# Evaluation of Combining Heat Induction and Laser Ablation for the Removal of Potentially Hazardous Bridge Coatings

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Abstract:
This project aimed to evaluate whether combining induction coating removal (ICR) and laser ablation coating removal (LACR) could be combined to remove hazardous bridge coatings at practical rates. This study included evaluations of the coating removal rates, surface cleanliness, surface profile, steel substrate mechanical properties, recoating adhesion performance, field demonstrations, and environmental and industrial hygiene evaluations of ICR, LACR, and ICR first plus LACR afterward (ICR+LACR). Coating removal data showed that using ICR+LACR could result in a coating removal rate approximately 10 times faster than using LACR alone. ICR can quickly remove the bulk coating layers but leave the residual primer on the steel surface. LACR can then quickly remove the remaining primer layer to provide a clean surface ready to be recoated.

Surface analysis showed that LACR provides a much cleaner surface, with fewer contaminants embedded in the surface compared with grit blasting. LACR also leaves less of a surface profile compared with grit blasting. However, LACR surfaces still meet the Virginia Department of Transportation (VDOT) specifications for surface profile before coating. Metallography and mechanical testing showed that the heat from LACR, ICR, and ICR+LACR changed only a very thin layer of the steel substrate, but this change did not affect the mechanical or fatigue properties of the underlying steel. Adhesion testing of inorganic and organic zinc coatings applied to LACR and ICR+LACR surfaces showed acceptable levels of adhesion that were comparable with surfaces cleaned by grit blasting, and the adhesion values met the coating manufacturer's recommendations. These findings are notable because, although LACR surfaces have a smaller profile than grit-blasted surfaces, LACR surfaces are much cleaner, thereby creating sufficient adhesion.

Environmental and industrial hygiene measurements indicated that LACR units that do not use an effective built-in fume extractor can expose employees to unacceptable levels of laser-generated air contaminants during coating systems removal. The quantity of hazardous waste generated by LACR and ICR is less than the amount of waste created through traditional blasting measures. ICR waste is not captured through debris collection and should be contained on tarpaulins or other similar drop cloths.

This study recommends that VDOT develop guidance and specifications for using the ICR+LACR method for bridge coating removal. The study also recommends that VDOT identify upcoming bridge coating removal projects, such as girder end recoating and repair projects, for which ICR+LACR could be specified or permitted as a removal method. In addition, the Virginia Transportation Research Council should initiate a technical assistance project to evaluate the mechanical properties of high-strength bolts subject to heat, such as from ICR. VDOT can achieve an environmentally and worker-friendly coating removal method by using ICR+LACR. This method is a competitive alternative to grit blasting and can be used in targeted locations to help extend the service life of steel bridges.

Supplemental materials can be found at https://library.vdot.virginia.gov/vtrc/supplements.

**FINAL REPORT**

# EVALUATION OF COMBINING HEAT INDUCTION AND LASER ABLATION FOR REMOVING POTENTIALLY HAZARDOUS BRIDGE COATINGS


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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

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VTRC 26-R10

## DISCLAIMER

**ABSTRACT**

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Environmental and industrial hygiene measurements indicated that LACR units that do not use an effective built-in fume extractor can expose employees to unacceptable levels of laser-generated air contaminants during coating removal. The quantity of hazardous waste generated by LACR and ICR is less than the amount of waste created through traditional blasting measures. ICR waste is not captured through debris collection and should be contained on tarpaulins or other similar drop cloths.

This study recommends that VDOT develop guidance and specifications for using the ICR+LACR method for bridge coating removal. The study also recommends that VDOT identify upcoming bridge coating removal projects, such as girder end recoating and repair projects, for which ICR+LACR could be specified or permitted as a removal method. In addition, the Virginia Transportation Research Council should initiate a technical assistance project to evaluate the mechanical properties of high-strength bolts subject to heat, such as from ICR. VDOT can achieve an environmentally and worker-friendly coating removal method by using ICR+LACR. This method is a competitive alternative to grit blasting and can be used in targeted locations to help extend the service life of steel bridges.

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## INTRODUCTION

Typically, on large-scale projects like recoating steel bridge girders, coating removal and surface preparation are accomplished using abrasive blasting. The Virginia Department of Transportation (VDOT) commonly uses abrasive media like recycled steel shot to remove the old coating from steel bridge girders and prepare the surface for the new coating. This approach is effective but generates a lot of waste and requires a sizable effort to capture the generated airborne dust. Therefore, to perform this task properly, VDOT requires containment to ensure that the toxic waste is captured, workers have extensive personal protective equipment (PPE), and the old coating waste is properly disposed (Figure 1).

For large-scale recoating projects, the production rate of the blasting process offsets the time required to construct a complex environmental containment system needed during an abrasive blasting operation. However, some recoating work, like damaged girder ends (Figure 2), would benefit from using a tool like laser ablation coating removal (LACR), which is better suited for smaller, more routine repairs before significant corrosion loss of the structural steel.

(a)


(b)


(c)

**Figure 1. To Safely Remove and Dispose of Older Bridge Coatings with Lead-Based Coating: (a) The Old Coating Must Be Contained During Removal; (b) Workers Must Be Protected; (c) The Waste Material Must Be Properly Disposed**

(a)

(b)

**Figure 2. Coated Steel Girder End: (a) Exhibiting Significant Corrosion Damage Mainly at the Girder End and Bearing due to Salt and Water Penetrating through the Deck Expansion Joint Above; (b) Close-up of a Different Bearing at the Pier Shows the Voluminous Nature of the Rust Product that Formed from the Iron in the Steel**

Recently, VDOT investigated the use of LACR to remove older bridge coatings from structural steel elements (Sharp, 2019). Although this previous research studied the feasibility and efficacy of using LACR for bridge coating maintenance, questions remain surrounding the coating removal rates and the adhesion of new coatings to these differently cleaned and prepared surfaces.

Another innovative coating removal technique is induction coating removal (ICR). ICR creates localized heat at the interface between the coating and the steel, thus causing the coating to debond from the steel. ICR is a highly productive, efficient method of removing bulk coatings from metal substrates to prepare them for recoating (Solhaug, 2022). Therefore, ICR appears to be another potential, worker-friendly coating removal process that could be used instead of LACR that does not require full containment.

Finally, ICR could be used in conjunction with LACR (hereafter, ICR+LACR) because the two techniques could be complementary. Both techniques remove coating without using conventional abrasive media. Therefore, collecting contaminated blast media is not required because only the coating waste must be captured. The coating removal rate for LACR is also sensitive to the coating volume to be removed, so a thicker coating could require more time for removal. ICR debonds the coating at the steel's surface, which is why it is known to have a high productivity rate even when dealing with thicker coatings. Thus, removing most of the coating material with ICR and then using LACR for final surface cleaning could improve the ICR+LACR rate and provide a surface ready to be recoated without requiring full containment.

Prior to this study, for ICR, ICR+LACR, and LACR, questions remained about the coating removal rates when removing steel bridge coatings, the suitability of the steel surface after cleaning it with ICR, and the adhesive properties of the typical steel bridge coatings applied to an ICR or LACR cleaned surface. Furthermore, the adhesion behavior after recoating a bridge is especially important because it greatly affects the longevity of the coating, which can directly affect the service life of the bridge. Therefore, understanding how ICR and LACR, when used separately or together for removing potentially hazardous bridge coatings, affect the steel behavior and coating adhesion, and whether this approach to coating removal can be done safely, is important.

## PURPOSE AND SCOPE

The purpose of this project was to evaluate whether combining ICR with LACR could make the combined coating removal process an alternative to abrasive grit blasting (GB). This project included an investigation of the coating removal rates, surface cleanliness, surface profile, steel substrate mechanical properties, adhesion performance of recoating, field demonstrations, and environmental and industrial hygiene evaluations of ICR, LACR, and ICR+LACR. The researchers then compared the surface cleanliness, surface profile, mechanical properties, adhesion performance, and field demonstrations with the conventional GB coating removal process.

The scope of this study included both laboratory experiments and field trials. The researchers conducted laboratory experiments on samples removed from a decommissioned bridge. These samples were cut out from the bridge members, and the coating was removed using one of four methods under study: (1) GB; (2) ICR; (3) LACR; and (4) ICR+LACR. After that step, the various samples were subject to mechanical testing, metallography, coating reapplication, and adhesion testing. Field trials included gathering condition data of coatings applied to a LACR surface approximately 7 years prior from one bridge and data on coating removal and recoating from a second bridge. For the second bridge project, coatings were removed from girder ends and bearing lines using ICR+LACR and recoated.

# METHODS

## Laboratory Samples

### Sample Fabrication

Steel samples for this research were sourced from the Route 189 Bridge over Blackwater River at South Quay, Virginia, which was a 1940s steel truss swing span bridge that had recently been decommissioned. The Route 189 Bridge members had never been blast cleaned and contained a lead-based coating system. Sample fabrication consisted of cutting 1.5-x-1-foot coated steel plate samples from the bridge's truss members. The samples were cut in 2021.

### Surface Analysis Before Coating Removal

The researchers examined cross sections of the steel samples using optical microscopy before removing the coating to characterize the initial steel surface and original coating on the samples.

### Coating Removal Process

The researchers removed the coating on the steel samples using one of four methods under study: (1) GB; (2) ICR; (3) LACR; and (4) ICR+LACR. All coating removal for the steel samples was performed at Norton Sandblasting in Chesapeake, Virginia, with representatives from the LACR and ICR equipment manufacturers on site. A single manufacturer makes both LACR systems evaluated, whereas different manufacturers make each of the ICR devices. Table 1 shows the LACR and ICR units used to remove the coating of the laboratory samples.

**Table 1. LACR and ICR Units Used During Coating Removal of Laboratory Samples**

| Coating Removal Process | Manufacturer Name and Model Tested | Features |
|---|---|---|
| LACR | cleanLASER 1000 | 1,000-watt output, pulsed laser, handheld |
| | cleanLASER effiSCAN | Lightweight, smaller laser for accessing tight spaces |
| ICR | EFD TERAC® 25/40 | 25,000- or 40,000-watt output, nominal or intermittent, handheld |
| | RPR 1650-2 | 50,000-watt output, handheld |

EFD = EFD Induction (company); ICR = induction coating removal; LACR = laser ablation coating removal; RPR = RPR Technologies (company).

The researchers performed environmental and industrial hygiene sampling to determine the levels of exposure for each coating removal process. Temperature, coating removal equipment run time, and removal area were also documented during the coating removal process.

### *Environmental Evaluation*

Sections 107 and 411.09 of VDOT's *2020 Road and Bridge Specifications* require the contractor to "protect the public and the environment from leaded paint or hazardous material resulting from coating preparation, cleaning, removal operations..." and to characterize the waste through sampling and analysis before proper disposal (VDOT, 2020). Waste characterization efforts were conducted during previous studies, which found that waste generated during lead-based coating removal for both LACR and ICR was considered hazardous for lead by the toxic characteristic leaching procedure and were not repeated during this study (Rickard, 2022). The researchers conducted environmental observations during this study to finalize environmental protection requirements for incorporating ICR and LACR technologies into the specifications.

### *Industrial Hygiene*

The researchers collected and characterized paint chip samples from the South Quay Bridge in 2021 before the steel samples were cut from the truss members. These samples determined that the coatings contained measurable quantities of aluminum, chromium, lead, zinc, silicates, and carbonates, along with other organic components (Rickard, 2022). Analytes evaluated during the laboratory trials discussed in this report included volatile organic compounds, aldehydes, and metal fumes. Table 2 outlines and describes the laboratory methods.

**Table 2. Analytes Evaluated During Laboratory Trials Using cleanLASER 1000 LACR, ICR + cleanLASER 1000 LACR, and ICR + cleanLASER effiSCAN LACR**

| Analyte | Sample Methods | Description of Method | Media, Laboratory |
|---|---|---|---|
| VOC Profile | EPA TO-15 | Determination of VOCs in Air Collected in Specially Prepared Canisters and Analyzed by Gas Chromatography–Mass Spectrometry | Evacuated Canister, 4-hour Regulator, SGS Galson |
| | 31-Panel VOC | NIOSH Methods, Gas Chromatography | Assay 566 BA, SGS Galson |
| Welding Fume Profile (metals) | NIOSH 7300 | Elements by Inductively Coupled Argon Plasma, Atomic Emission Spectroscopy | Mixed Cellulose Ester Membrane Filter, 0.8 µm, 37 mm, SGS Galson |
| Aldehyde Profile | OSHA 1007M | Diffuse Sampler, Liquid Chromatography Using Ultraviolet Detector | Assay 571 Badge, Assay Technologies |

EPA = U.S. Environmental Protection Agency; ICR = induction coating removal; LACR = laser ablation coating removal; NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration; VOC = volatile organic compound.

## Surface Analysis After Coating Removal

After coating removal, the researchers analyzed the samples for surface cleanliness, surface profile, and roughness because each could affect the adhesion performance of reapplied coatings.

### *Surface Cleanliness*

Cleanliness of the surfaces of the steel samples after coating removal was paramount for investigation throughout this study. Surface contamination can affect both adhesion and corrosion protection if chlorides and other salts are present on the steel substrate after coating removal. The researchers evaluated the surface cleanliness using metallographic analysis and then compared the cleanliness of the different surfaces. Samples were approximately 1 inch by 1 inch and were polished using conventional polishing techniques, with up to 1,200 grit size polishing paper and then with 3 micron, 1 micron, and colloidal polishing solutions. Samples were etched using a 2% Nital etchant (2% nitric acid, 98% ethanol volume per volume). Both planar and cross-sectional analyses were conducted using optical microscopy and scanning electron microscopy (SEM). In addition, the surface composition of the samples was determined using energy dispersive spectroscopy (EDS). EDS area maps were used to determine the elemental composition and distribution of cross sections, surface layers, and top planar surfaces for the GB, ICR, and LACR surfaces. Material characterization also employed an X-ray diffractometer with a standard copper $K_\alpha$ X-ray source set to 40-kV accelerating voltage and 45-mA source current. The X-ray diffraction (XRD) library pattern software indexed and matched diffraction patterns.

### *Surface Profile and Roughness*

This project's surface profile and roughness were key aspects because they can affect adhesion. KTA-Tator, Inc. (hereafter, KTA) made surface profile measurements on the surfaces before recoating the samples and provided the results to the University of Virginia, which the Virginia Transportation Research Council (VTRC) contracted to evaluate the adhesion behavior. Stylus profilometry was also performed to measure a macroscale surface roughness profile and average roughness of the surfaces studied. Throughout this report, surface profile, as it is commonly termed in industry, refers to the distance between the tallest peak and the lowest valley across the measured profile, whereas average roughness, $R_a$, refers to a statistical measurement or average of the distribution of points along the surface profile from the mean height (Gadelmawla et al., 2002). SEM analysis was also used to view the surface topography.

## Recoating Samples

After coating removal, the steel plate samples were shipped to KTA, which applied new coating systems to them. Two different VDOT-approved, three-layer coating systems were applied to each side of the plates: an inorganic zinc (IOZ) primer and an organic zinc (OZ) primer. Both primers complied with VDOT System B coatings (VDOT, 2020). Table 3 shows the individual coating layers applied to the steel plates. KTA performed profile measurements after receiving the steel samples and before coating, as well as coating thickness measurements.

**Table 3. Two Coating Systems Applied to Each Side of the Steel Plates**

| Sample Side (Primer Color) | Primer | Intermediate Coat | Topcoat |
|---|---|---|---|
| Side 1 (Green) | Inorganic Zinc Carbozinc 11 HS | Epoxy Carboguard 893 | Polyurethane 133LV |
| Side 2 (Gray) | Organic Zinc Carbozinc 859 | Epoxy Carboguard 893 | Polyurethane 133LV |

## Adhesion and Cohesion Testing

The researchers tested the adhesion of the IOZ and OZ coating systems that were reapplied to each different coating removal surface condition using pull-off pneumatic adhesion tensile testing instrument (PATTI) tests. PATTI tests were conducted according to ASTM D4541 (ASTM International, 2022a). After PATTI testing, the stubs and substrate fracture surfaces were analyzed by SEM to determine if the tests failed in adhesion, cohesion, or a combination of the two mechanisms.

