A Laser-based Surface Treatment of Aluminum and Titanium Alloys for Enhanced Coating Adhesion

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Objective **Investigate laser-interference structuring techniques as a replacement for chemical conversion coatings.**

Background

- **DoD maintains tens of thousands of aircraft, ground vehicles, and ships**
- **Corrosion protection is accomplished using multi-step, complex painting/coating processes requiring cadmium, volatile organic compounds, and chromates**
  - **DoD cost for corrosion protection is larger than $20 billion/year**
  - **Chromate solutions (hexavalent chrome - type I) are highly toxic.**

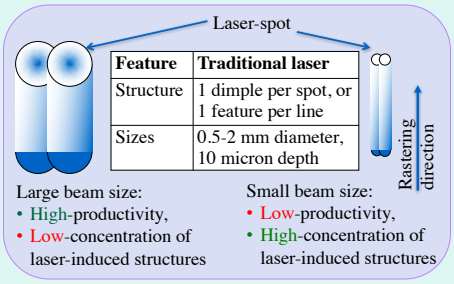
Challenge

New non-chemical processes for surface preparation would drastically reduce environmental impact, risks, and costs.

Approach

- **Use laser processing for surface preparation**
- **Use interference to create regions of alternating high-power and low-power that were sub-beam and micron-scale on treated surfaces,**
- **Investigate surface chemistry, topology, and wetting behavior following laser-interference**
- **Investigate sub-surface microstructure**

Current state-of-the art in laser structuring



Feature	Traditional laser
Structure	1 dimple per spot, or 1 feature per line
Sizes	0.5-2 mm diameter, 10 micron depth

Large beam size:
- High-productivity,
- Low-concentration of laser-induced structures

Small beam size:
- Low-productivity,
- High-concentration of laser-induced structures

Figure 1. Schematic of surface structuring using traditional one-laser-beam rastering. The induced surface structuring sizes is proportional and limited to the beam size.

Facility

- **Q-switched Nd:YAG laser system with an harmonic generator enabling the selection of very sharp wavelengths of 1064, 532, 355, or 266 nm.**
- **Pulse duration 10ns (heating and cooling rates > 10^{11}K/s),**
- **Frequency 10Hz.**

Principle of laser-interference

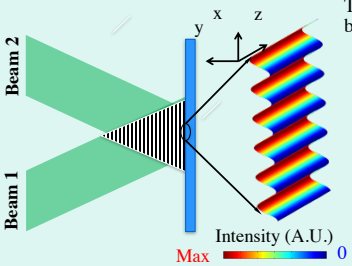


Figure 2. Through wave-interference, alternating regions of high-power and low-power are created on the specimen surface:

- Constructive interference of two (or more) laser beams intensifies power,
- Destructive interference yields no power.

The laser interference power profile is created by splitting the beam and guiding those beams to the sample surface by overlapping each other with defined angles to each other.

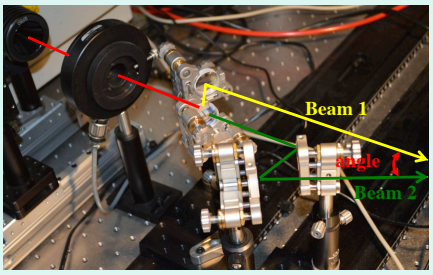


Figure 3. Laser setup for two beam interference.

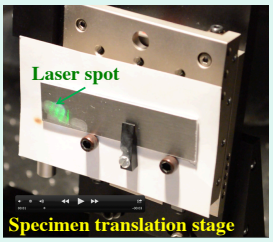


Figure 4. Sample is mounted on a translational stage controlled by LabView.

Laser-interference enables major paradigm shift in surface preparation: *"More structuring at the same productivity"*

Laser-interference technique systematically "roughens" the surface:

- Maxima of wave interference yields pits on the surface through localized melting and resolidification, while
- Minima leaves the surface unchanged.

