issues attendant to the use of blast processes in confined shipboard spaces. In many cases, the use of blast processes is significantly constrained because of the potential to contaminate critical shipboard machinery with the waste stream from the process.

The development of laser systems designed for surface preparation and surface modification applications emerged in the early 1990s. In contrast to continuous-wave (CW) industrial laser systems that are designed for metal cutting and welding operations, surface preparation systems primarily rely on a pulsed-laser

architecture. Pulsed lasers more readily achieve accurate control of the spatial distribution of laser energy on the target substrate surface than CW types. In any case, repeatable control of laser energy spatial distribution is required in order to avoid unintended heating effects and degradation of the mechanical properties of the substrate material.

TECHNICAL DISCUSSION

Original research in laser ablation of paint coatings was performed by Katherine Liu and Elsa Garmire at the University of Southern California Center for Laser Studies in 1985². This research established the feasibility of removing graffiti from concrete material with a Q-switched Nd: YAG laser. This research also discovered the higher paint removal efficiency of the pulsed Nd: YAG laser system versus a CO₂ laser system operating in CW mode. The Liu and Garmire work also established important empirical relationships between laser pulse width, laser fluence (energy per unit area), and irradiance (power per unit area) versus paint removal efficiency.

Beginning in approximately the early 1990s, practical laser decoating systems were developed. These systems feature Q-switched Nd: YAG lasers, CO₂ lasers operated in CW mode, pulsed CO₂ lasers, and more recently, fiber lasers. The figure below maps a number of the various laser systems against pulse width and peak irradiance parameters. Note that there are regimes of performance that correspond to paint charring and plasma generation effects. In between these extremes there is a regime that corresponds to “ablation” (photoablation) where the laser parameters are balanced in order to achieve efficient coating removal while minimizing undesirable heating effects.

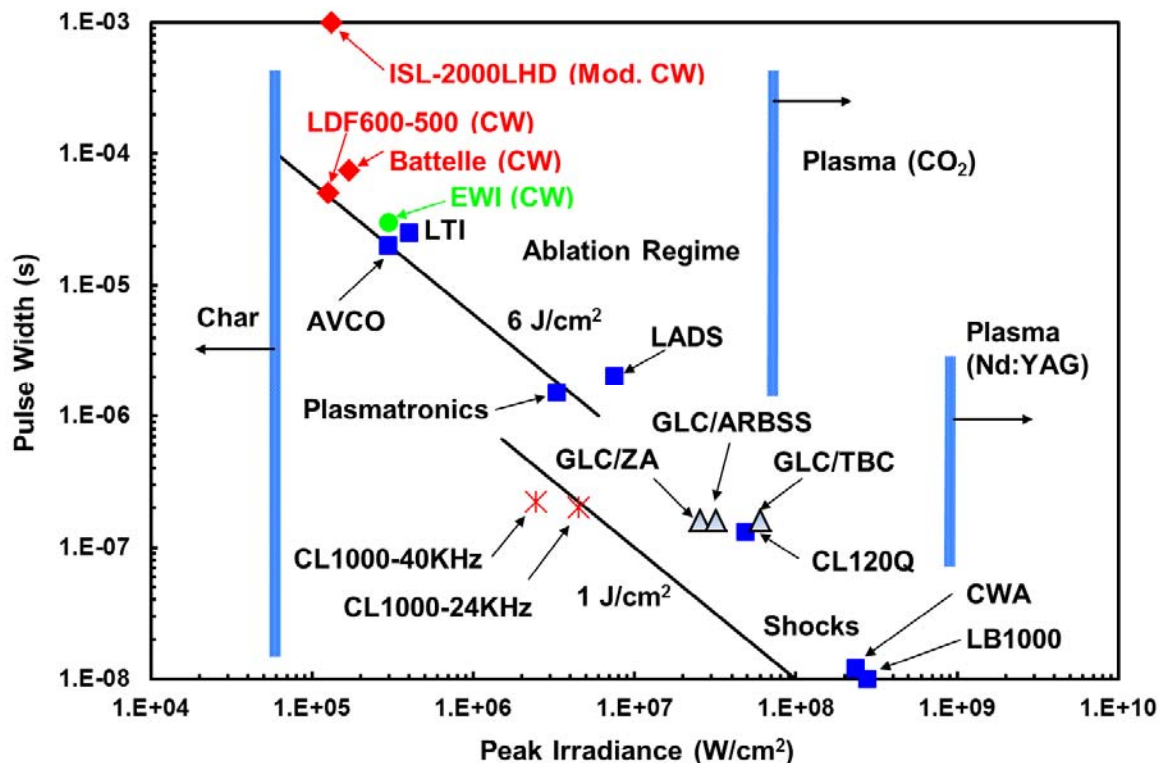


FIGURE 1 Various pulse widths and peak irradiance values for laser paint stripping applications. Source: Stan Ream, the Edison Welding Institute; (several data points added by author)

Efficient removal of paint coatings requires a proper balance of laser parameters, including pulse width, peak irradiance, and fluence. The diagonal black lines depict pulse width and irradiance parameters that produce constant fluence values of 1 and 6 J/cm², respectively. These fluence values are representative of

laser parameters that have been employed in a number of laser coating removal applications. The key is to produce a sufficiently short but intense laser pulse that “photoablates” (vaporizes) the paint coating so rapidly that significant heat conduction into the substrate is avoided. In this manner, a hemispherical high-velocity flux of gas-phase material combined with approximately a 30 – 50% mass fraction of hydrocarbon molecules and particulates is ejected from the laser-illuminated spot on the target substrate. Some studies have measured the ejection velocities of such mass flux from polymer materials as greater than 1500 m/s, even at threshold fluence values³. The figure below is a schematic depiction of the photoablation process.