Adhesion test results were also used to determine whether mechanical testing was required for a given coating removal method or coating system. The criteria for success were that all test data needed to meet the minimum pull-off adhesion strength value listed by the coating manufacturer.

## Mechanical Testing

ICR alone did not meet the required criteria for adhesion. Therefore, the researchers did not perform mechanical testing on that set of samples. This finding will be discussed further in the Results and Discussion section of this report.

### *Tensile Testing*

The researchers conducted tensile tests to determine if heat from the ICR and LACR processes caused a change in the mechanical properties of the underlying steel. Six tension samples were machined from the steel samples subjected to the following coating removal methods: GB, LACR, and ICR+LACR. All tension samples were machined and tested according to the requirements for sheet-type specimens in ASTM E8 (ASTM International, 2022b). Tension samples were tested in a servo-hydraulic controlled uniaxial test frame with a 55-kip capacity actuator (ASTM International, 2022b). Strain data were measured using a video extensometer and digital image correlation software and analysis. Load data were measured using the load cell from the load frame. Yield stress was calculated using a 0.2% offset, and the percentage of elongation was determined using a 2-inch gauge length.

### *Fatigue Testing*

The researchers conducted fatigue testing to determine if the LACR or ICR+LACR processes created a heat-affected zone that altered the fatigue performance of the underlying steel. Six fatigue samples were machined from the steel plates subjected to the LACR and ICR+LACR methods. Fatigue tests were not conducted on GB samples because their fatigue performance is already well understood. All fatigue samples were machined according to the sheet-type tension specimens in ASTM E8 and were tested in a servo-hydraulic controlled load frame (ASTM International, 2022b). The fatigue test specimens were cycled at a 32-ksi constant amplitude stress range, with respective minimum and maximum stress levels of 1 and 33 ksi. The 32-ksi cyclic stress range was selected to be large enough to produce fatigue failures within a reasonable time and small enough that the steel maintained elastic behavior during testing. If specimens did not fail after 5 million cycles, they were considered “run-outs,” and testing was stopped. Test results were compared with the fatigue design specifications in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2020).

## Field Trials

### Route 695 Bridge over Route 460

The Route 695 Bridge over Route 460 (Federal Bridge No. 14007) is in Prince Edward County near Farmville, Virginia. This bridge was the first in which VDOT used LACR to remove the coating from selected girder ends. The cross frame, the bottom nuts, bolts, and washers between girders No. 3 and 4, and the interior and exterior 3 feet of the girder ends on Girder No. 4 at Abutment B were cleaned with LACR. The coating removal process was initiated in August 2017 and is documented in VTRC Final Report No. 20-R1 (Fitz-Gerald et al., 2019). Following coating removal, cleaned areas were recoated with a VDOT System F coating (VDOT, 2020).

The researchers evaluated the coating condition of the Route 695 Bridge using two mechanisms. First, researchers reviewed VDOT bridge inspection records to determine if any information related to changes in coating condition had been noted. Second, they visited the bridge site on July 10, 2024, approximately 7 years after the coating was applied, and documented the coating condition.

### Route 301 Bridge over Pamunkey River

Following the successful ICR+LACR laboratory testing, VDOT pursued a field demonstration project to determine if ICR+LACR could be successfully performed under actual field conditions. The project required coating selected areas of girder ends and bearing lines on the Route 301 Bridge over the Pamunkey River (Federal Bridge No. 9461) in Hanover County, Virginia.

#### *Coating Removal*

Route 301 Bridge consists of four simple spans with eight bearing lines. The project required the primary contractor to remove the coating and recoat five of the girder ends and bearing lines using conventional methods for coating removal, access, and containment. A specialty coating removal contractor familiar with ICR and LACR was hired as a subcontractor. The specialty subcontractor was required to remove the coating from three of the girder ends and bearing lines using ICR+LACR, then the primary contractor was responsible for recoating those areas. All recoating was performed with a VDOT System B coating (VDOT, 2020).

Coatings were to be removed from all surfaces within 5 feet of the girder ends and included the girders, connector plates, diaphragms, bolts, and bearings. The primary coating contractor was also directed during the work to remove coating using GB for additional girder length adjacent to ICR+LACR at Abutment A for aesthetic purposes, where a previous recoating was completed in a different color.

*Environmental Evaluation*

Environmental observations were made during both the ICR and LACR processes, similar to those made for the laboratory samples for this project. Waste was not sampled during the ICR and LACR processes. However, waste results were assumed to be hazardous based on the results of previous sampling events.

*Industrial Hygiene Evaluation*

On November 8, 2024, the researchers used a GrayWolf hot-wire anemometer to collect real-time ventilation measurements for velocity in feet per minute at the face of the cleanLASER effiSCAN fume extractor and the 12-inch positionable flex-duct.

The researchers collected personal breathing zone (PBZ) samples, which indicate an employee’s actual exposure to a particular contaminant, and area samples, which indicate a worker’s potential exposure to a contaminant, during the exposure assessments. VDOT collected samples from PBZ and area exposure monitoring for metals, aldehydes, acid vapors, and other organic vapors at the Route 301 Bridge project in partnership with the specialty subcontractor during LACR, ICR, and grinding (Rickard, 2024). Sample analysis was conducted according to methods outlined in the National Institute for Occupational Safety and Health’s *Manual of Analytical Methods* (Schlecht and O’Connor, 1994), U.S. Environmental Protection Agency (2024) methods, and Occupational Safety and Health Administration (2024) methods. Table 4 outlines the analytes and analysis methods used during the Route 301 Bridge evaluation.

**Table 4. Route 301 Bridge Industrial Hygiene Sample Methodology**

| Analyte | Sample Methods | Description of Method | Media, Laboratory |
|---|---|---|---|
| Carbon Monoxide | Dräger Accuro Hand Pump | | EW-86514-27, 5–700 ppm Detector Tubes, Real-Time |
| Acid Gases | Real-Time Monitor | | Not Applicable, Real-Time |
| Cadmium | NIOSH 7303M | Inductively Coupled Argon Plasma, Atomic Emission Spectroscopy, Microwave Digestion | Mixed Cellulose Ester Membrane Filter, 0.8 µm, 37 mm, SGS Galson |
| Chromium | | | |
| Iron | | | |
| Lead | | | |
| Zinc | | | |
| Lead (specialty subcontractor-provided data) | NIOSH 7082 | Lead by Atomic Absorption Spectrophotometer, Flame | |
| Phthalic Anhydride | OSHA Method 90 | High-Performance Liquid Chromatography with Ultraviolet Detector | 225-9021, Treated Glass Fiber Filter, SGS Galson |
| Acetic Acid | OSHA PV2119, Modified | Ion Chromatography Analysis, Conductivity Detector | Assay 543 Badge, Assay Technologies |
| Acetaldehyde | | | |

| Analyte | Sample Methods | Description of Method | Media, Laboratory |
|---|---|---|---|
| Benzaldehyde | EPA TO-11, Modified | Adsorbent Cartridge Followed by High-Performance Liquid Chromatography | Assay 571 Badge, Assay Technologies |
| Crotonaldehyde | | | |
| Formaldehyde | | | |
| Glutaraldehyde | | | |
| Hexanal | | | |
| m-Tolualdehyde | | | |
| Propionaldehyde | | | |
| Valeraldehyde | | | |
| 1,1,2-Trichlorethane | NIOSH 1003 | Halogenated Hydrocarbons by Gas Chromatography, Flame Ionization Detection | Assay 566 BA, SGS Galson |
| 1,1-Dichloroethane | | | |
| 1,2-Dichloroethane | | | |
| Chlorobenzene | | | |
| Chloroform | | | |
| m-Dichlorobenzene | | | |
| Methyl Chloroform | | | |
| o-Dichlorobenzene | | | |
| p-Dichlorobenzene | | | |
| Tetrachloroethylene | | | |
| Methylene Chloride | NIOSH 1005 | Methylene Chloride by Gas Chromatography, Flame Ionization Detection | |
| Trichloroethylene | NIOSH 1022 | Trichloroethylene by Gas Chromatography, Flame Ionization Detection | |
| Acetone | NIOSH 1300 | Ketones I by Gas Chromatography, Flame Ionization Detection | |
| Cyclohexanone | | | |
| Methyl Ethyl Ketone | | | |
| Methyl n-Propyl Ketone | | | |
| Ethyl Alcohol | NIOSH 1400 | Alcohols I by Gas Chromatography, Flame Ionization Detection | |
| Isopropyl Alcohol | | | |
| n-Butyl Acetate | NIOSH 1450 | Esters I by Gas Chromatography, Flame Ionization Detection | |
| n-Propyl Acetate | | | |
| Cyclohexane | NIOSH 1500 | Hydrocarbons, Boiling Point 36–216 °C by Gas Chromatography, Flame Ionization Detection | |
| Cyclohexene | | | |
| n-Hexane | | | |
| n-Pentane | | | |
| Benzene | NIOSH 1501 | Aromatic Hydrocarbons by Gas Chromatography, Flame Ionization Detection | |
| Cumene | | | |
| Ethylbenzene | | | |
| Toluene | | | |
| Xylene | | | |
| Tetrahydrofuran | NIOSH 1609 | Tetrahydrofuran by Gas Chromatography, Flame Ionization Detection | |

EPA = U.S. Environmental Protection Agency; NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration.

Following laboratory analysis, the researchers compared field data from the Route 301 Bridge with data collected during the 2016 UVA cleanLASER 1000 laboratory study, the 2017 Route 695 Bridge over Route 460 cleanLASER 1000 field study (VDOT, 2017), the 2018 cleanLASER 1000 laboratory study at Norton Sandblasting, and the 2022 Norton LACR+ICR study for aldehydes, metals, and volatile organic compounds observed above the Limit of Detection (LOD) (Rickard, 2022), which is the lowest quantity of material that the analytical method can identify as being statistically greater than zero. This level is not, in itself, indicative of a particular exposure hazard. The results of VDOT's PBZ samples for lead were statistically compared for similarity with the specialty subcontractor's PBZ samples collected at Route 301 Bridge using the Excel® data analysis tool, Microsoft® Excel for Microsoft 365 MSO (Version 2405 Build 16.0.17628.20006) 64-bit, natural logarithm (Ln) transformed two-tailed *t*-test, assuming unequal variances.

PBZ results for lead collected at Route 301 Bridge were compared with the 2017 air sampling results collected at Route 695 Bridge over Route 460 (VDOT, 2017) and at Norton Sandblasting, in Chesapeake, Virginia (EI Group, 2016; Rickard, 2018), where the 1,000-Watt cleanLASER with built-in fume extraction was used. In addition, the Route 301 Bridge data were compared with the 2022 data collected at Norton Sandblasting (Rickard, 2022), where the cleanLASER 1000 and ICR were used in combination. A visual data comparison was created using "Tool 3" of the University of Montreal program Expostats Bayesian Calculator, with which the cleanLASER effiSCAN LACR+ICR, cleanLASER 1000 LACR+ICR, and cleanLASER 1000 were compared (Lavoué et al., 2015). Area sample results from the various projects were not compared during the Bayesian analysis.

*Coating Condition Evaluation After 10 Months of Service*

The researchers conducted a site visit at Route 301 Bridge approximately 10 months after the bridge had been recoated following the ICR+LACR process. This visit was undertaken to evaluate the condition of the coating and to document it.

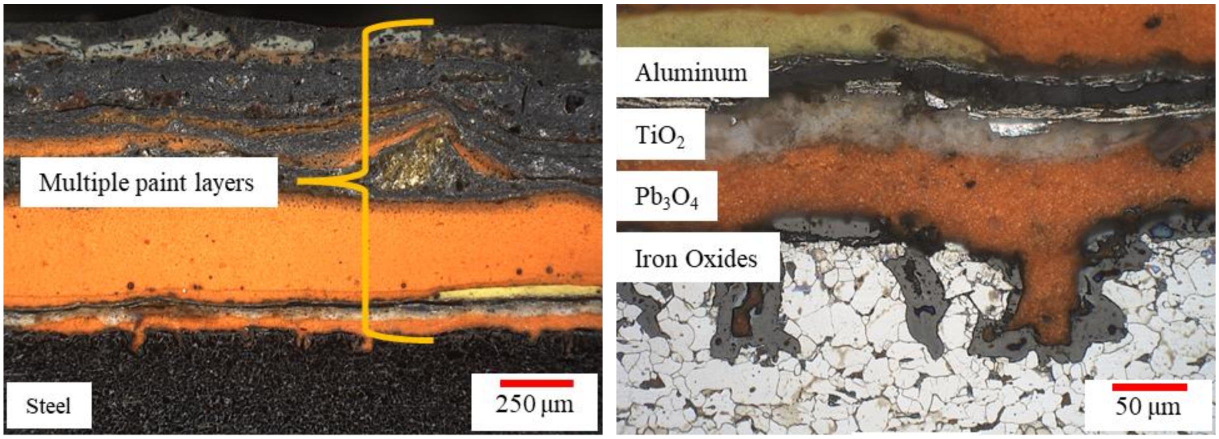
# RESULTS AND DISCUSSION

## Laboratory Samples

### Surface Analysis Before Coating Removal

Cross sections of the steel samples before coating removal showed multiple layers of material were present on the samples. This circumstance was because the bridge from which the samples came was built in the 1940s and had accumulated coatings during decades of service life. Figure 3 shows an optical micrograph of a cross section with the many layers of coatings visible.

Further analysis shows the presence of a continuous oxide layer, commonly referred to as mill scale, below the coating because the girders were manufactured before GB was standard procedure prior to painting. Cross sections show the continuous nature of the iron oxide layer and the lead-based coating that covers the iron oxide surface. Figure 3 shows an optical microscopy cross section of the base material and how the lead-based coating fills in pits present on the surface.




**(a)** **(b)**

**Figure 3. Optical Microscope Images of Received Coated Bridge Steel Showing: (a) Steel Cross Section with Multiple Layers of Coatings Present; (b) The Interface Between the Iron Oxide Layer on the Steel and How the Lead-Based Coating Fills in Pits Present on the Surface. $Pb_3O_4$ = lead tetroxide; $TiO_2$ = titanium dioxide.**

## Coating Removal Process

### *Coating Removal Observations*

Coating removal rate calculations can exhibit variability, especially for coatings on bridge members that have been in service for many years, as those used for this study's steel samples. As Table 5 shows, this calculation is sensitive to things like coating thickness and can change because of the geometry of the surface (such as a flat plate or a welded girder) in which the coating is being removed. Furthermore, the EFD Induction ICR device remained static during coating removal, whereas the RPR Technologies ICR device was slowly moved across the surface. Table 5 also shows how, during ICR, a thin 1- to 2-mil layer of the original primer remained on the surface. Therefore, ICR does not leave a clean surface ready to be recoated without additional coating removal. However, when LACR is used, either on its own or after ICR, the thickness of the original primer is zero, meaning it is completely removed, and the surface is ready to be recoated.