Method	Traditional (1 beam laser)	New laser-Interference (2 or more beams)
Structure	1 dimple per spot	300 to 15,000 mini-dimples (pits) per spot
Sizes	500 μm diameter 10 μm depth	0.4-20 μm diameter <500 nm depth

For each laser spot (100s-1,000s lines example for 2 laser beams setup)

Main variables for laser-structuring:

- **wavelength,**
- **beam angle,**
- **spot size,**
- **power,**
- **rastering speed.**

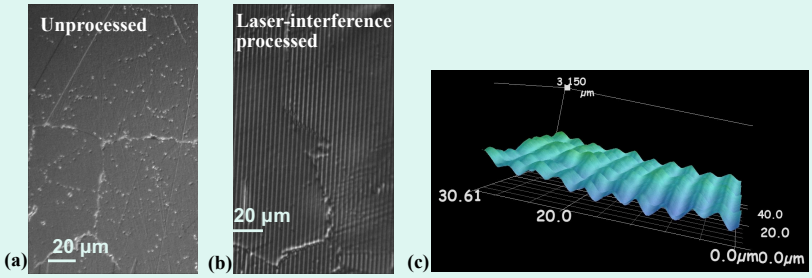


Figure 5. Laser-interference structuring of a polished 316 stainless steel surface at an average power 1.5 W and 8cm diameter beam spot: (a) before laser structuring, (b) laser interference processed, and (c) 3D surface profile of laser structured surface.

Acknowledgements This research was conducted at UT-Battelle, LLC, for the project "Laser-Interference Surface Preparation for Enhanced Coating Adhesion and Adhesive Joining of Multi-Materials." This project, WP-2743, has been funded by the Strategic Environmental Research and Development Program (SERDP) Weapon Systems & Platforms 4800 Mark Center Drive, Suite 17D03, Alexandria, VA 22350-3605.

A Laser-based Surface Treatment of Aluminum and Titanium Alloys for Enhanced Coating Adhesion - Results

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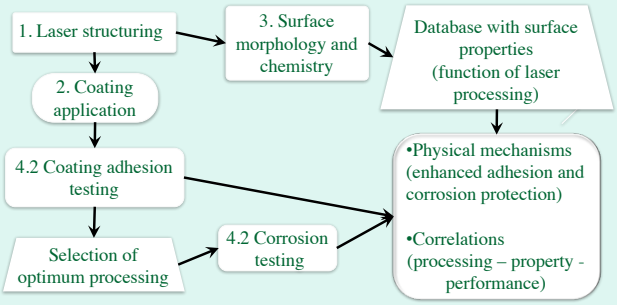

Figure 1. Flow chart of main tasks and deliverables.

The technical questions sought to be answered by the research project are:

- How effective is laser-interference in cleaning the surface?
- What surface structuring laser-interference can produce?
- How damaging is the laser structuring to the top surface?
- Does laser-interference induce surface cracks, as seen with traditional laser structuring?
- How beneficial is laser-interference structuring for mechanical strength of joints?

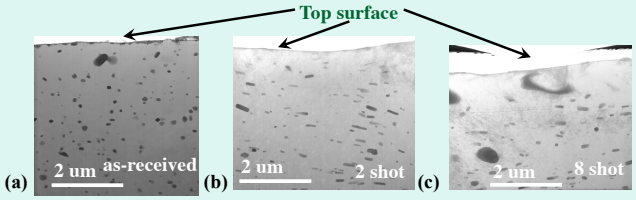

Figure 4. Scanning transmission electron micrographs (STEM) showing distribution of precipitates (black or dark gray colors) in vertical cross-sections near the top surface for Al2024-T3 specimens: (a) as-received and laser-interference processed with (b) 2 shots-per-spot and (c) 8 shots-per-spot.

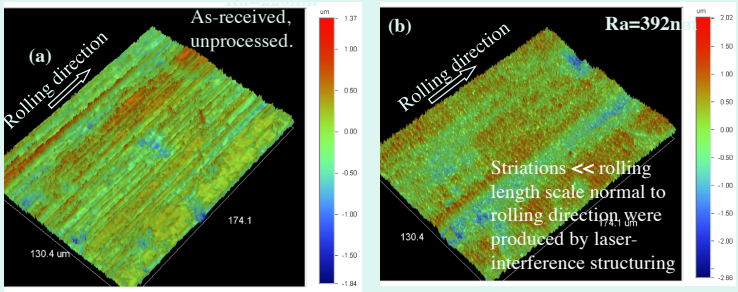

Figure 2. Surface profilometry data for Al5182, showing that roughness increased from 226 nm for the as-received surface to 392 nm for the laser-interference structured surface (10 pulses/spot).