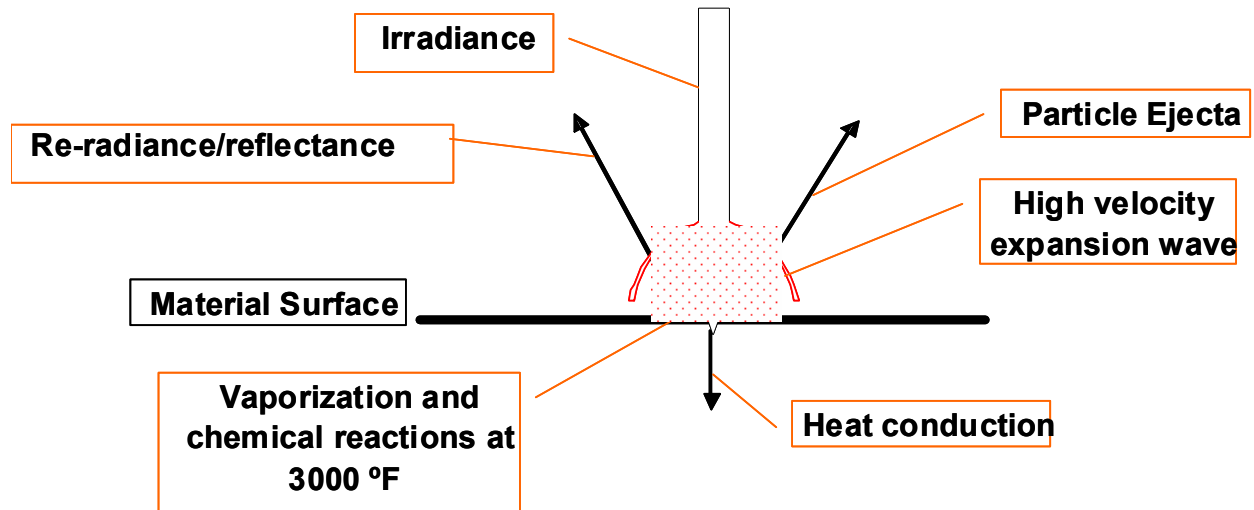


FIGURE 2 Schematic representation of the photoablation process.

When the laser parameters are properly balanced, the rapidly expanding mass flux carries most of the laser energy away from the target substrate, thereby avoiding undesirable heat input that could degrade critical mechanical properties. When laser parameters are not correctly balanced, undesirable heating effects occur, including paint charring, substrate melting, substrate metallurgical transformations, and changes in substrate mechanical properties, including hardness, ductility, fracture toughness, and fatigue properties.

Some of these deleterious effects have been observed in recent laser coating removal studies employing open-loop laser systems with high strength low alloy (HSLA) steel alloys for Navy ship hull and machinery applications. Open-loop laser systems typically rely on galvanometer (“galvo”) scanning devices to raster the laser beam back and forth as the scanner is translated over the target substrate. The spatial distribution of laser energy on the substrate is thus controlled by the laser output parameters, the galvo scan parameters, and the manual translation of the laser scanning device. Open-loop laser systems, particularly when configured with hand-held laser scanning tools, are typically less capable of generating a closely controlled and repeatable distribution of laser energy on the substrate surface than closed-loop laser systems.

A key element in laser system design for surface preparation has been the development of target-point, closed-loop control technology. The basis of closed-loop control technology involves an active, real-time optical feedback loop that modulates the pulsed laser firing based on the optical signature of the target point on the substrate surface where the laser is aimed. The primary characteristic of the optical signature that is extracted from the feedback loop can include color and/or other parameters that are relevant to a specific laser application. This active feedback loop acts to divide the substrate surface into a series of optical “pixels” that correspond to the instantaneous aim point of the laser system during operation. These “pixels” correspond to the millimeter-sized spot that is illuminated on the substrate surface by each individual laser pulse emitted from the scanning tool optics.

For true closed-loop control, this optical feedback loop and the associated modulation of laser firing must function at the pulse repetition rate of the laser. Typically, the laser pulse repetition rate for coating removal applications is in the range of 5 – 50 kHz (5,000 to 50,000 pulses per second). Under active, closed-loop control, the Q-switched laser essentially fires “on condition”, based on the optical signature of the laser aim point on the target substrate surface. This process enables a highly controlled photoablation process that automatically compensates for the coating thickness variations and other differences in surface condition that are always present under real-world shipyard conditions.

As shown in Figure 3, below, the level of control achieved by the closed-loop laser system enables the removal of individual coating layers on a substrate. In this case, the “Marine One” finish paint is removed from a VH-71 (Presidential helicopter) airframe sample while leaving the zinc chromate primer layer intact. This sample shows two types of laser scan patterns that can be employed: 1.) the X-Y raster pattern on the left that is employed with robotic applications, and; 2.) the rotary scan pattern on the right that is employed with hand-held, closed-loop laser tools.