**Table 5. ICR and LACR Rate and Surface Temperature Data Collected**

| Bridge Member Name | Bridge Member Type | Coating Removal Technique | Removal Time, min | Area Removed, $ft^2$ | Beginning Coating Thickness, mil | Ending Coating Thickness, mil | Estimated Coating Removal Rate, $ft^2/h$ | Surface Temp., °F |
|---|---|---|---|---|---|---|---|---|
| IH Beam 6A | Flat I-girder with 8-in. flange | EFD ICR | 34.8 | 9.6 | 10.7 | 1.5 | 16.6 | 134–325 |
| | | RPR ICR (VDOT operated) | 8.9 | 6.4 | 6.8 | 1.05 | 43.4 | 220–260 |
| | | ICR+LACR | 2.3 | 1.4 | 1.05 | 0 | 36.0 | N/A |
| IH Beam 6 | Welded Channel with Stiffener | RPR ICR (RPR operated) | 8.0 | 8.1 | 13.5 | 2.75 | 60.9 | 180–200 |
| | | ICR+LACR | 2.9 | 1.5 | 2.75 | 0 | 30.5 | N/A |
| Angle Iron 8 | | RPR ICR | 6.7 | 0.9 | 18.5 | 1.5 | 7.8 | 230–320 |
| | | ICR+LACR | 2.1 | 0.9 | 1.5 | 0 | 25.6 | N/A |

| Bridge Member Name | Bridge Member Type | Coating Removal Technique | Removal Time, min | Area Removed, $ft^2$ | Beginning Coating Thickness, mil | Ending Coating Thickness, mil | Estimated Coating Removal Rate, $ft^2/h$ | Surface Temp., °F |
|---|---|---|---|---|---|---|---|---|
| Angle Iron 9 | Rolled Steel Angle | LACR | 25.3 | 0.9 | 25.0 | 0 | 2.08 | N/A |
| Beam Study 18M-049 | I-girder | LACR | 226 | 27.5 | 15 | 0 | 7.3 | N/A |

EFD = EFD Induction (company); ICR = induction coating removal; LACR = laser ablation coating removal; N/A = not applicable; RPR = RPR Technologies (company).

Table 6 summarizes the coating removal rate data after being grouped into two categories of surface geometries: flat with right angles (such as for I-girders, channels, or angles) and completely flat. When comparing only the flat geometries, LACR had a removal rate of approximately 7.3 square feet per hour. Compare that rate with ICR+LACR, which had a removal rate of 11.1 to 33.3 square feet per hour. This rate represents up to a 4.5-times increase in the coating removal rate when ICR is applied before LACR compared with LACR alone. When comparing only the flat with right-angle geometries, the ICR+LACR rate was up to 12.2 times faster than LACR alone. In both geometries, these rates illustrate that coating can be removed substantially faster when ICR is used before LACR. Using LACR as the final step is required because ICR alone did not completely remove all the coating.

**Table 6. Coating Removal Rates for LACR, ICR, and ICR+LACR when Grouped by Surface Geometry**

| Surface Geometry | Coating Removal Technique | Coating Removal Rate to Bare Steel, $ft^2/h$ |
|---|---|---|
| Flat with Right Angles | LACR | 2.1 |
| | RPR ICR | Coating not completely removed |
| | ICR+LACR | 25.6 |
| | ICR+LACR | 6.0 |
| Flat | LACR | 7.3 |
| | ICR+LACR | 33.2 |
| | EFD ICR | Coating not completely removed |
| | RPR ICR | Coating not completely removed |
| | EFD ICR+LACR | 11.1 |
| | RPR ICR+LACR | 33.3 |

EFD = EFD Induction (company); ICR = induction coating removal; LACR = laser ablation coating removal; RPR = RPR Technologies (company).

Table 5 also provides the steel surface temperature ranges for the two different ICR devices used. Surface temperatures were not measured during LACR because the steel surfaces remained cool enough to be comfortably touched by hand. Overall, the surface temperatures ranged from 134 to 325 °F when conducting ICR. The researchers observed that coating removal rates were not greater when the maximum temperature exceeded 300 °F. However, when the difference in the temperature range was small and kept below 300 °F during ICR, the coating removal rate was higher, which might have been because of more evenly debonding the coating from the steel’s surface.

## Surface Analysis After Coating Removal

### *Cleanliness of Grit Blasting Surfaces*

The researchers compared cross sections of samples cleaned with ICR, ICR+LACR, and GB to evaluate their cleanliness after coating removal. Metallographic samples of LACR-only processed surfaces have been studied and discussed previously in a previous report (Fitz-Gerald et al., 2019). The researchers found that GB effectively removes all the coating layers, including the iron oxide layer, but also drives some of the iron oxide into the steel below the surface. Figure 4a shows both SEM and EDS maps of the GB surface in a cross section and how the iron oxide is driven into the steel because of the GB treatment. Although not tested in this research, the inclusions and crevices created by impacting the oxide layer could potentially introduce corrosion initiation sites by allowing electrolytes to enter and concentrate.

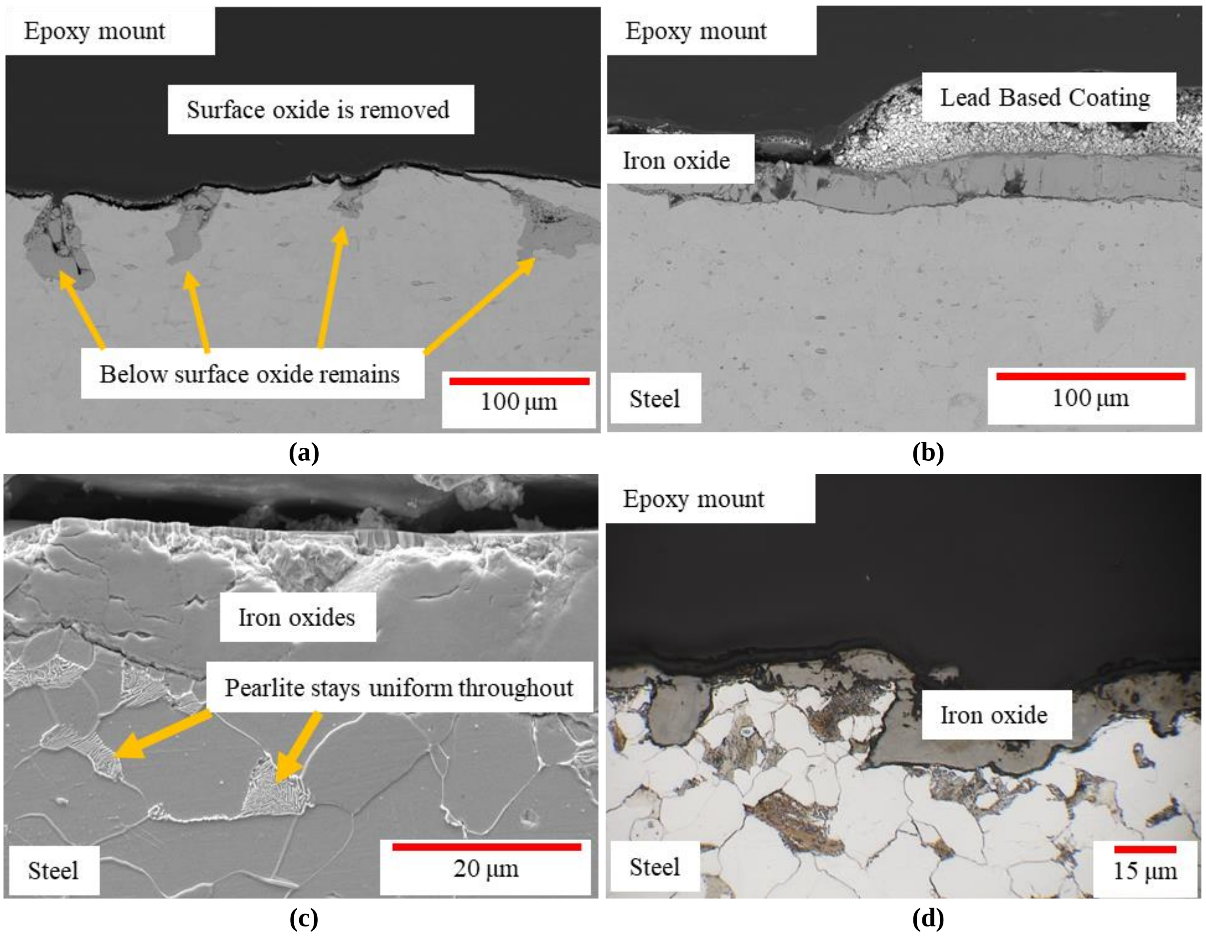
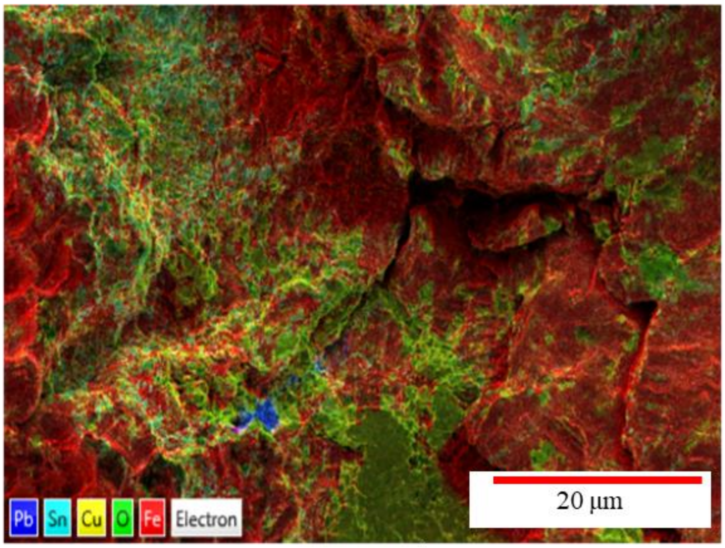


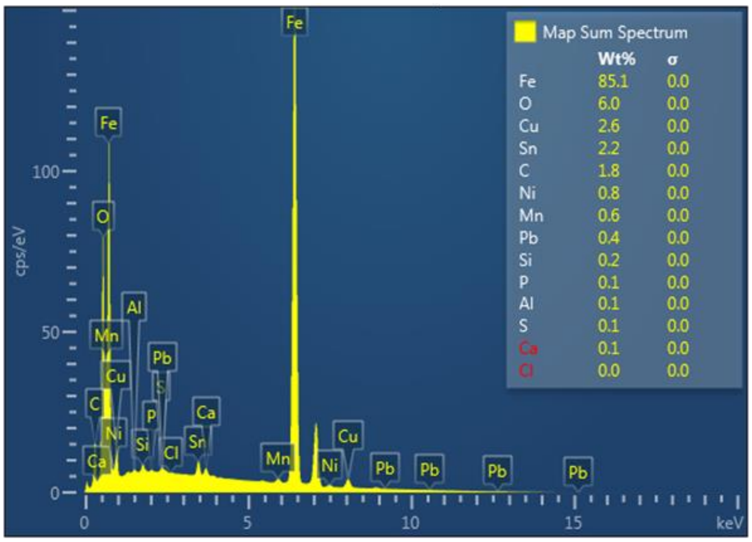

**Figure 4. SEM Cross Section of: (a) GB Sample; (b) ICR Sample; (c) ICR+LACR Sample; and (d) Optical Micrograph of an ICR+LACR Cross Section. The GB cross section in (a) shows the presence of iron oxide inclusions below the steel surface that have been driven in from the GB process. The ICR cross section in (b) shows the remaining lead-based coating on top of the iron oxide that continuously covers the steel after ICR treatment. The ICR+LACR cross-section SEM micrograph in (c), centered on the interface between the iron oxide and steel, shows unaltered low-carbon steel microstructures below the iron oxide layer. The intact Pearlite shows that heating from ICR and LACR does not affect the steel microstructure. The ICR+LACR cross section in (d) shows the full removal of coatings and the iron oxide mill scale layer that stays intact across the steel surface. The "epoxy mount" label refers to a metallographic sample preparation process and**

**is labeled here for clarity. GB = grit blasting; ICR = induction coating removal; LACR = laser ablation coating removal; SEM = scanning electron microscopy.**

Figure 5 shows an EDS map of a GB surface-to-surface chemistry and level of contamination. As evident in Figure 5, the GB surface contains many elements, likely introduced from the impacts of the GB media on the steel. Overall, the GB surface appears to contain many contaminants.



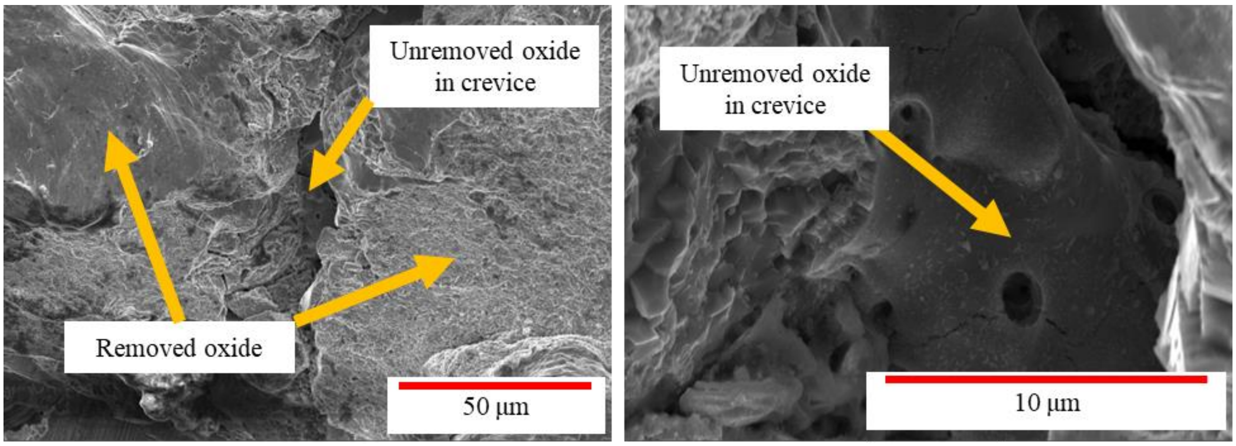

**(a)**




**(b)**

**Figure 5. (a) Energy Dispersive Spectroscopy Map of the Grit Blasting Surface at 800x Magnification and (b) Corresponding Energy Dispersive Spectroscopy Spectrum Showing the Large Number of Elements Detected on the Grit Blasting Surface Even at this Length Scale. Dark blue = Pb (lead); light blue = Sn (tin); yellow = Cu (copper); green = O (oxygen); and red = Fe (iron). Al = aluminum; C = carbon; Ca = calcium; Cl = chloride; Mn =manganese; Ni = nickel; P = phosphorus; S = sulfur; Si = silicon; Wt = weight; *σ* = standard deviation.**

In addition to introducing contaminants to the surface after GB, evidence of the remaining original coating material after blasting was present. Specifically, SEM shows the remaining iron oxide within the crevices and grooves of the surface post-GB. This observation indicates that GB has numerous elements present on the surface after GB. Furthermore, the GB process appears to bury and embed contaminants into the steel. In Figure 6, an SEM image of the GB surface shows how remnants of the iron oxide remain loosely on top of the steel.




**(a)** **(b)**

**Figure 6. SEM Micrographs of the Grit Blasting Surface Showing How Iron Oxide Remains Even after the Grit Blasting Treatment Is Completed: (a) Shows How Iron Oxide Is Found within Crevices on the Grit Blasting Surface at 600x Magnification; (b) Shown at 5000x High Magnification. SEM = scanning electron microscopy.**

*Cleanliness of Induction Coating Removal Surfaces*

Visual analysis of the ICR surfaces revealed that ICR could remove most of the coating system but not all of it. This remaining layer on the ICR surfaces was covered with residual contamination from the lead-based coating layer, which appeared as a film. The large amount of lead-based coating remaining on the surface after ICR could easily be seen visually, without a microscope. The presence of the lead-based coating was confirmed using SEM analysis, as Figure 4b shows, along with the iron oxide layer on top of the steel below the primer. Figure 7 shows the bright red-orange color of the lead-based coating and the scrape marks left from scraping away the outer coatings. XRD analysis determined that the lead-based coating consisted of red lead, a mixed valence lead oxide material ($Pb_3O_4$) that was commonly used in the past for corrosion protection on bridges.