Condition	Ra [µm]	Rq [µm]	Rt [µm]
untreated	0.226	0.286	3.21
Laser treated	0.391	0.493	4.68

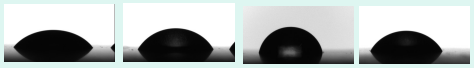

Figure 5. Pictures used for contact angle measurements of liquid droplets on Al2024-T3 specimens laser-interference processed with 8mm/s raster speed (from left to right, liquid used were Diiodomethane, Ethylene Glycol, H_2O, and Thiodethanol, respectively).

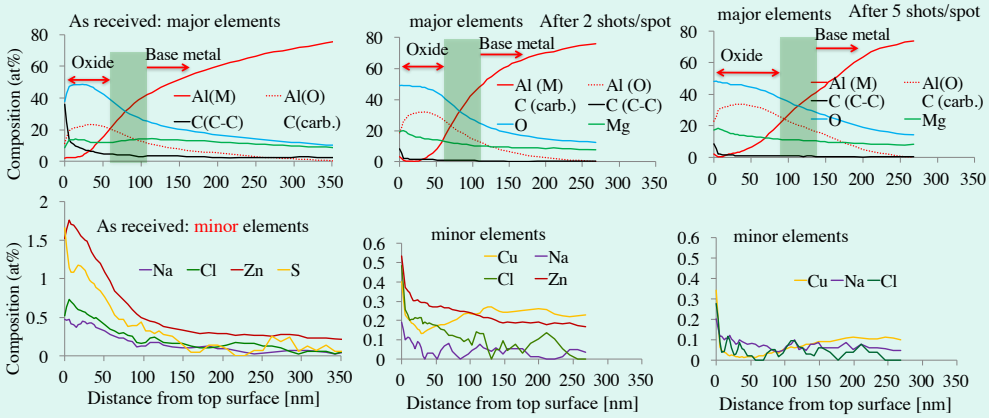

Figure 3. Laser-interference is very effective in cleaning the surface of Al5182, eliminating the need for solvent cleaning (results for spot-by-spot mode), as seen in the Ar-ion depth profile obtained with X-ray photoelectron spectroscopy (XPS).

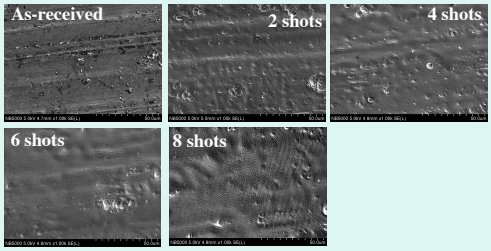

Figure 6. Field Emission Scanning Electron Microscopy (FESEM) images show that laser-interference technique "smooth-out" all the sharp features from the as-received rolling surface, minimizing surface defects. (Note that micro-cracking of Al alloy surfaces are seen around melt cavities produced with for "traditional one-beam" laser surface structuring).

Figure 7. An existent paint booth with explosion-proof exhaust was setup at ORNL for spray coating of MIL-PRF-23377, Type I, Class N and MIL-PRF-85582, Type I, Class N.

Conclusions and Benefits to DoD and End-users

- A new non-chemical surface preparation methodology for enhanced coating adhesion based on laser-interference technique was used at ORNL for structuring Al alloy surfaces with fine feature sizes: 0.4-5µm spacing, <500 nm depth
- This technique is based on constructive and destructive interference from two laser coherent beams to create a periodical pattern that results in making 200 to 20,000 ridges, (pits, wells) at once, i.e., per each laser spot, enabling the following:
  - a large, non-planar contact area for enhanced coating adhesion – by sub-scale beam size laser-interference structuring,
  - elimination of solvent cleaning by removal of mold releases and surface contaminates in one-step,
  - minimization of surface defects as all the sharp features from a rolling surface were "smooth-out" by laser-structuring,
- New understanding of surface science for laser-interference processing will be uncovered;
- A property-processing database will be provided to understand the physical mechanisms for enhanced coating adhesion.

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