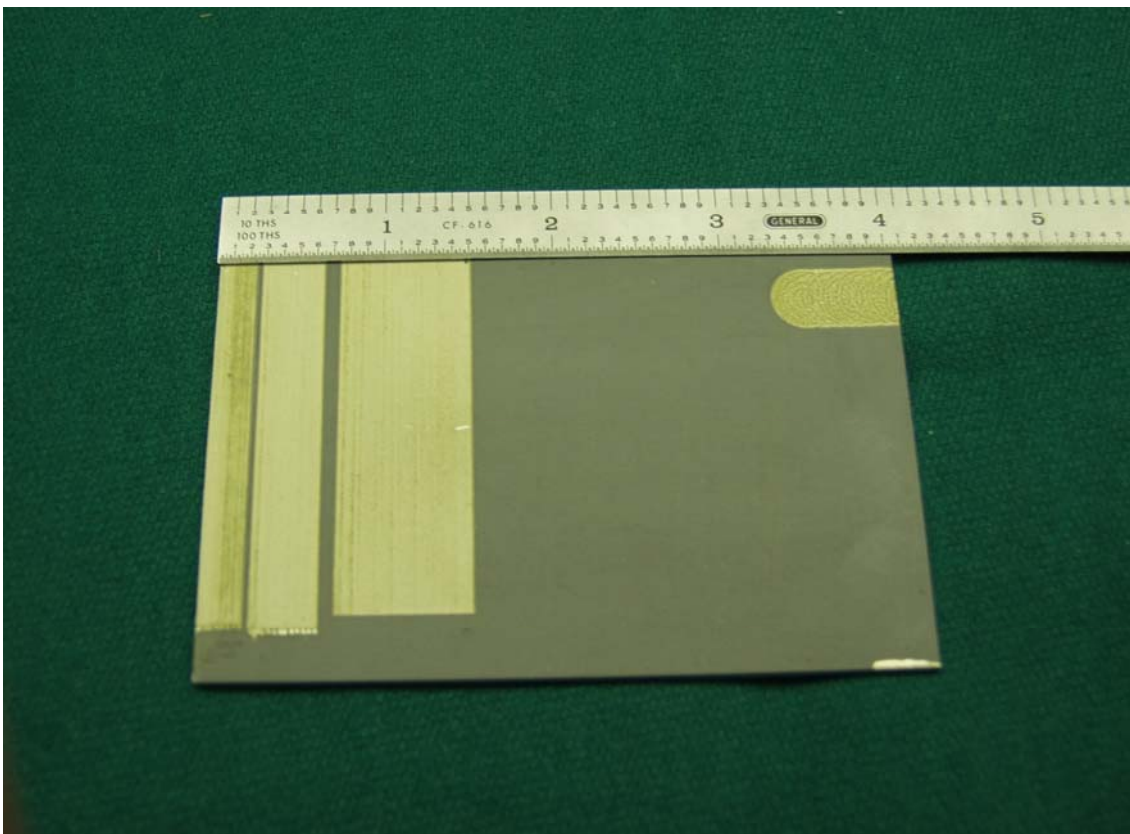


FIGURE 3 Test panel for VH-71 aircraft; note raster and rotary laser scan patterns.

The efficiency with which metal-oxide compounds absorb near-infrared (1064 nm) laser energy enables very effective stripping of corrosion products from metal surfaces. The laser rapidly consumes rust, corrosion products, and passivation layers that are produced in all of the significant metal alloy systems including steel, aluminum, titanium, and magnesium types.

In a shipyard environment, this means that a single laser tool operating with a single set of process parameters can switch between different surface preparation applications without being reconfigured. The

figure below shows the effect of laser scanning on a heavily rusted and pitted steel plate (note the high reflectance in the laser-stripped area produced by clean, oxide-free facets in the metal surface).