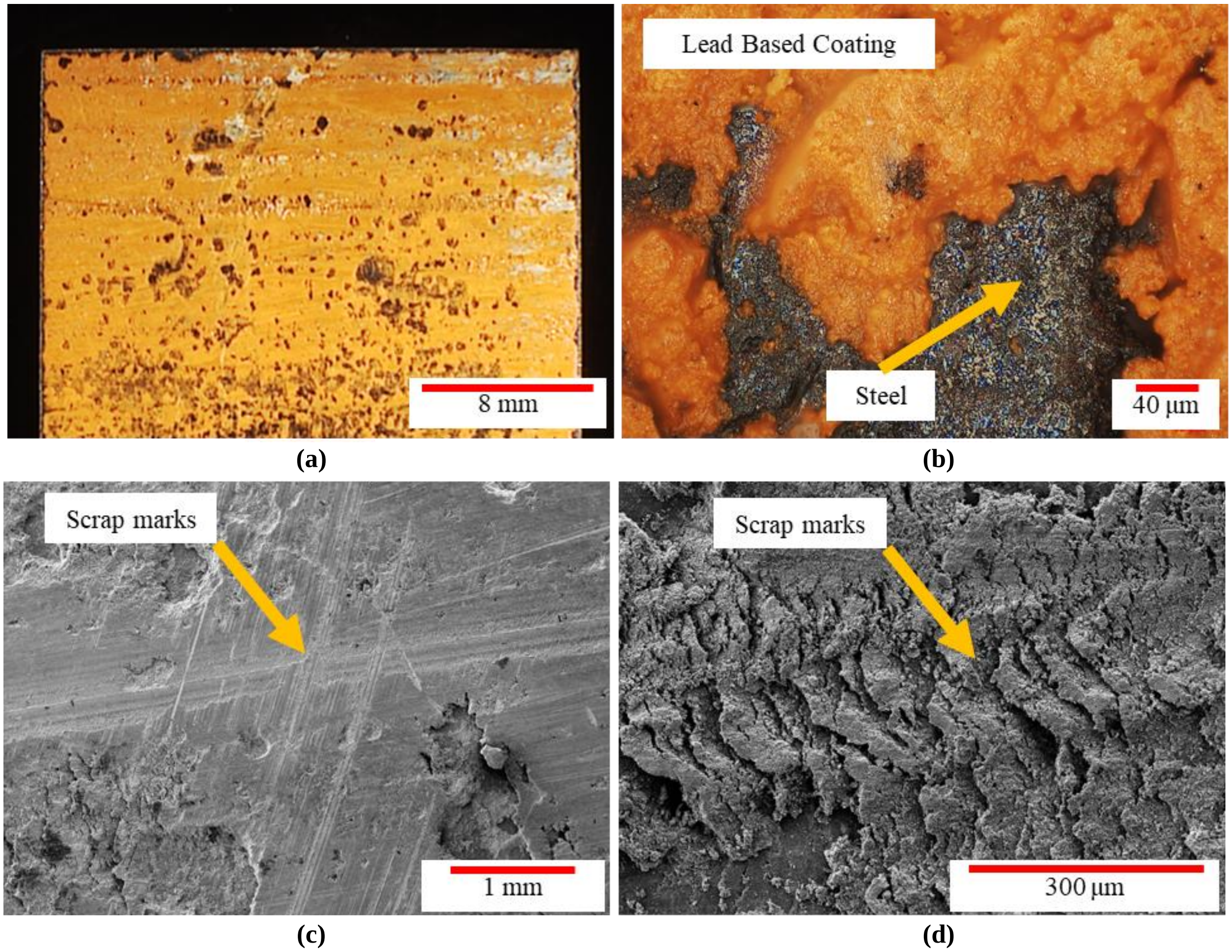


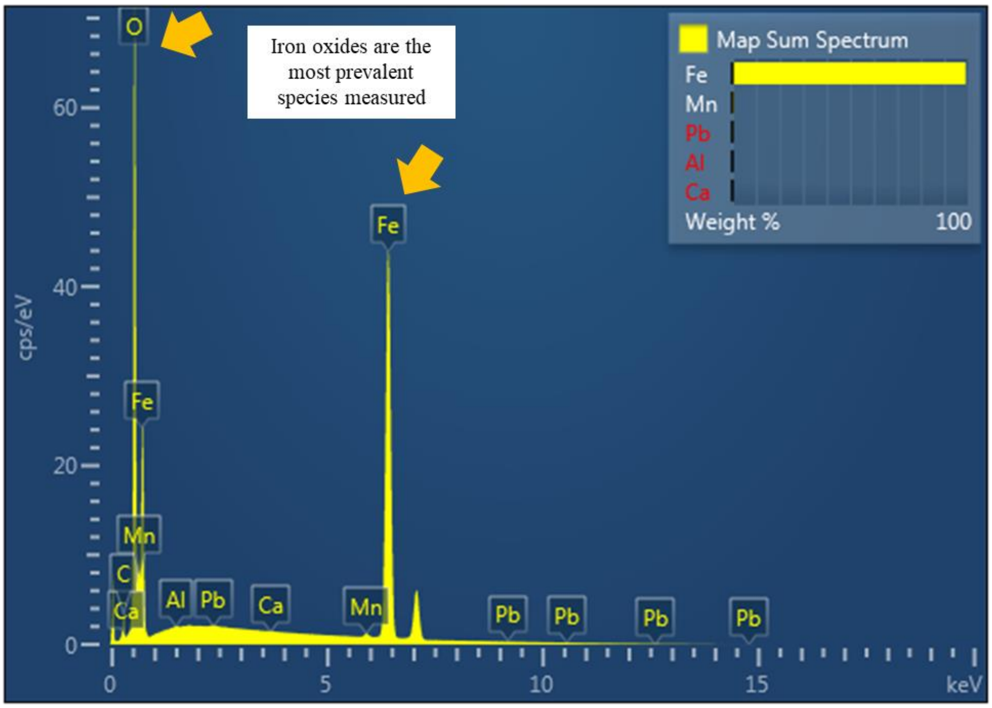

**Figure 7. Surface Appearance after Induction Coating Removal Processing: (a) Macro-Optical Image Shows the Large Amount of Remaining Lead-Based Coating on the Surface; (b) Higher Magnification Micrograph Shows Exposed Iron Oxide Using Optical Microscopy at 160x Magnification; Scanning Electron Microscopy Shows Scrap Marks after Scrapping off the Removed Coatings on the top of the Lead at: (c) 40x Magnification and (d) 160x Magnification**

*Cleanliness of ICR+LACR Surfaces*

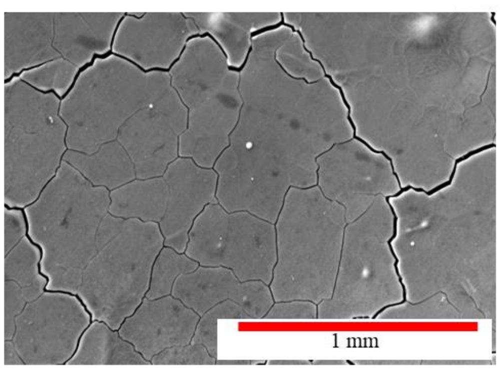
Visual analysis of the surfaces revealed that LACR applied after ICR effectively removed the lead-based coating, unlike the surfaces cleaned with ICR alone. As Figure 4c shows, the ICR+LACR surfaces contained an iron oxide layer. On closer examination with high-magnification SEM, the iron oxide surface was apparently melted. Using high-resolution SEM, the researchers determined that roughly 1 micron (equivalent to 0.039 mils) of the iron oxide layer was melted. The boundary between LACR-melted material and unmelted iron oxide can be distinguished. Figure 4c also shows that deeper into the bulk material, below the iron oxide layer, the steel did not exhibit any melting and was unaffected by the heat input from both ICR and LACR.

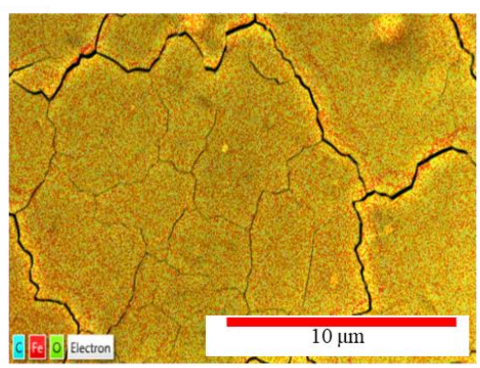
The researchers performed XRD to characterize the chemical composition of the iron oxide layer and determined that the oxide consisted of the phase's magnetite ($Fe_3O_4$) and wustite, both typical of steel mill scale.

SEM and EDS analysis of the ICR+LACR surface showed that the resulting surface condition was clean, with mostly iron and oxygen present, and only residual amounts of lead, aluminum, and calcium were detected. These elements are likely present because of contamination from the multiple previous paint layers present on the surface before coating removal. Both the smooth and rough regions on the iron oxide surface were examined in SEM. In Figure 8, SEM and EDS mapping shows how ICR+LACR leaves the surface clean with a homogenous distribution of elements and only residual amounts of lead, aluminum, and calcium.




**(a)**




**(b)** **(c)**

**Figure 8. EDS Maps Show How Homogenous the Surface Is Chemically, with a Near-Uniform Distribution of Elements. (a) The spectrum shows that mostly Fe (iron) and O (oxygen) are left on the surface, with only residual Mn (manganese) present on the steel composition and with Pb (lead), Al (aluminum), and Ca (calcium). (b) Scanning electron microscopy micrograph of the EDS-mapped area. (c) Shows the uniformity of the composition across the surface. Blue = C (carbon); red = Fe (iron); green = O (oxygen). EDS = energy dispersive spectroscopy.**

In contrast with the smoother regions, the rougher regions contained some remaining lead-based coating. Because the rougher regions contain valleys and trenches compared with the relatively smooth regions, these recessed areas make it more difficult for LACR to fully remove the primer in these areas. EDS mapping in Figure 9 shows how the lead-based coating that remains on the ICR+LACR surface is concentrated in these recessed regions.

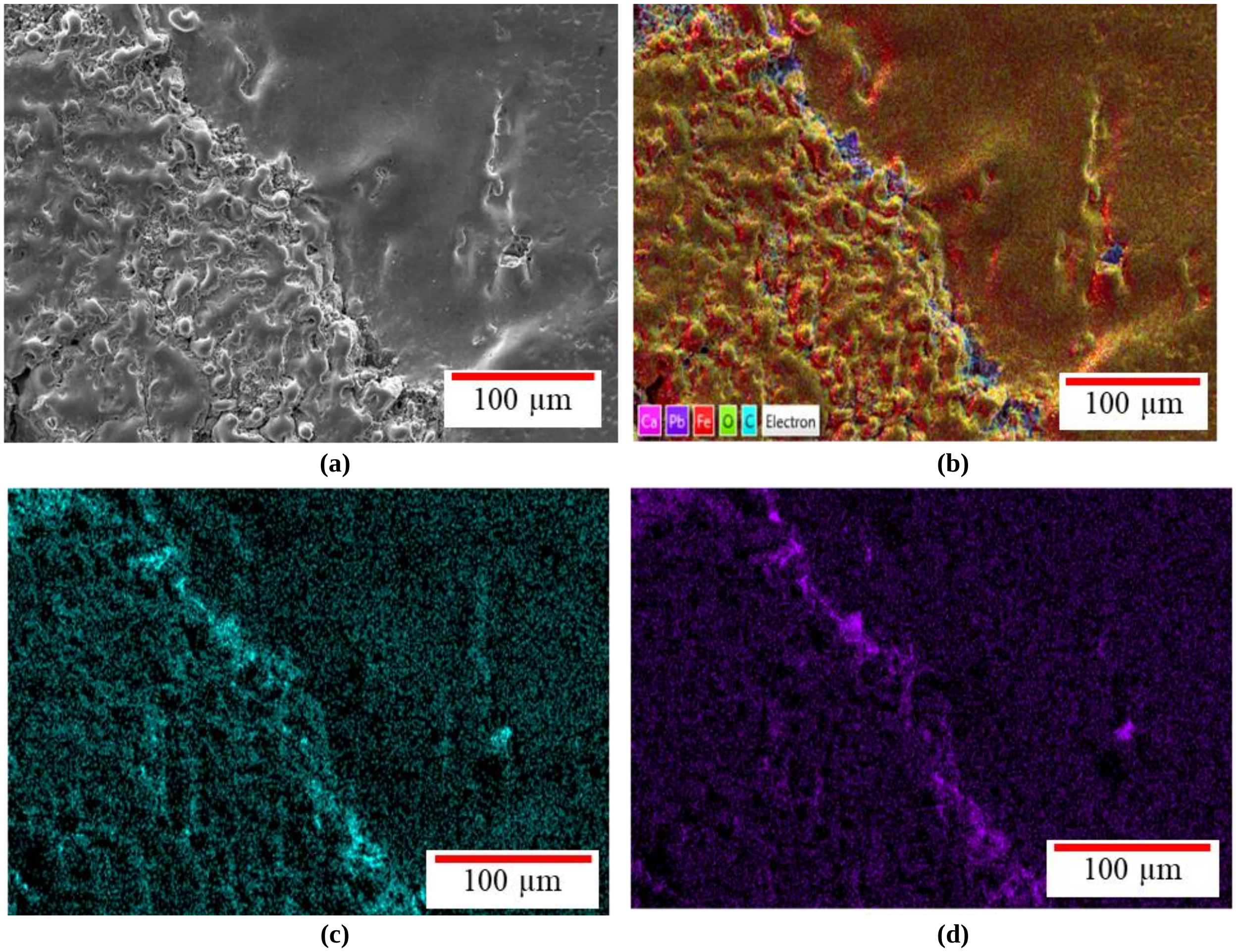



**Figure 9. EDS Maps of the Boundary between the Smooth and Rough Oxide Surface Regions: (a) Shows a Micrograph of the EDS-Mapped Area; (b) Shows the Corresponding EDS Map. (c) Carbon and (d) lead signals show how the lead-based coating is concentrated in the valley present at the boundary between the smoother and rougher regions. Pink = Ca (calcium); purple = Pb (lead); red = Fe (iron); green = O (oxygen); blue = C (carbon). EDS = energy dispersive spectroscopy.**

The researchers performed XRD to characterize the chemical composition of the iron oxide layer and determined that the oxide consisted of the phase's magnetite ($Fe_3O_4$) and wustite, both typical of steel mill scale.

Overall, the ICR+LACR surfaces were left in a much cleaner state compared with the conventionally prepared GB samples.

*Surface Profile*

KTA performed surface profile measurements on each of the surface conditions. The profile was substantially rougher on the GB surfaces, with a measured profile of 5.4 mils compared with the ICR+LACR or LACR surfaces, which were determined to have respective profiles of 2.1 and 1.9 mils. These surfaces were not specified to meet a Society for Protective Coatings surface preparation standard, but these measurements show that the profile values meet the minimum profiles requirements for several of the VDOT surface preparation methods in the *2020 Road and Bridge Specifications*, Section 411.04 (VDOT, 2020). As noted previously in the Surface Profile and Roughness section, these surface profiles reflect the distances between the highest peak and the lowest valleys. Table 7 shows the surface profile results as measured by the surface coating provider.

**Table 7. Surface Profiles Measured by KTA-Tator, Inc.**

| Sample | Testex Course Measurement, mils | Testex X-Course Measurement, mils | Average Profile Depth Measurement, mils |
|---|---|---|---|
| GB | — | 5.4 | 5.4 |
| ICR+LACR | 1.7 | 2.4 | 2.1 |
| LACR | 1.7 | 2.1 | 1.9 |

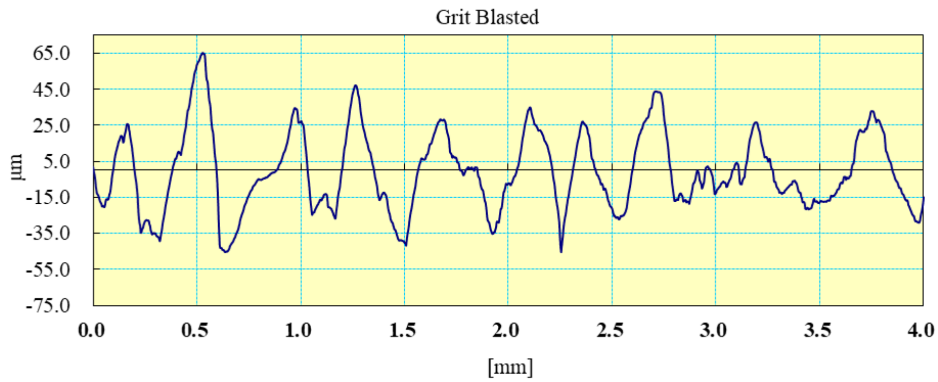
GB = grit blasting; ICR = induction coating removal; LACR = laser ablation coating removal.