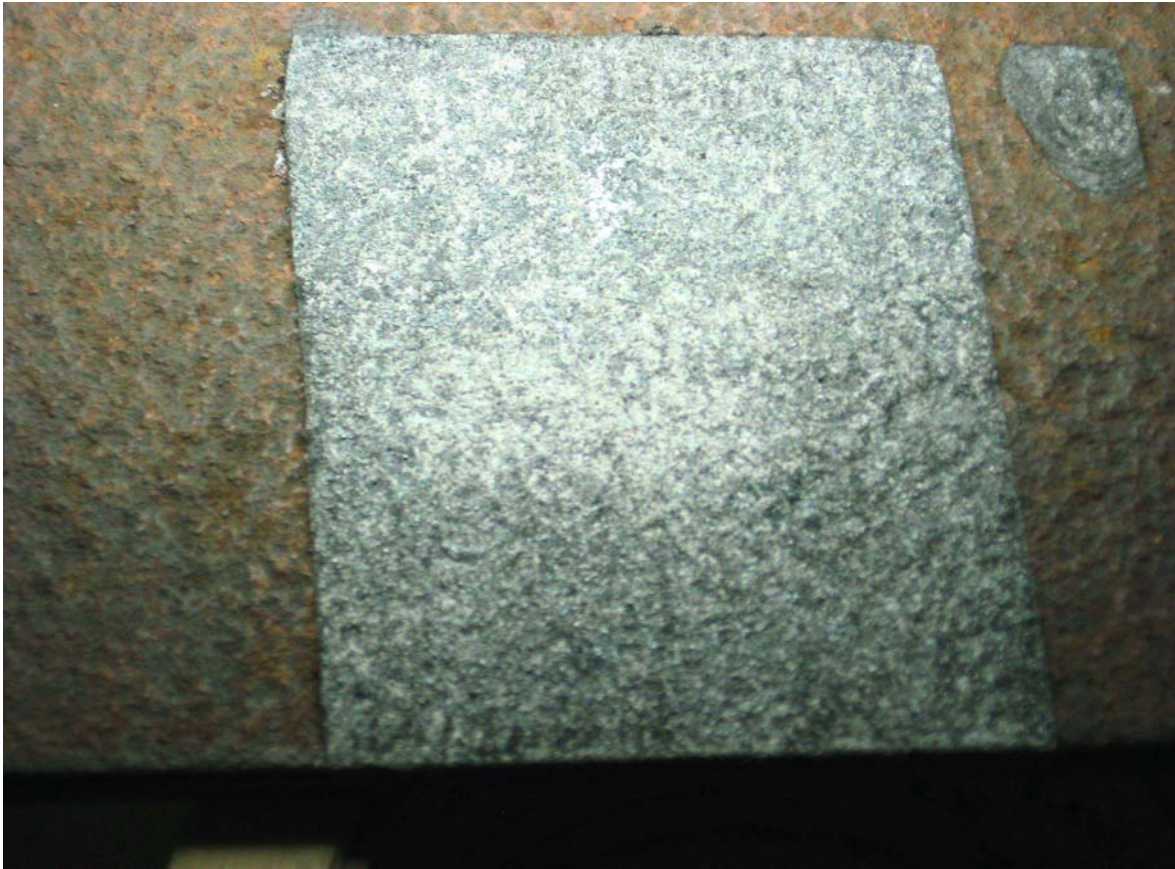


FIGURE 4 Laser removal of rust from a heavily rusted and pitted steel plate.

In a similar manner, the laser is also efficiently absorbed in organic coating materials including primer and paint coatings as well as the new high-solids coating materials and high-metal-content coatings. For organic coating materials there is an empirical relationship between the area of the coating removed (ft²), coating thickness (mils), average laser power delivered to the substrate surface (kW), and time (min):

$$\text{Coating removal rate} = \frac{2 \cdot \text{ft}^2 \cdot \text{mils}}{\text{kW} \cdot \text{min}}$$

Experience with high-solids and metal-filled coating materials have shown that these types of second-phase materials typically do not absorb laser energy as readily as the organic binders in such coating systems. This effect actually tends to improve the efficiency of the laser ablation process. Experience with these types of special coatings has shown that the laser can efficiently ablate these types of coating materials without any significant loss in productivity.

Weld surface preparation for nondestructive inspection (NDI) or for the application of preservation coatings is another shipyard application for which the laser is very well suited. The textured surfaces of the

weld and notch details at the weld toe are easily and efficiently cleaned by the laser. The laser ablation process is not subject to the same limitations as mechanical surface preparation techniques.

In comparison to chemical stripping techniques, the laser is significantly faster with a far smaller waste stream. Chemical stripping of paint coatings is a lengthy process that often requires at least three days to completely prepare weld surfaces for NDI. This cycle time results from the requirement to iteratively apply and then remove the chemical stripping agent following a 12 - 24 hour soak, during which the chemical dissolves the paint. In contrast to this, the laser can strip the weld surfaces in minutes while achieving more than a one hundred-fold decrease in waste stream¹.

The laser represents an economical alternative to conventional media-blast processes from a waste management standpoint. A key technical attribute of the laser is that it converts a significant mass fraction of the coating material into gaseous species that do not contribute to the process waste stream. The following cost comparison with an example media-blast process shows that the total cost basis for the laser, incorporating waste management costs, compares favorably with the conventional process:

Ship's Hull Stripping Factors:

Surface area:	Area:	100,000 sq. ft.
Paint thickness:	Thickness:	20 mils
Paint waste weight:	.0073 lb/ft ² -mil	14,600 lb

Sand Blast

waste including media blast:	4.1 X Wt. of removed mat'l	Note 1	59,860 lb
Tons of waste generated:			29.93 tons
Tipping charges: Solid Waste:	\$475/ton	Note 3	\$ 14,217
RCRA Haulage Surcharges:	\$1000/2 ton load	Note 3	\$ 14,965
Waste Hauling & Insurance:	\$200/ton	Note 4	\$ 5,986
Total Disposal Costs:		Note 5	\$ 35,168
Total Cost/sq. ft.			\$ 0.35

Laser Ablation

waste using laser ablation:	0.5 X Wt. of removed mat'l	Note 2	7,300 lb
Tons of waste generated:			3.65 tons
Tipping charges: Solid Waste:	\$475/ton	Note 3	\$ 1,734
RCRA Haulage Surcharges:	\$1000/2 ton load	Note 3	\$ 1,825
Waste Hauling & Insurance:	\$200/ton	Note 4	\$ 730
Total Disposal Costs:		Note 5	\$ 4,289
Total Cost/sq. ft.			\$ 0.04

Note 1: Potential Alternative Report for the Portable Handheld Laser Small Area Supplemental Coating Removal System, Prepared for USAF by SAIC, Feb 2001

Note 2: Penn State Applied Research Laboratory, Automated Rotor Blade Stripping System (ARBSS) study for the USN, 2005

Note 3: Quote by Kleen Industrial, 6/30/2009, for disposal at Kettleman City, CA.