Although the GB surfaces were not specified to meet a Society for Protective Coatings surface preparation standard, they were similar to a SP10-blasted surface but exceeded the single reading and average surface profile limits indicated in the *2020 Road and Bridge Specifications*, Section 411.04, Method 5 (VDOT, 2020). The focus was not on qualifying each surface-to-surface standards but on the relative surface profiles for each coating removal process.

*Surface Roughness*

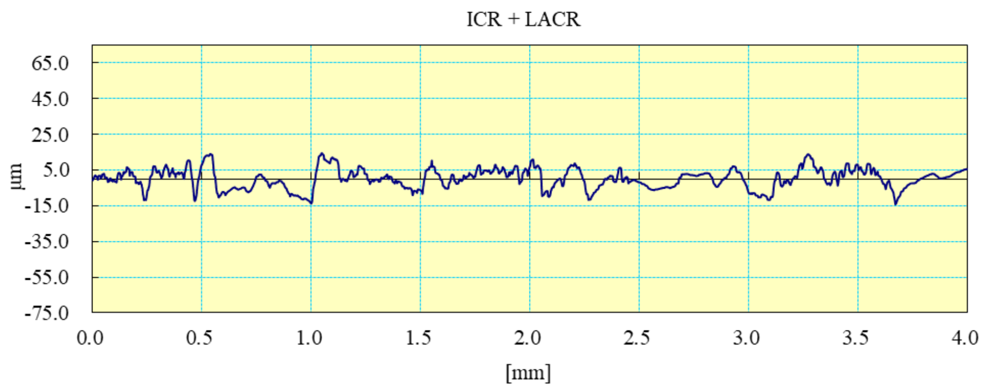
Surface roughness was a key aspect of this project because it can affect adhesion, which is commonly known. Furthermore, a large part of this research was focused on determining how the surface profile influences the adhesion of the coatings, especially considering how LACR may affect the surface roughness and associated adhesion.

Stylus profilometry was used to measure the macroscale surface roughness profile. Figure 10 shows the representative surface roughness profiles of the GB and ICR+LACR surfaces. An earlier report presented the surface profiles of the LACR-only processed surface. The profiles clearly show a difference in roughness, with respective average roughness values of 12.3 and 4.0 microns for the GB and ICR+LACR surfaces. The researchers also observed that the peak-to-valley ranges captured by profilometry closely match those that KTA measured.




**Average Roughness (Ra): 12.252** µm

**(a)**




**Average Roughness (Ra): 4.015** µm

**(b)**

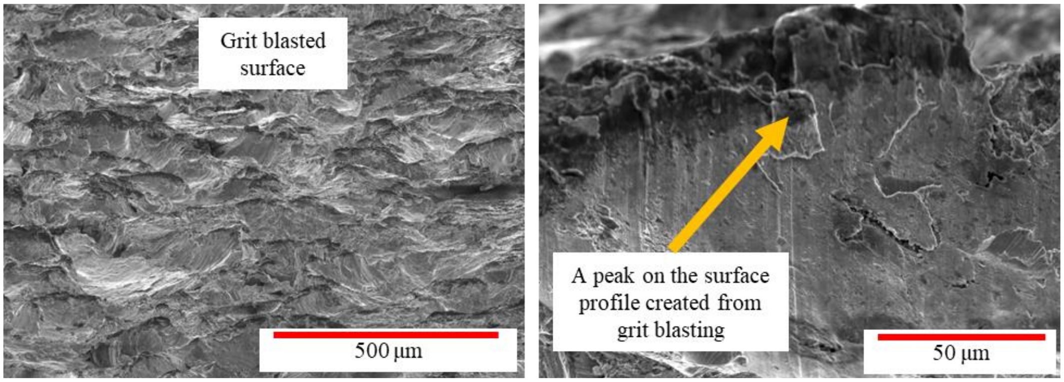
**Figure 10. Representative Profilometry Scan Surface Roughness Profiles of: (a) The Grit Blasting Surface; (b) The ICR+LACR Surface. The average roughness for each surface is noted below each respective profile. ICR = induction coating removal; LACR = laser ablation coating removal.**

The GB surface is a high-amplitude but low-frequency surface profile, created from the large plastic deformation occurring on the steel during grit media impacts occuring during the GB process. On the other hand, the ICR+LACR surface contains a much smaller amplitude but higher frequency profile. The ICR+LACR surface also has an average roughness of about one-third of the GB surface. The ICR+LACR surface is smoother than the GB surface because it is covered in a continuous mill-scale iron oxide layer that is not removed through either ICR or LACR. None of these steel samples had undergone GB during their original fabrication in the 1940s.

In addition to profilometry and surface profile measurements, SEM was used to obtain a qualitative view and understanding of the surface topography and roughness.

*Scanning Electron Microscopy Assessment of Surface Roughness and Profile*

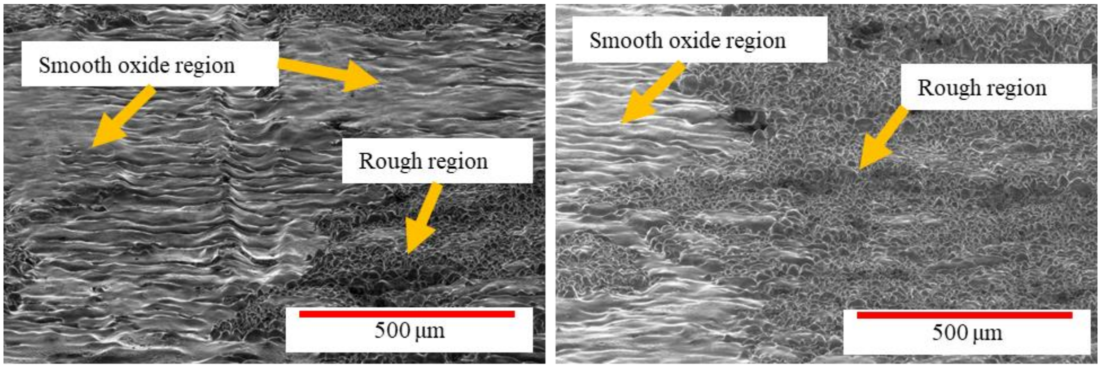
Figure 11 shows a SEM image of the GB surface. The image shows that the topography matches what was determined through surface profile and roughness measurements. The surface consists of randomly distributed peaks and valleys, with clear impact craters left behind where grit media had deformed the steel surface. This finding agrees with the surface roughness measurements showing high-amplitude peaks and valleys. The finding also agrees with the cross-sectional analysis in which impacted grit media is observed below the surface, along with the significant plastic deformation in the near-surface region. The relatively smooth appearance of the slopes can be observed, whereas the large distance between peaks and valleys is also apparent in the image.




**(a)** **(b)**

**Figure 11. Scanning Electron Microscopy Micrographs Showing: (a) Details of the Grit Blasted Surface; (b) A Magnified View of the Grit Blasted Surface and the Side of a Peak Showing the Smoothness Present on this Smaller Scale.**

Similarly, SEM imaging of the ICR+LACR surface in Figure 12 shows how a relatively smooth surface is left. No bare steel is observed, and an iron oxide mill scale layer continuously covers the surface. On closer examination, the researchers observed two different roughness profiled regions on the surface. Both rougher and smoother surface regions were identified that were randomly distributed across the surface. The smoother areas consist of iron oxide, with a slowly undulating appearance without any sharp, distinct peaks or valleys. The rougher regions present well-defined and closely spaced peaks and valleys. These observations agree with the surface roughness measurements, which showed the high-frequency, low-amplitude surface profile.




**(a)** **(b)**

**Figure 12. Scanning Electron Microscopy Micrographs Show the Distribution of Rough and Smooth Regions across the Surface of Induction Coating Removal and Laser Ablation Coating Removal Cleaned Samples. Both (a) and (b) show how the distribution of rough and smooth areas varies across the surface.**

## Mechanical Testing

### *Tensile Testing*

Because the surface analysis showed that ICR was not effective at removing all the coating on the surface and therefore would not be used on its own for bridge coating removal, tensile testing was not conducted on the ICR samples. Figure 13 shows complete stress versus strain data for each tensile test. All the curves follow a typical stress versus strain behavior consistent with typical steels used for bridges from the 1940s. No indications suggest that either the LACR or ICR+LACR, when used within the parameters in this study, caused a change in the overall mechanical behavior of the steel. The variations in the curves are likely due to the expected variations in tensile testing of any steel samples.

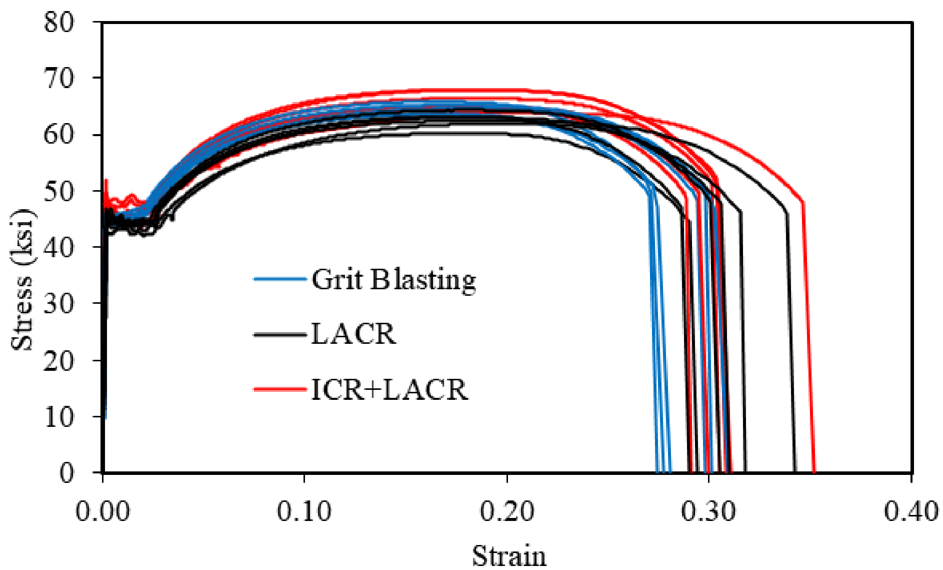



**Figure 13. Stress versus Strain Data for Tensile Tests on Steel Samples Subject to Grit Blasting and Cleaned Using LACR and ICR+LACR with a Maximum Surface Temperature of 325 °F. ICR = induction coating removal; LACR = laser ablation coating removal.**

Table 8 shows the average modulus of elasticity, yield stress, ultimate strength, and percentage elongation for each coating removal method. The modulus of elasticity of each of the three conditions is similar to the expected value of 29,000 ksi for steel. Because the steel for these samples was taken from a retired bridge, the type is unknown. However, based on the tensile test data, it appears to be similar to an ASTM A36 steel, which has a minimum yield strength of 36 ksi, a minimum ultimate strength of 58 ksi, and a minimum elongation of 23% (ASTM International, 2019). As Table 8 shows, the average yield stress, average ultimate strength, and average percentage elongation for each of the three conditions are similar, and all exceed the expected results for an ASTM A36 steel. It is important to note that the maximum measured surface temperature during ICR was 325 °F. If the surface temperature were to increase drastically, then changes in the mechanical properties could occur.

**Table 8. Average Tensile Testing Results Subject to GB, LACR, and ICR+LACR with a Maximum Surface Temperature of 325 °F**

| Coating Removal Method | Average Modulus of Elasticity, ksi | Average Yield Stress, ksi | Average Ultimate Strength, ksi | Average Percent Elongation, % |
|---|---|---|---|---|
| GB | 25,500 | 45.1 | 64.6 | 23 |
| LACR | 25,000 | 44.7 | 62.5 | 24 |
| ICR+LACR | 26,800 | 46.5 | 65.9 | 28 |

GB = grit blasting; ICR = induction coating removal; LACR = laser ablation coating removal.

### *Fatigue Testing*

Figure 14 shows the fatigue test results of the LACR and ICR+LACR samples. In Figure 14, the solid lines represent the AASHTO fatigue detail categories A through E, whereas the dashed lines indicate the constant amplitude fatigue limits for each AASTHO fatigue detail category (AASHTO, 2020). As Figure 14 shows, all the samples reached 5 million cycles and were considered run-outs. This outcome is why all the results lie on the same point in the figure. All the data points lie above the line for a fatigue detail category A, which is steel base metal, meaning that the LACR or ICR+LACR samples can be expected to have similar fatigue performance compared with steel base metal not subject to any coating removal process. This result shows that LACR and ICR+LACR, when used at the parameters per this study, do not cause a degradation in the fatigue performance of the steel. Similar to the mechanical properties, increasing the surface temperature far past 325 °F could cause a change in fatigue performance.

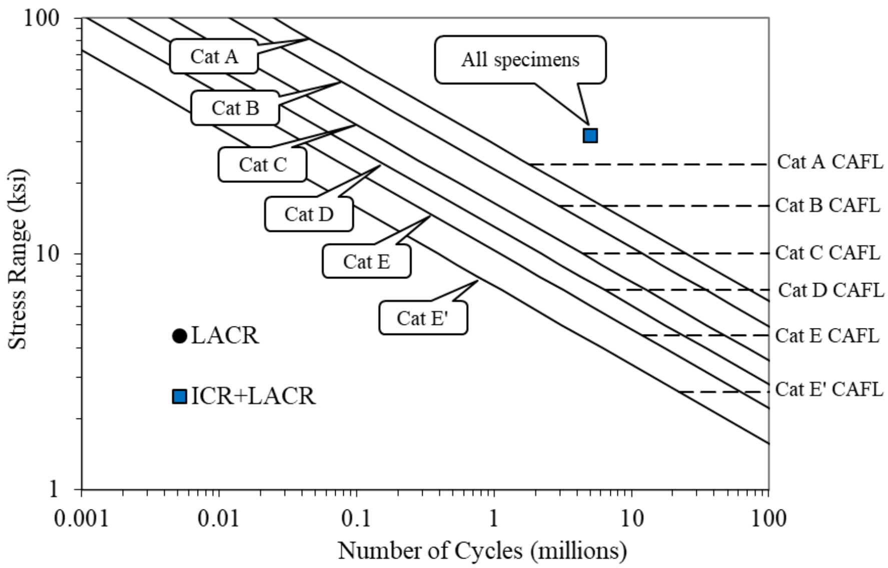



**Figure 14. Fatigue Test Results on Steel Samples Subject to LACR and ICR+LACR with a Maximum Surface Temperature of 325 °F. CAFL = constant amplitude fatigue detail; Cat = category, representing AASHTO fatigue detail category; ICR = induction coating removal; LACR = laser ablation coating removal.**

## Adhesion Testing

Figure 15 shows the PATTI test results for all the samples recoated with the OZ primer. The empty square in each box-and-whisker plot represents median (i.e., average) values. The mode for each sample dataset is shown as a line through the middle of the box. The lower and upper bounds for the boxes are the 25th and 75th percentiles, and the whiskers represent the 10th to the 90th percentile range. Global minimums and maximums are represented with a short horizontal line below and above the whiskers, respectively. The horizontal red line across the graph represents the minimum accepted adhesion value of 600 psi, as stated by the coating manufacturer.

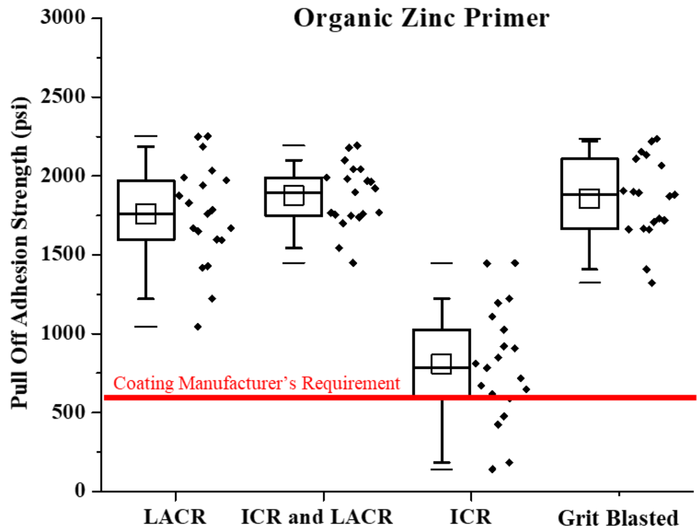



**Figure 15. Pneumatic Adhesion Tensile Testing Instrument Test Results for the Organic Zinc Primed Surfaces. The red line at 600 psi marks the minimum accepted adhesion value, as stated by the coating manufacturer. The mode for each sample dataset is shown as a line through the middle of the box. The lower and upper bounds for the boxes are the 25th and 75th percentiles, and the whiskers represent the 10th–90th percentile range. Global minimums and maximums are represented with a short horizontal line below and above the whiskers, respectively. ICR = induction coating removal; LACR = laser ablation coating removal.**

Figure 15 shows that the adhesion for the LACR, ICR+LACR, and GB samples met the coating manufacturer's adhesion requirements, whereas approximately 25% of the ICR samples do not meet the manufacturer's adhesion requirements. The median adhesion values for the ICR, LACR, ICR+LACR, and GB samples were determined to be 809.2, 1,758.6, 1,876.7, and 1,854.9 psi, respectively. The median values closely matched the modes for each sample type.

SEM analysis of the PATTI fracture surfaces found that the GB surfaces contained regions that had failed cohesively, leaving either regions with zinc particles and primer, or regions with only a thin film of epoxy on the substrate. Similarly, the LACR surfaces also exhibited cohesive coating failure in the primer layer, with the surface exhibiting, again, both regions with zinc particles plus epoxy primer and regions with only epoxy primer (Moffat, 2023).

Figure 16 shows the PATTI data for the IOZ-primed samples using the same box-and-whisker information shown in Figure 15. The horizontal red line represents the minimum accepted adhesion value of 200 psi, as stated by the coating manufacturer. Figure 16 shows that the adhesion for the LACR, ICR+LACR, and GB samples all meet the coating manufacturer's requirements for adhesion, whereas approximately 15% of the ICR samples do not. The average adhesion values for the ICR, LACR, ICR+LACR, and the GB surface were found to be 462.7, 935.6, 1,006.0, and 1,003.7 psi, respectively. In general, the samples recoated with IOZ primer displayed lower adhesion across all coating removal techniques compared with the OZ-coated surfaces. This result is likely due to the significantly lower strength and toughness of the inorganic silica matrix compared with the organic epoxy matrix binder used in the OZ primers.

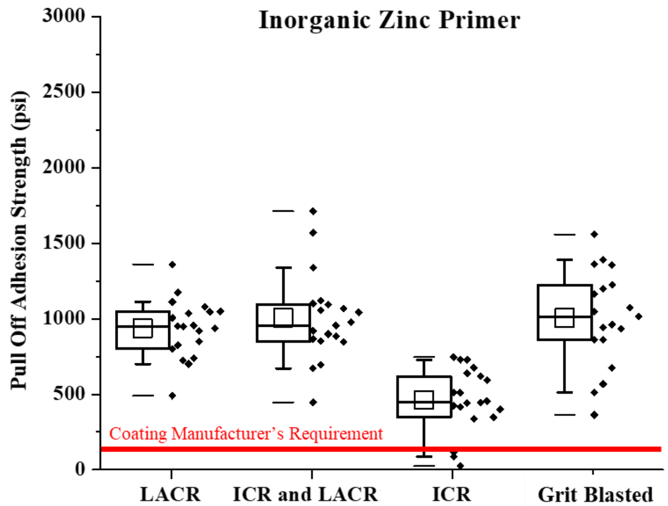



**Figure 16. Pneumatic Adhesion Tensile Testing Instrument Data for the Inorganic Zinc-Primed Samples. The red line represents the minimum adhesion value of 200 psi, as stated by the coating manufacturer. The mode for each sample dataset is shown as a line through the middle of the box. The lower and upper bounds for the boxes are the 25th and 75th percentiles, and the whiskers represent the 10th–90th percentile range. Global minimums and maximums are represented with a short horizontal line below and above the whiskers, respectively. ICR = induction coating removal; LACR = laser ablation coating removal.**

In contrast to the OZ-coated samples, SEM analysis showed that the IOZ-coated samples exhibited both adhesive and cohesive failures, exposing the steel substrate and fracturing within the IOZ primer matrix. The IOZ primed surfaces showed regions of adhesive failure that still left the zinc pigment fully encapsulated within the silica matrix, and the cohesively failed regions tended to occur around the presence of aluminum particles that were present in the primer.

For the IOZ primer, the research team observed a lower adhesion value for both the GB and the ICR+LACR cleaned surfaces compared with the OZ primer. The LACR and GB surfaces all showed acceptable performance, but some of the ICR surfaces did not. This condition can be seen in Figures 15 and 16, as the LACR, ICR+LACR, and GB test values exceeded the minimum manufacturer adhesion value, but some of the ICR sample values did not. Additional detailed research comparing the adhesion behavior of the OZ and IOZ primers is available in other publications associated with this research project (Moffat, 2023; Moffat et al., 2024; Moffat et al., unpublished).

## Field Studies

### Route 695 Bridge over Route 460

According to VTRC Final Report No. 20-R1, the original coating on Route 695 Bridge had been in service for about 44 years before VDOT's first use of LACR on a bridge (Fitz-Gerald et al., 2019). Thickness measurements of that coating indicated approximately 6 mils on the girders and approximately 11 mils on the cross frames. After LACR was successfully completed in August 2017, as Figure 17 shows, the areas were recoated with a VDOT System F coating system. The inspector estimated that approximately 50 square feet of surface area had been cleaned with LACR during a 3-day period, with the LACR-cleaned surfaces being recoated each day with primer. The coating system used was an Epoxy Mastic Aluminum II primer with an Acrolon 218 HS finish coating. The inspector also noted that, although LACR was extremely clean and favorable for workers and the environment, the coating removal rate was too slow to be used for production.

(a) (b)

(c)

**Figure 17. Laser Ablation Coating Removal and Recoating of Route 695 Bridge in August 2017 Showing: (a) After Coating Is Removed on Facia Girder Using Laser Ablation Coating Removal; (b) After Prime Coat Is Applied to Facia Girder No. 4 at Abutment B; (c) After Finish Coat Is Applied to Cross Frame between Girders No. 3 and 4 and to the Bottom of Girder No. 4.**

*Coating Condition Evaluation After 7 Years of Service*

The research team conducted a field assessment on Route 695 Bridge on July 10, 2024, approximately 7 years after LACR had been used to remove the original coating, and a new coating, meeting the requirements for VDOT Coating System F, had been reapplied to selected locations on the bridge. Before the field assessment, the researchers reviewed the interim 2016, 2018, 2020, and 2022 inspection reports. The reports indicated "rust/corrosion and paint peeling on structural steel," some of which can be seen in Figure 17. Several photographs in the reports included examples of coating damage on the girders. However, during the field assessment in July, although several small rust spots were observed along the edge of the girder in the areas where LACR was used to prepare the surface, "paint peeling on structural steel" was not observed in the recoated areas, as Figure 18 shows.

(a) (b) (c) (d)

**Figure 18. Examples of Areas Cleaned with LACR Alone and Recoated and Areas that Were Not. (a) The girder on the left (girder no. 3, near abutment B) was not cleaned and recoated, whereas the cross frame and girder end on the right (girder no. 4, near abutment B) were cleaned with LACR and recoated. (b) Magnified view of stain and uncoated test area on recoated steel cross frame is also seen near the top of the cross frame, shown in (a). The stain is due to a leaking joint, allowing moisture to seep between the bottom of the end bolster and the top of the secondary member interface because of the failed joint. The uncoated corroded area in the middle of the photo was intentionally left uncoated as part of the first study to observe a LACR cleaned but uncoated area over time. (c) Coating loss and exposed steel are shown where LACR repair would benefit the bridge by mitigating steel loss on the bottom flange and web at the bay 2 side of girder no. 3 near abutment B. (d) The transition on exterior girder no. 4 near abutment B from the original coating to the LACR cleaned and recoated area illustrating how the old coating has numerous small rust sites. LACR = laser ablation coating removal.**

The research team also reviewed the condition of the expansion joint at abutment B because this joint is above the area where the girder ends were recoated. The 2018 inspection report indicated that both abutments have compression joint seals, but at abutment B, the joint is depressed up to a ½ inch for 12 feet. In the 2020 inspection report, the joint is depressed up to 1 inch for 12 feet. In the 2022 inspection report, the joint seal at abutment B was loose or had fallen through for 12 feet. During the field visit in July of 2024, the joint seal had clearly fallen, and the joint was open. Based on this information, researchers concluded that the expansion joint had not been acting as a barrier to the ingress of water and salts for at least 2 to 4 years, which had accelerated corrosion damage of the girder ends in the originally coated areas.

## Route 301 Bridge over Pamunkey River

### *Coating Removal*

Coating removal work on Route 301 Bridge started in late October and was completed in early November 2023. During the field demonstration of ICR+LACR on Route 301 Bridge, several adjustments had to be made because of unexpected cold temperatures, the malfunctioning of one of the laser control heads, pack rust in the bearing areas, and the tight spacing between the diaphragm and back wall—all which resulted in challenges for the specialty subcontractor.

During the week of work, the nighttime low temperatures reached 40 °F, which caused issues with the specialty subcontractor's equipment (Weather Underground, 2024). The specialty subcontractor made adjustments during the first week of the project to address pressure issues with the ICR cooling system and used localized heating units to address this issue. These remedies improved the coating removal rates as the project progressed, and the specialty subcontractor was able to adapt the equipment for bridge coating removal. Therefore, the specialty subcontractor was able to perform the coating removal task within the estimated time, even with the delays from the unexpected challenges.

During LACR, the integrated fume extraction nozzle malfunctioned, which rendered the unit that captured air contaminants at the source inoperable. These malfunctions resulted in greater use of a newer model LACR control head, the cleanLASER effiSCAN, which collected fumes through an unintegrated and mounted nozzle-type fume extraction system.

The tight area between the diaphragm and abutment back wall, as seen in Figure 19a, provided insufficient distance to clean the back of the diaphragms using the ICR and LACR equipment. As Figure 19b shows, the protruding girder sections were accessible to and cleaned by ICR+LACR. The areas on the backside of the diaphragm were cleaned using mechanical means. Having these two coating removal methods close together showed the difference in the rate of flash rusting when LACR and conventional coating removal methods are compared, which has been observed in laboratory work. As Figure 19c shows, the mechanically cleaned surfaces exhibited flash rust in less than 24 hours compared with the LACR-cleaned surfaces, which slowly showed flash rust after several days. Both the ICR and LACR heads require modification to access similarly tight areas.

**(a)**

**(b)**

**(c)**

**Figure 19. Difficulty Accessing the Back Wall Area with Induction Coating Removal and LACR and Flash Rust Comparison in this Area. (a) Capturing bay 1 channel 1, the diaphragm is close to the back wall. (b) Capturing bay 5 channel 3 after performing the final cleaning with LACR on the girder end but before mechanically removing the coating on the diaphragm and around the nuts, bolts, and washers; (c) After the diaphragm coating was removed and the steel was left uncoated overnight (less than 24 hours), but the LACR-cleaned surface did not change. LACR = laser ablation coating removal.**

The thicker lamellar and pack rust formations in Figure 20 that existed on this bridge also required mechanical means to remove the adherent corrosion layer completely to ensure corrosion does not reinitiate. Ideally, this process would include the removal of all salts trapped between rust layers or other materials like bearing pads, but this step is not practical. Therefore, properly cleaning the accessible areas, like flanges, webs, and other uncovered steel surfaces before recoating them is important to mitigate continued corrosion loss of steel and rust staining after the steel is recoated.

(a) (b) (c) (d)

**Figure 20. Rust Products on Bridge Girders and Bearings Result in Several Types of Corrosion, Including Lamellar and Pack Rust Formations, often due to Leaking Bridge Joints. (a) Before coating removal, the web and bottom flange, plus the bearing, exhibit corrosion attack that is voluminous in nature. (b) Loose rust product and more adherent product are shown on the bearing, bottom flange, and web. (c) A more lamellar corrosion behavior is seen along the upper part of the web and the top flange. (d) Removing this product, which can be tightly adherent, can require mechanical removal, which is shown in this case using a pneumatic chisel breaking off the more tightly adherent product that must be removed to ensure salts (chlorides) are exposed and removed before performing a final cleaning step with Laser Ablation Coating Removal.**

The specialty subcontractor was able to prepare all the coated surfaces for recoating within the 3-week contract period. During this time, the specialty subcontractor indicated that they were able to rectify the temperature and chiller-related issues at the jobsite. They also shared that the ICR and LACR manufacturers indicated they could modify induction and laser equipment so that it would be able to access the tighter spaces.

During ICR and LACR, the research team monitored the steel's surface temperature to ensure it did not exceed 400 °F, which was the maximum value specified in the contract. On average, ICR-induced temperatures were approximately 290 °F, with the highest value recorded at 390 °F and the lowest at 220 °F. The temperature range was mainly due to the specialty subcontractor changing the size of the induction head or adjusting the output of the device. When the temperature of 390 °F was reached, the specialty subcontractor quickly reduced the output from 70 to 60% to ensure the temperature would remain lower. During this process, VDOT decided that an additional technical assistance project should be initiated to evaluate high-strength bolts subject to heat during ICR. This additional technical assistance project will subject bolts to elevated temperatures in both stressed and unstressed conditions. The results from this additional technical assistance project will eventually be made available as an auxiliary publication as part of the supplementary materials in conjunction with this report.

After completing the work, the researchers determined that calculating an actual coating removal rate would be difficult. When comparing the ICR+LACR with the GB work on this project, it is important to recognize that other factors can strongly affect the total project cost and schedule, although a typical value for the coating removal rate for a particular job could be estimated. Table 9 shows some of those factors for GB and ICR+LACR. The items listed in the table can add days to the project schedule, plus additional personnel hours, both of which influence the total project cost. For example, erecting platforms for GB is commonly needed and requires several craft workers and days to erect and then remove them. For ICR+LACR, however, if an aerial work platform can be used for a project, work can begin almost immediately, and the cost associated with that additional time to erect and remove platforms is eliminated. In addition, if the cost of managing the waste is considered, then GB is expected to generate a greater quantity of waste to transport and dispose of at the end of the project compared with ICR+LACR. Therefore, combining ICR with LACR could make the combined coating removal process an alternative to GB for smaller area removal operations because ICR+LACR would often provide time and labor savings compared with GB for the items in Table 9.

**Table 9. Examples of Factors that Can Influence the Contractor's Coating Removal Cost when Comparing Grit Blasting and ICR+LACR**

| Grit Blasting | ICR+LACR |
|---|---|
| Erecting platforms | Using aerial work platforms is possible instead of erected platforms |
| Installing tarping and sealing containment | Installing ground cover, poly, tarpaulins, and so on, as well as laser curtains |
| Running hoses and preparing equipment for abrasive blasting | Running hoses and positioning ventilation systems |
| Removing hoses, tarps, and sealing materials | Removing tarping, laser curtains, and hoses |
| Removing platforms | Removing platforms if aerial work platforms cannot be used |
| Cleaning up | Cleaning up |

ICR = induction coating removal; LACR = laser ablation coating removal.