Note 4: Estimated cost to transport waste plus originator liability insurance charges

Note 5: Note that the total cost, \$1175 per ton, or \$0.59 per pound, is documented for California disposal; however, US Navy sources advise a similar total cost nationwide.

NAVY CLOSED-LOOP LASER APPLICATIONS

Since 2004, the Naval Air Systems Command has commissioned two closed-loop laser applications. The Automated Rotor Blade Stripping System (ARBSS), now operational at Fleet Readiness Center – East, Cherry Point, NC, is one such application. ARBSS is a robotic laser system that is designed to strip the finish coat of polyurethane paint from the main rotor blades of Sikorsky H-53 aircraft during depot-level overhaul. The H-53 is a heavy-lift helicopter and the rotor blades are approximately 40 feet long. ARBSS incorporates a triple-laser scanning head that is equipped with an integral waste extraction / HEPA filtration system. The system employs color-selective, closed-loop controls for each of the three lasers that are connected to the triple scanning head via fiber-optic umbilicals. An industrial robot moves the scanning head over the rotor blade surfaces in a tool path that is conditioned by an automatic three-dimensional laser scan of the rotor blade prior to laser stripping.

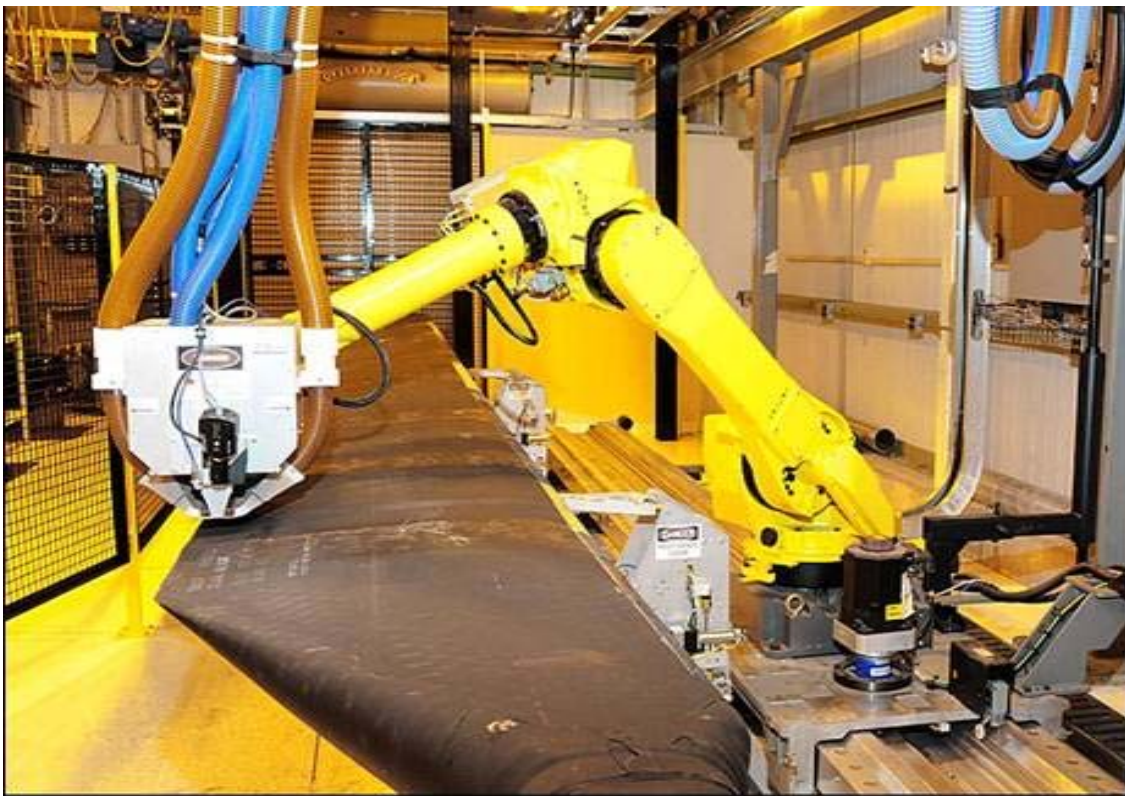


FIGURE 5 The ARBSS at FRC-East Cherry Point, NC.

A key factor in funding the development of this system was the significant cost-benefit that could be achieved with an automated rotor blade overhaul technology. These cost benefits include significant reductions in touch labor, maintenance cycle time, unintended damage to the rotor blades, and waste stream. In terms of direct labor alone, ARBSS generates approximately \$1100 in cost savings for each rotor blade that is processed. FRC-East overhauls approximately 900 rotor blades annually. The baseline manual abrasive process typically requires approximately 22 – 24 hours to complete and generates significant airborne particulate waste containing hexavalent chromium. This type of waste stream requires a specialized facility in addition to enhanced personnel protection and waste management practices.

In comparison, the ARBSS laser system, currently configured with three older 200W lasers, processes an H-53 rotor blade in 8 hours with a negligible waste stream. When upgraded to the original design specification incorporating three 400W lasers, the ARBSS will process an H-53 rotor blade in 2 – 3 hours.