Fortunately, the coating removal area can be estimated with reasonable accuracy. For each bearing line, approximately 450 square feet of coating was removed, and because ICR+LACR was used along three bearing lines, the total coating removal area was approximately 1,350 square feet. The specialty subcontractor started work on October 30, 2023, and completed work on November 16, 2023. However, during that period, equipment issues slowed work efficiency for some days, and 1 full day was used to demonstrate the technology to VDOT staff. Also, this period included several weekends. Therefore, a conservative coating removal estimate was determined to be 100 square feet per day. However, this coating removal rate could increase as the ICR and LACR equipment is better ruggedized for the field environment and specialty subcontractor crews become more accustomed to working on bridges.

Comparisons between the coating removal rates on Route 301 Bridge and in a controlled environment, as shown previously in Table 6, illustrate that the coating removal rate on Route 301 Bridge is reasonable. It is also reasonable to expect that the coating removal rate will increase in the future as ICR and LACR technology improves.

*Environmental Evaluation*

During the ICR portion of the project, workers removed the coating using hand scrapers. No wind was present during the ICR portion, so additional protections in the form of tarpaulins were not installed to limit the dispersion of removed coatings. In general, small strips and pieces of coating were removed and recovered via high-efficiency particulate air vacuuming of the girders or poly. Larger pieces were recovered by hand and placed in a waste drum. During ICR on the bridge's exterior girder, the research team observed that the poly ground covering stopped just beyond the girder surface, and a minor amount of coating was deposited beyond the edge of the poly and onto the riprap. The material was subsequently recovered and properly managed as hazardous waste.

The specialty subcontractor set up a control area prior to any ICR or LACR work. The control area included Class 4 laser signage for the LACR and an electromagnetic field warning sign for ICR outside the cordoned-off regulated area (Laser Institute of America, 2014). Electromagnetic fields can potentially disrupt metallic implants, such as pacemakers, and could present an unreasonable hazard to susceptible populations. Workers also placed laser curtains around the immediate LACR work area to block the public from the possibility of inadvertently viewing laser light. The LACR curtained work area was equipped with additional general mechanical ventilation using a dust collector with 12-inch flexible ducting to evacuate potential fumes from the work area. Workers inside the control area wore laser safety eyewear for protection from the 1,000-watt laser at a wavelength of 1,064 nm and half-face respirators for protection from the potential metal fumes generated through the LACR and ICR processes. Overall, this control area successfully provided protection to the public and to the workers during both ICR and LACR work. All environmental controls employed during the LACR portion of the project were consistent with previous VDOT studies (Rickard, 2018, 2022, 2024; VDOT, 2017).

The researchers observed visible fumes during all tasks the specialty subcontractor completed. The fume was most evident during the cleanLASER effiSCAN LACR unit usage, whose mounted fume extraction nozzle was cumbersome for the employees working in tight spaces. Employees were observed removing the LACR fume extraction nozzle during operation (Figure 21a). Even when mounted, the LACR fume extraction nozzle was several inches away from the coating surface, decreasing the nozzle's effectiveness. In addition, the ICR device was not designed with an integrated fume extraction nozzle, so capturing contaminants was less efficient (Figure 21b).

(a) (b)

**Figure 21. Fume Extraction Issues with LACR and ICR.(a) Employees observed using the effiSCAN LACR with the fume extraction nozzle removed; (b) The ICR unit was not equipped with any fume extraction, and workers were observed holding a 12-inch flexible duct near the work area in an attempt to capture dust and fume. ICR = induction coating removal; LACR = laser ablation coating removal.**

LACR systems with appropriately designed fume extraction systems are critical for controlling and recovering the waste generated during the removal activity. Given the uncertainty of whether the technology would temporarily bind the lead or other heavy metals similar to steel GB for the removal process to subsequently pass the toxic characteristic leaching procedure test, the researchers determined that total analysis for metals and the "Rule-of-20" would be used to determine the waste characterization until additional studies are conducted. For the ICR systems, appropriate controls such as poly and tarpaulins are required to be installed and maintained to conform with the regulatory requirements and *2020 Road and Bridge Specifications* (VDOT, 2020). In this study, the researchers assumed that the waste was hazardous for lead and was disposed of as lead waste without performing a toxic characteristic leaching procedure characterization test.

*Industrial Hygiene Evaluation*

The area sample for carbon monoxide was below the LOD, indicating ventilation in the workspace was sufficient to remove any accumulations of carbon monoxide. Carbon monoxide measurements were similar to those observed in previous sampling events at Norton Sandblasting, where carbon monoxide levels did not exceed background levels.

At Route 301 Bridge, PBZ samples for aldehydes ($n$ = 3), which included acetaldehyde, benzaldehyde, crotonaldehyde, formaldehyde, glutaraldehyde, m-tolualdehyde, and valeraldehyde, were below LOD. Aldehyde results at Route 301 Bridge were like those observed in previous cleanLASER 1000 LACR and cleanLASER 1000 LACR+ICR work, for which results were also below the LOD for the same analytes. Aldehyde measurements did not exceed any regulatory limits.

PBZ samples for acetic acid ($n$ = 3) and phthalic anhydride ($n$ = 3) indicated that coating removal with the cleanLASER effiSCAN LACR+ICR produced low levels of phthalic anhydride in one sample (0.0075 mg/m$^3$), and it did not produce measurable concentrations of acetic acid in any of the samples. Real-time area measurements of nonspecific acid gases in the exhaust trailer indicated a peak background acid gas concentration of 1.1 ppm. This VDOT project was the first one in which acid gases were measured using gas-specific methodology. Acid gas measurements did not exceed any regulatory limits.

Of the organics evaluated in the organic panel described in Table 2 in the Methods section, only isopropyl alcohol was observed to be above the LOD in one sample at 1.8 mg/m³. Isopropyl alcohol wipes are used to clean the LACR focusing lens and may not have been created as a product of thermal decomposition. Similar low levels of organic vapors were observed in the 2022 VDOT cleanLASER 1000 LACR+ICR work at Norton Sandblasting, in which detectable levels of ethyl acetate, isopropyl alcohol, methyl ethyl ketone, toluene, trichloroethylene, and xylene were observed. Organic sample results during previous events were also well below applicable regulatory limits.

The results of the VDOT PBZ samples for cadmium, chromium, iron, lead, and zinc and the specialty subcontractor's PBZ sample results for lead that were compared with the data from the previous University of Virginia and VDOT studies—18M-049 (Rickard, 2018), 22M-015 (Rickard, 2022), 23S-054 (Rickard, 2024), VDOT (2017), and EI Group (2016)—with these reports available as supplementary materials. As in these previous studies, the results of lead were above the LOD (Table 10). The results of the cadmium, chromium, iron, and zinc PBZ samples were well below regulatory limits during all sampling events.

**Table 10. Comparison of Personal Air Sampling Results for Metals Using the cleanLASER 1000 LACR, the cleanLASER 1000 LACR+ICR, and the cleanLASER effiSCAN LACR+ICR**

| **Study** | **2016–2018: VDOT Data** | | | | **2022: VDOT Lab Data** | | | | **2023: VDOT and Specialty Subcontractor Field Data** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **cleanLASER 1000 LACR** | | | | **cleanLASER 1000 LACR+ICR** | | | | **cleanLASER effiSCAN LACR+ICR+Grinding** | | | |
| Analyte Reported in µg/m³ | *n* | GM | GSD | 95th UCL | *n* | GM | GSD | 95th UCL | *n* | GM | GSD | 95th UCL |
| Cadmium | 6 | < 0.5 | | | 3 | < 19.9 | | | 4 | < 0.23 | | |
| Chromium | 6 | < 9.3 | | | 3 | < 17.7 | | | 3 | 28.40 | 3.3 | 201.1 |
| Iron | 4 | < 13.2 | | | 3 | < 28.8 | | | 4 | 408.00 | 2.6 | 1958 |
| Lead | 6 | 5.1 | 2.6 | 24.7 | 5 | 10.8 | 2.7 | 53.9 | 22 | 272.00 | 4.5 | 3236 |
| Zinc | 4 | < 3.6 | | | 3 | < 12.4 | | | 4 | 5.95 | 1.2 | 7.62 |

GM = geometric mean; GSD = geometric standard deviation; ICR = induction coating removal; LACR = laser ablation coating removal; UCL = upper confidence limit.

The samples collected at Route 301 Bridge indicated lead exposures in several orders of magnitude greater than those observed with the cleanLASER 1000 LACR and cleanLASER 1000 LACR+ICR. Unlike the 2016–2018 cleanLASER 1000 LACR data and the 2022 cleanLASER 1000 LACR+ICR data. The metals chromium, iron, lead, and zinc were observed to be above LOD at Route 301 Bridge, and when exposures are above regulatory limits, additional controls such as us PPE are warranted.

The ExpoStats calculator was used to visually show differences between personal lead exposures when using the cleanLASER 1000 LACR with built-in fume extraction (Lavoué et al., 2015), the cleanLASER 1000 LACR with built-in fume extraction and ICR, and the cleanLASER effiSCAN LACR with the mounted fume extractor and ICR (Figure 22). The vertical red line indicates the maximum acceptable concentration of 50 µg/m³. When lead exposures exceed, or are likely to exceed, the occupational exposure limit of 50 µg/m³ as an 8-hour time-weighted average, additional control measures, such as engineering and administrative controls, medical surveillance of employees, and personal protective equipment (PPE, such as coveralls and respirators, is required.

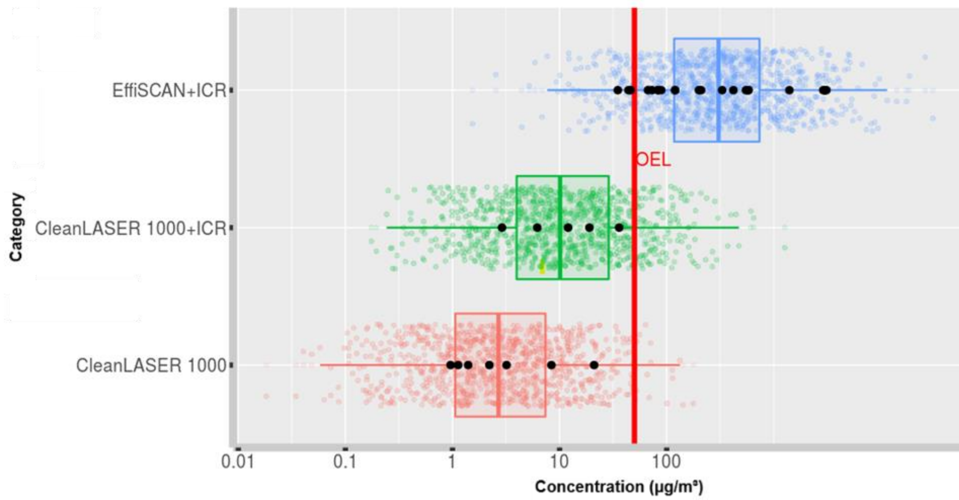



**Figure 22. Bayesian Comparison of Lead Personal Air Sampling Data in µg/m³. The red line represents the occupational exposure limit of 50 µg/m³ as a concentration, reported on a log scale. ICR = induction coating removal.**

When comparing the specialty subcontractor data between LACR and ICR operators using the Excel data analysis tool (Table 11), the two-sided *t*-test on the Ln transformed data indicated that the *t*-statistic of 2.28 is not more extreme than the *t*-critical value of 2.31. The *P*-critical value of 0.052 is greater than 0.050, indicating that the differences in specialty subcontractor data observed between the LACR and ICR operators is likely to be insignificant.

**Table 11. Statistical Comparison of the Specialty Subcontractor Data between LACR and ICR Operators**

| ***t*-Test of Natural Logarithm Transformed Data: Two-Sample Assuming Unequal Variances** | | |
|---|---|---|
| *Specialty Subcontractor LACR and ICR Data Comparison* | *LACR* | *ICR* |
| Mean | 6.43 | 4.78 |
| Variance | 3.07 | 0.77 |
| Observations | 7 | 9 |
| Hypothesized Mean Difference | 0 | |
| Degrees of Freedom | 8 | |
| *t*-Statistic | 2.28 | |
| $P\ (T \leq t)$ two-tail | 0.052 | |
| *t*-Critical two-tail | 2.31 | |

ICR = induction coating removal; LACR = laser ablation coating removal.

When comparing the VDOT personal lead samples data from Route 301 Bridge with the specialty subcontractor data from the same location (Table 12), the two-sided *t*-test Ln transformed *t*-critical value of 0.51 is not more extreme than the *t*-critical value of 2.26. The *P*-critical value of 0.62 is greater than 0.050, indicating that the difference between the VDOT combined ICR+LACR data and the disaggregated specialty subcontractor data is not statistically significant. Based on the similarity of ICR and LACR lead air sampling data collected from the Route 301 Bridge site during ICR+LACR work, VDOT and specialty subcontractor samples were combined as one dataset.

**Table 12. Statistical Comparison of the VDOT and Specialty Subcontractor Personal Lead Sample Results from Route 301 Bridge**

| ***t*-Test of Natural Logarithm Transformed Data: Two-Sample Assuming Unequal Variances** | | |
|---|---|---|
| *VDOT and Specialty Subcontractor Data Comparison* | *Specialty Subcontractor* | *VDOT* |
| Mean | 5.51 | 5.88 |
| Variance | 2.35 | 2.33 |
| Observations | 16 | 6 |
| Hypothesized Mean Difference | 0 | |
| Degrees of Freedom | 9 | |
| *t*-Statistic | − 0.51 | |
| *P* ($T \leq t$) two-tail | 0.62 | |
| *t*-Critical two-tail | 2.26 | |

LACR = laser ablation coating removal.

### *Coating Condition Evaluation After 10 Months of Service*

The researchers inspected the recoating work after 10 months of service and found that the coating on the ICR+LACR surfaces looked good overall (Figure 23). Based on this inspection, the researchers made the following three observations about several systematic deficiencies:

- In areas where access to the surface was favorable or the adherent corrosion product (i.e., lamellar or pack rust) was removed, the recoated steel looked good on both the GB and ICR+LACR surfaces (Figure 23).

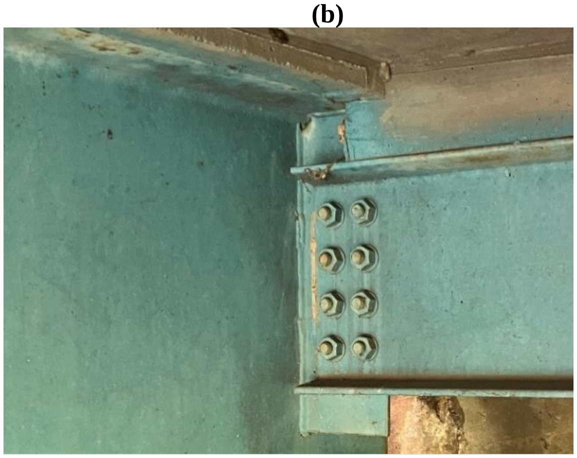
- In areas where access to the surface was difficult or blocked, the recoated steel exhibited rust staining on GB and ICR+LACR prepared surfaces (Figure 24).

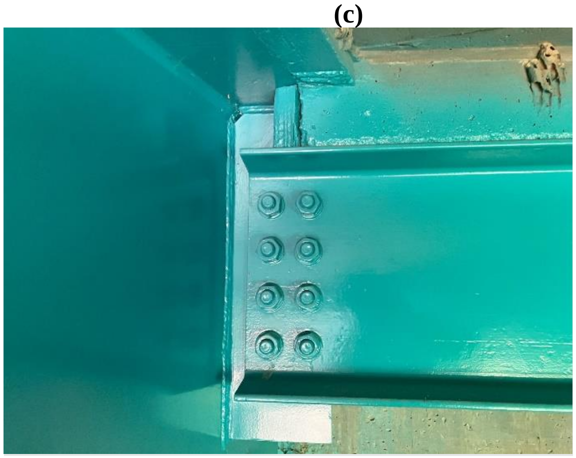
- In areas where adherent corrosion product was not completely removed, the thicker lamellar and pack rust formations, with rust staining present, could be seen on the recoated steel, indicating corrosion activity was present on these GB and ICR+LACR prepared surfaces (Figure 25).