In addition to significant reductions in touch labor and waste stream, the closed-loop laser technology enables other cost savings as well. The color-selective laser ablation process makes it possible to remove the black finish paint coating while leaving the zinc chromate primer coating intact, ready for re-use. This means that the primer system is not converted to hazmat waste material and also no replacement primer is procured or applied during the overhaul cycle.

The rotor blade is a dynamic, flight-critical airframe component and accordingly, an extensive laser process qualification effort was undertaken. Rigorous testing at Penn State Applied Research Laboratory (ARL) established that closed-loop, color-selective laser stripping process was qualified to remove the black finish paint coating on the rotor blade without compromising the structure of the rotor blade or the adhesive bond between the thin composite skin and the honeycomb core.

Sikorsky built a rotor blade test article incorporating low thermal mass foil-type thermocouples in various layers within the blade structure. Real-time in-situ temperature measurements during laser stripping revealed peak instantaneous values of less than 82°C at the adhesive bond line between the skin and the core of the rotor blade. This value is safely below the glass transition temperature (T_g) of the adhesive material in the blade, thereby assuring that no thermal damage to the rotor blade structure will occur during laser processing. The systems integration and the qualification testing effort for this system were performed at the Naval Undersea Warfare Center (NUWC), Keyport, WA.

The small-area coating removal system for the VH-71 (Presidential helicopter) program at NAS Patuxent River is another Navy closed-loop laser application (note the hand-held laser tool in the Figure 6 below). This system was designed to provide the efficiency and flexibility of a hand-held laser tool for small-area depaint and surface preparation in the maintenance program for the VH-71 airframe.

In order to provide the selectivity and control of the laser process that is required for this application, a hand-held laser tool incorporating closed-loop, color-selective control was developed. As depicted in Figure 3, above, this tool is capable of selective coating layer removal without the need for robotic tool positioning (see rotary laser scan pattern in the upper right corner of Figure 3).

This capability allows the operator to walk around the aircraft and remove coatings from localized areas on the airframe for a variety of maintenance operations. The ease of use and versatility of this system is exceptional since no robotic tool path programming or other integration work is required in order to perform surface preparation in many different locations and geometries on the airframe.

Since the laser scanning tool produces both visual and audible cues for manually maintaining the optimum focal distance from the substrate surface, it is very easy to train technicians for efficient operation of the laser system. The optics of the scanning tool are designed to achieve the optimum energy density for best stripping efficiency at the focus condition. When the laser tool is focused, the brightness level of the laser scan pattern is maximized and a characteristic sound is emitted. Operating the laser tool too close or too far away from the substrate surface simply reduces coating removal efficiency without any deleterious effects on the substrate.



FIGURE 6 Laser System at Patuxent River in VH-71 hangar.

The Patuxent River system has the same basic configuration of system that would be employed in shipyard maintenance applications (see Figure 6, above). The hand-held color-selective laser tool is connected to the laser cabinet via a 50-meter fiber optic umbilical (see gray cabinet in the figure above). As shown in the figure above, the laser and chiller cabinets were fitted with “extension legs” to meet Navy requirements that potential ignition sources of flammable vapors be elevated at least 18 inches above the hangar floor.

In shipyard maintenance applications, the laser and chiller cabinets would be positioned on or adjacent to the ship being overhauled. The laser tool could then be operated in interior compartments or on the exterior surfaces of the vessel. Although a 50-meter fiber optic umbilical is standard, longer umbilicals can be provided. This laser system configuration facilitates operation even in very confined spaces such as tanks, bilges, and interior compartments. Since the laser process effluent can be captured and sequestered with a vacuum/filter system, it can be operated around machinery inside tight interior compartments with only basic precautions.

Figure 7, below, shows a confined-space laser tool that incorporates a high-depth-of-field CCD camera. This laser tool is effective in situations where the laser operator cannot readily establish a direct line of sight to the surface to be processed. The operator employs a commercial head-mounted display in order to operate this tool in a non-line-of-sight mode. This laser tool demonstrated a twenty-five-fold improvement in surface preparation efficiency during an Air Force project to demonstrate sealant removal in the center wing box fuel tanks of A-10 aircraft⁴.



FIGURE 7 Camera-equipped laser tool for confined-space operations.

A standard hand-held scanning tool configuration is shown in Figure 8, below. This tool incorporates the same optics as the confined-space tool but is configured for manual positioning under normal situations where the operator can see and access the surfaces to be processed.



FIGURE 8 Standard hand-held laser tool configuration.

The laser scanning tools are intrinsically safe with only 12V power and signal connections to the electronics in the laser cabinet. This means that the laser tool can be operated outdoors, under inclement weather conditions if necessary. The laser tool also incorporates active protection of the output lens in

order to prevent the substrate effluent mass flux from contaminating the optics during operation. Optics contamination has been an ongoing maintenance issue in many laser systems. In these cases, laser systems require frequent cleaning of the optics in order to maintain operability, thereby reducing productivity.

Figure 9, below, shows a recent laser project entailing the removal of corrosion products and industrial contaminants from bronze statuary on the Philadelphia City Hall. This work was performed under conditions that are similar to a shipyard: The laser equipment was moved to a work platform over 400 feet above ground level using a temporary construction elevator. The laser was operated 90 hours a week for over 2000 hours under damp, outdoor conditions with just basic maintenance by field personnel. No optics cleaning and no OEM maintenance services were required during the entire project.



FIGURE 9 Laser surface prep of bronze statuary on Philadelphia City Hall.

This application illustrates an important laser capability: Laser ablation is exceptionally effective in removing metal oxide compounds from metal surfaces. In addition to removing corrosion products and passivation layers as a surface preparation for the application of preservation coatings, the laser is also very effective for nuclear decontamination applications. This stems from the fact that radionuclide contaminants on the surfaces of nuclear plant components tend to become entrained in the coating materials and metal oxides that are typically found on the contaminated surfaces. Laser decontamination has been tested in collaboration with the Electric Power Research Institute (EPRI), Framatome, and the Tennessee Valley Authority (TVA). Tools and components treated in a glovebox fixture were decontaminated to “free release” status with laser processing for approximately 6 – 7 minutes.

The efficiency and selectivity with which the laser removes metal oxide compounds from metal surfaces also provides the opportunity for significant cost benefits in pre-NDI surface preparation applications. The

focus of conventional NDI procedures in metal structures is to detect and size cracks or “linear indications” that could potentially be cracks. It is well known to NDI practitioners that reliable, first-pass NDI is dependent on surface cleanliness – and hence surface preparation. The reason for this is that residual surface contaminants degrade the sensitivity and reliability of the inspection process. Accordingly, most NDI procedures specify the complete removal of residual coating materials, sealants, and corrosion products from the surfaces to be inspected.

The primary techniques for detecting surface-open cracks or linear indications include visual test (VT), eddy-current test (ET), dye penetrant test (PT), fluorescent dye penetrant test (FPI), and ultrasonic test (UT). For purposes of this paper, radiographic test (RT) is neglected since this method is susceptible to radiation orientation issues in the detection of fine, surface-open cracks and a competent discussion of these issues is beyond the scope of this writing.

That limitation notwithstanding, a key issue in pre-NDI surface preparation is the removal of contaminants from the area of inspection, particularly metal-oxide corrosion/passivation products that tend to accumulate in and around cracks and crack-like defects. These metal oxides preferentially grow in surface-open cracks because cracks represent higher-energy surfaces than the surrounding material. Crack propagation, in general, produces higher energy surfaces owing to the presence of localized elastic and plastic strain gradients that surround the crack tip and the plane of crack propagation. The localized strain gradients (localized compliance) also tend to produce fretting contact between the crack surfaces. As the metal structure experiences cyclic loads in the service environment, the crack surfaces are subjected mechanical fretting (scrubbing) of the free surfaces as the crack propagates. These fretting effects, accelerated by crevice corrosion effects, serve to accelerate the growth of metal oxide corrosion products in surface-open cracks.

The net outcome of this process is that cracks tend to grow oxide corrosion products at a higher rate than the adjacent component surfaces. The negative impact of this process is that metal-oxide corrosion products that grow inside the crack volume tend to reduce the sensitivity and the fidelity of NDI processes.

In detailed NDI tests performed for the Federal Aviation Administration (FAA), the laser has demonstrated the capability of enhancing ET and FPI inspection procedures. As discussed above, the mechanism of the laser pre-NDI surface preparation process is its ability to remove metal oxide corrosion products from surface-open cracks. Figures 10 & 11, below, show a scanning electron microscope (SEM) image of a laser-processed test sample containing a fatigue crack and a visual image of the resulting FPI test of that sample. This test sample was taken from an older Boeing 737-200 that had accumulated over 40,000 flight cycles.

A complete discussion of the NDI benefits of laser surface preparation is beyond the scope of this paper but the FAA testing effort demonstrated that the laser enhances the sensitivity and fidelity of crack detection with ET and FPI procedures in most samples. In all of the other test samples, the ET and FPI results were not distinguishable from the baseline test results (before laser surface preparation). This study shows that the laser energy is able to penetrate into crack geometries and ablate the metal-oxide corrosion products that tend to occlude the mouth of surface-open cracks. The removal of these corrosion products enhances the reliability of the NDI process.

Based on the results of this test program, the FAA issued an Alternate Means of Compliance (AMOC) approval for use of this laser process on commercial transport-category aircraft.