Therefore, tight or restricted access limits the ability of both conventional GB and ICR+LACR to clean the steel completely for recoating. In addition, hand and power tools are necessary to remove tightly adherent corrosion product before using LACR to clean the steel surface and apply the prime coat. Any area where sufficient chlorides remain can shorten the beneficial life of the coating. Therefore, where ICR or LACR are used, removing the thick adherent rust formations (i.e., pack rust) before using LACR on the final cleaning pass before recoating the steel is important.

**(a)**

**(b)** **(c)**



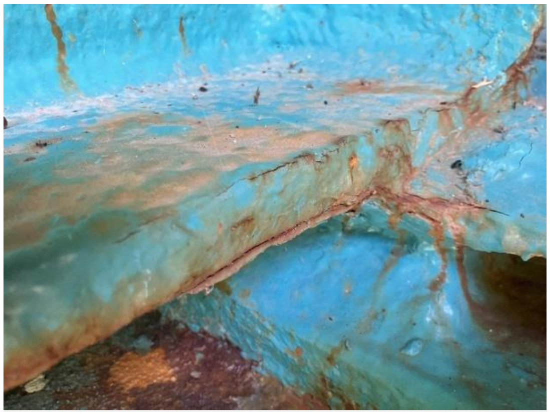


**(d)** **(e)**

**Figure 23. South Abutment A: (a) Overall Image After Recoating Was Completed; (b) Close-up Image of Diaphragm Connection to Girder 3 Outside (West) before and (c) after ICR+LACR Cleaning and Recoating; (d) North Abutment B Diaphragm Connection to Girder 5 before and (e) after Abrasive Blast Cleaning and Recoating Showing Similar Favorable Coating Condition Observed at Bolted Diaphragm Connections Where ICR+LACR Was Used. ICR = induction coating removal; LACR = laser ablation coating removal.**

**(a)**

**(b)**



**(c)**

**(d)**

**(e)**

**Figure 24. South Abutment A Girder No. 1: (a) Before Coating Removal, Showing a Cable Anchored above the Bearing for Abrasive Blast Cleaning by the Induction Coating Removal and Laser Ablation Coating Removal Specialty Subcontractor; (b and c) The Cable Passes between the Bolt and Stiffener before Recoating, Creating Difficulties Accessing this Area and Resulting in Rusting; (d) North Abutment B Girder No. 4 Bridge Bearing before and (e) after Abrasive Blast and Recoating Showing Rusting under the Plate due to Difficulties Accessing this Area.**

**(a)** **(b)**

**(c)** **(d)**

**Figure 25. Pier 1 Girder No. 1 Interior: (a) Showing Pack Rust Under Sole Plate before ICR+LACR and then (b) after Sufficiently Cleaning Most of the Bearing Area with ICR+LACR but Leaving Some of the Pack Rust on the Bottom of the Sole Plate; (c) Abutment B Girder No. 4 Bridge Bearing before Abrasive Blast Cleaning and (d) also Showing Incomplete Removal of Pack Rust, Resulting in the Salt Initiating Corrosion Again. ICR = induction coating removal; LACR = laser ablation coating removal.**

## Summary of Findings

The following section provides a summary of the findings in this project, divided by topic area:

### Coating Removal

- *Using ICR combined with LACR can increase the coating removal rate to approximately 10 times faster than LACR alone.* By incorporating ICR before LACR, bulk thick coating layers were efficiently removed, leaving only residual primer on the surface. LACR can then be used to quickly remove the remaining primer to provide a clean, prepared surface for recoating.

- *Sufficient access to surfaces is important for coating removal, regardless of the method used.* Field trials faced challenges in achieving adequate coating removal with abrasive GB, LACR, and ICR+LACR in tight spaces. Inspection after coating removal in tight areas is important to ensure surfaces are completely cleaned of corrosion before recoating, and coatings are applied to all cleaned surfaces.

- *ICR and LACR equipment require manufacturer modifications to clean all areas with tight access.* The standard ICR and LACR units have large head units, which are difficult to maneuver in tight spaces to perform satisfactory coating removal. ICR and LACR manufacturers have responded positively to adapting their equipment to clean areas with tight access.

- *Removing pack rust and other thick oxides is critical, and their removal is necessary before using LACR.* LACR will not remove pack rust, scale rust, or thick oxides. Instead, thick, tightly adherent layers of rust should be removed using pneumatic tools before using LACR as the final coating removal and cleaning step. Pneumatic tools are also required before GB for these tightly adherent layers. Inspection after coating removal in areas prone to the formation of pack rust is critical to ensure the pack rust has been removed before the final LACR cleaning to prepare a steel surface for recoating.

- *ICR and LACR equipment operators must be mindful of the systems' high- and low-ambient temperature limits to ensure maximum coating removal rates.*

**Cleanliness**

- *ICR can quickly remove bulk layers of coating but cannot completely remove lead-based coatings on its own.* LACR is required after ICR to completely remove the remaining coating and prepare a steel surface for recoating. ICR was not sensitive to coating thickness. It consistently removed coatings with different dry film thicknesses to a standard thickness, with approximately 2 mils of lead-based coating remaining on the steel after ICR.

- *LACR provides a cleaner surface than the GB surfaces.* The GB process causes many contaminants to become embedded in the steel surface, leaving a somewhat dirty surface microscopically. On the other hand, the LACR process results in only residual amounts of contaminants, leaving a much cleaner surface microscopically.

- *Mechanically cleaned surfaces exhibited flash rust much more quickly than LACR-cleaned surfaces.* This result was observed in the field trials of the current project and in previous laboratory testing.

**Surface Profile**

- *The LACR process results in less of a surface profile compared with GB, but the surface still meets the VDOT specifications for surface profile for recoating* (VDOT, 2020). Surface profile measurements on GB and LACR surfaces were approximately 5 and 2 mil, respectively. The surface profile after ICR was not measured because of the remaining lead-based coating, such that recoating is not practical.

### Microstructure and Mechanical Behavior Effects of ICR and LACR Surfaces

- *ICR and LACR do not cause any adverse effects on the steel's microstructure*. LACR melted only a microscopic region of approximately 1 micron thick of iron oxide on the surface.

- *Neither ICR+LACR nor LACR alone causes a degradation in the mechanical properties of the underlying steel girders when surface temperatures are limited to approximately 325 °F.* Based on mechanical testing, the average yield stress, average ultimate strength, and average percentage elongation were similar for ICR+LACR, LACR, and GB samples. However, this study did not evaluate changes in the mechanical behavior of high-strength heavy hex bolts following ICR.

- *Neither ICR+LACR nor LACR alone causes a degradation in the fatigue performance of the underlying steel.* Fatigue test samples subject to both ICR+LACR and LACR all produced results similar to steel base metal not subject to any coating removal process.

### Adhesion of Coating Applied to ICR and LACR Surfaces

- *ICR+LACR and LACR, on their own, both provide sufficient adhesion of both organic and inorganic coatings that are applied after coating removal.* The adhesion values of ICR+LACR and LACR-alone surfaces were equivalent to surfaces cleaned using GB. All the adhesion values also met the coating manufacturer's requirements. This result is notable because the LACR surfaces have a smaller profile than the GB surfaces. However, the LACR surfaces are much cleaner than GB surfaces, thereby creating sufficient adhesion.

- *Some adhesion tests on ICR surfaces did not meet the manufacturer's requirements.* For the OZ and IOZ recoating samples, approximately 25 and 15%, respectively, failed to meet the manufacturer's required adhesion values. LACR is required after ICR to provide a clean surface with equivalent adhesion to GB surfaces.

- *Different types of primers have different failure mechanisms when subject to adhesion testing.* All adhesion tests for OZ primers resulted in cohesive failures, whereas the IOZ primers resulted in a mix of adhesive and cohesive failures.

- *Coatings applied to a LACR surface can perform well over time on a bridge.* Seven-year field data indicated that a VDOT System F coating performs adequately on a LACR surface on a bridge in service. In addition, field inspections suggest that the VDOT System B coating performs adequately on an ICR+LACR surface on a bridge after 10 months of service.

### Environmental

- *LACR systems with appropriately designed fume extraction systems are critical for controlling and recovering the waste generated during coating removal.*

- *ICR and LACR can be operated within a control area, which can be successfully used to protect the public during these coating removal operations.* The control area should include laser signage placed at the boundary of the control area alerting workers and the public to the hazards of laser light within, ICR signage placed outside of the control area alerting the public and other workers to the potential for electromagnetic field exposures within, and laser curtains to prevent exposing the public to laser light.

- *Appropriate controls, such as ground cover, poly, tarpaulins, and so on, must be installed during ICR to ensure coating removed from the girders does not contact the ground surface below.*

**Industrial Hygiene**

- *The combination of the cleanLASER effiSCAN LACR, ICR, and mechanical removal of coatings at Route 301 Bridge reduced lead exposures to a geometric mean concentration of 272 µg/m³, a fraction of what would be observed during GB, which is expected to expose workers to a geometric mean concentration of about 4,000 µg/m³ of lead* (Center for Construction Research and Training, 2018).

- *Concentrations of lead during the cleanLASER effiSCAN LACR, ICR, and mechanical coating removal were significantly reduced compared with GB. However, contractors were still exposed to lead above the regulatory limit of 50 µg/m³ as an 8-hour time-weighted average.* Exposures above regulatory limits indicate a need to implement worker controls, such as using engineering and administrative controls and PPE. Where feasible controls such as fume extraction cannot fully remove the hazard, using PPE such as respirators is a sufficient method for protecting workers.

- *Laser safety glasses that protect against the laser's particular power and wavelength are required for workers inside the LACR-regulated area.*

- *The fume extraction device on the cleanLASER effiSCAN LACR unit was insufficient at removing leaded fume from the processes.* The mounted ventilation nozzle on the cleanLASER effiSCAN LACR unit was notably less effective than the built-in fume extraction system on the cleanLASER 1000 LACR unit.

- *The combination of LACR and ICR increased employee exposure to lead with both the cleanLASER 1000 LACR and the cleanLASER effiSCAN LACR.* This situation was likely because ICR did not have a built-in ventilation system for extracting and collecting dust and fume. In addition to built-in fume extraction, a dust collector, or negative air machine, is recommended inside the laser-curtained area to further reduce the airborne concentrations of laser fume for both LACR and ICR.

## CONCLUSIONS

- *Using ICR before LACR makes the combined ICR+LACR process a competitive alternative to GB.* Test results showed that the ICR+LACR process performed well in terms of its coating removal rate, environmental effects, industrial hygiene, and adhesion of reapplied coatings. The mechanical properties of the steel plate after ICR+LACR were not degraded, but high-strength bolts were not evaluated.

- *ICR and pulsed LACR can be used on bridges without containment.* For this practice to be performed while still meeting environmental and industrial hygiene requirements, control areas with laser curtains and proper LACR and ICR signage must be used, LACR operators must wear proper laser safety glasses, LACR and ICR units must have built-in fume extraction and ventilation systems with sufficient negative draw, and tarpaulins must be used to catch coating strips as they fall or are scraped away during ICR.

## RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should work with VTRC and VDOT's Materials Division and Environmental Division to develop guidance and specifications for using ICR+LACR for bridges.*

2. *VDOT's Structure and Bridge Division should identify upcoming bridge coating removal projects in which to specify or allow ICR+LACR to be used.*

3. *VTRC should initiate a technical assistance project to evaluate the mechanical properties of high-strength bolts after they are subjected to heat during ICR.*

## IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

### Implementation

Regarding Recommendation 1, VDOT's Structure and Bridge Division, with input from VTRC and VDOT's Materials and Environmental Divisions, has developed specifications for ICR+LACR to adopt into the *2020 Road and Bridge Specifications* (VDOT, 2020). These specifications have been drafted and are in the review stage. These specifications for ICR+LACR are proposed to be added as Method 10 of Section 411.04, Surface Preparation and Coating Application. Some notable items within these specifications include contractor removal of loose material before ICR+LACR, a steel surface temperature limit of 400 °F, use of a fume extraction unit with a negative draft of 1,300 feet per second, allowance to remove the fume extraction unit when it impedes access to surfaces to be cleaned, use of respiratory protection, use of a pulsed laser unit, and demonstration of equipment use and process acceptance. This specification is anticipated for small coating removal areas, up to 100 square feet per day. Representatives from multiple LACR and ICR equipment manufacturers have reviewed these specifications and have provided comments.

Regarding Recommendation 2, VDOT's Structure and Bridge Division has begun internal deliberations to add ICR+LACR as an option to upcoming coating removal projects, allowing the contractor to determine when and where to economically utilize ICR+LACR, GB, or other surface preparation methods. Potential projects will focus on small coating removal jobs, like girder end recoating and repair projects, because ICR and LACR are most effective at cleaning small areas. VDOT's Structure and Bridge Division has also put out a bid for an on-call service contract for VDOT district bridge maintenance crews to have ICR+LACR performed to remove coatings before steel repair work. Work performed under this on-call contract may allow VDOT to accumulate a database that will permit an accurate estimate of the frequency of applicability and the magnitude of the cost savings.

Regarding Recommendation 3, VTRC has initiated collaborative technical assistance with the University of Virgina Materials Science Department to evaluate high-strength bolts subject to elevated temperatures in both stressed and unstressed loading conditions. This technical assistance project will include metallography, hardness testing, stress relaxation, tensile testing, and rotational capacity testing of bolts after being subjected to heat to determine their upper temperature limit before property degradation. Results from this technical assistance project will eventually be made available as an auxiliary publication as part of the supplementary materials in conjunction with this report.

## Benefits

The combined coating removal process of using ICR before LACR would benefit VDOT in terms of industrial hygiene, environmental effects, potential for reducing the scope of coating removal projects, and increasing the coating removal rate. The following paragraphs address all four of these topics.

ICR and LACR expose workers to notable decreases in lead compared with GB. Abrasive GB requires a containment system with dust collection as an environmental control and the use of Type CE respirators. Although full containment works to protect the public and the environment, it causes an increase in worker exposure to airborne lead inside the containment area, reduces visibility, and increases the risk of slip and fall injuries (Federal Highway Administration, n.d.). Workers using ICR and LACR can conduct operations in areas with greater visibility and a reduced risk of slip and fall injuries compared with GB. Although respiratory protection like half- or full-face respirators with high-efficiency particulate air filtration is recommended during ICR and LACR work, ICR and LACR work can proceed without the need for heavy Type CE air breathing systems.

ICR and LACR are more much environmentally friendly coating removal processes than GB. Environmental protocols for ICR and LACR consist of control areas with proper signage, laser curtains to protect the public from the laser light, properly sized built-in fume extraction and ventilation systems on the ICR and LACR devices, and tarpaulins to catch pieces of coating removed during ICR. On the other hand, GB requires containment structures to capture all the coating and abrasive media during the GB process. In addition, when GB is used, it is often more cost effective to provide containment over a large portion or the entire bridge rather than only the small portion of the bridge that truly requires coating work. This approach means multiple days are typically needed to set up and break down these large containment structures before and after the actual coating removal work. Because ICR and LACR do not require these large containment structures, their setup and breakdown time is minimized, which maximizes their coating removal time. When considering the setup and breakdown time of GB and the reduced coating removal rate of ICR+LACR, the time required for the project may possibly be similar for both GB and ICR+LACR.

Because large full-containment structures are not necessary for ICR and LACR, coating removal projects could possibly have reduced scopes to include only the areas truly in need of coating removal. As previously mentioned, providing larger full-containment structures than are needed for the areas truly in need of coating removal is typically cost effective during GB projects. However, with ICR+LACR, smaller coating removal projects could be used, such as those targeted at the girder end, bearing line, or other areas in need of repair. The cost savings associated with smaller coating removal projects could allow VDOT to undertake these types of projects more frequently and earlier in a bridge's service life. Such a maintenance program would extend the length of time before major rehabilitation or replacement becomes necessary, reducing the life-cycle cost of a steel bridge.

Using ICR combined with LACR increased the coating removal rate up to approximately 10 times faster than LACR alone. This faster coating removal rate for ICR+LACR should result in reduced project times, cost savings, and worker and environmental benefits.

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