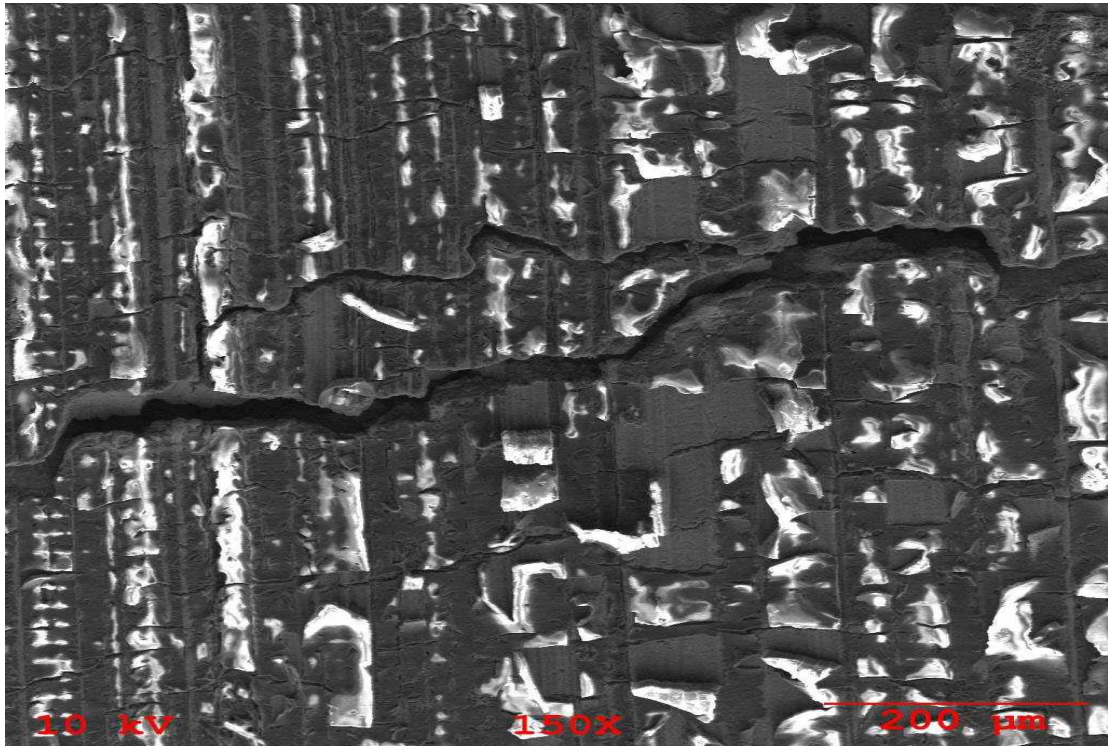


FIGURE 10 SEM photomicrograph of B737-200 fatigue crack.

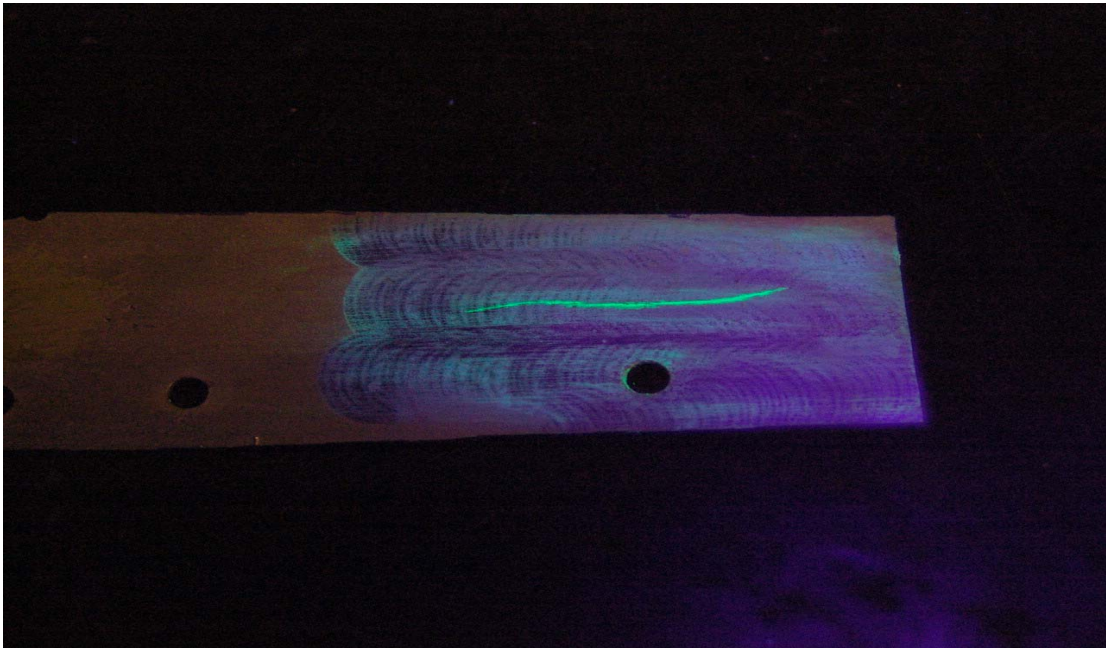


FIGURE 11 Post-laser FPI signature of B737 crack.

CONCLUSIONS

1. The closed-loop laser process has demonstrated controlled and repeatable ablation of organic and inorganic coating materials in a number of critical military applications.
2. The closed-loop laser process has been demonstrated in both robotic and hand-held laser configurations in a number of critical military applications.
3. Pursuant to rigorous qualification testing, the closed-loop laser process has gained military and FAA approval for critical aerospace applications including metallic and composite airframe materials.
4. The closed-loop laser process enables significant cost-benefits for Navy shipyard applications, including productivity improvements and waste management cost reductions.
5. The closed-loop laser process has demonstrated the capability to efficiently remove corrosion products and to ablate standard Navy hull coatings on exemplar steel plate samples.
6. The closed-loop laser process provides exceptional productivity improvements in corrosion removal and surface preparation for shipboard applications, particularly in confined-space situations.
7. The closed-loop laser process has demonstrated effectiveness in nuclear decontamination applications, including decon of contaminated components to free-release criteria.
8. The closed-loop laser process has demonstrated an effective pre-NDI surface preparation capability for enhanced first-pass ET and FPI inspection reliability under an FAA qualification test program.

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