Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications

primary project goal

LumiShield Technologies is developing and demonstrating durable and inexpensive anti-corrosion coatings for application on carbon steel, which is used extensively in vessels and piping of power plant boilers and capture systems. By reducing corrosion and allowing substitution of coated mild or carbon steel for expensive stainless steel, capital costs of power plant systems could be significantly reduced, helping to enable cost-effective carbon dioxide (CO_2) capture for coal- and natural gas-fired power generation.

The multi-layer coating structure consists of a novel mixed metal oxide coat covered with an organic anti-corrosion coating. Project objectives are initially focusing on optimizing the metal oxide base layer for applying the organic coatings and proving the effectiveness of a prototype two-layer coating in preventing corrosion. Subsequently, the objectives are for optimization through identification of the organic coatings that give the best performance in combination with the optimized metal oxide base layer and showing the economic advantage of using the coatings through cost-benefit analysis.

technical goals

- Improve the corrosion resistance of organically coated steel (by at least 10% in terms of higher salt spray hours) by addition of the LumiShield metal oxide base coat underneath the conventional organic top coat.
- Perform lab-scale testing of LumiShield-coated carbon steel samples in simulated amine capture system conditions (CO_2 saturated 30% monoethanolamine [MEA] solution at 60ºC) and realistic flue gas conditions.
- Optimize top-coating chemistry to maximize adhesion to LumiShield aluminum oxide coating under exposure to acids and amines, as evidenced by no change in appearance or adhesion, including blistering or swelling of organic coatings under realistic testing/exposure conditions.
- Provide a cost-benefit analysis for completed composites and compare with existing coatings and materials, making quantified estimates of: (1) how much stainless steel is replaceable by carbon steel with LumiShield coating in a baseline system, and (2) savings in capital and operating costs for the baseline system (with the quantitative target that at least one of the coatings should result in a decrease in cost per tonne of CO_2 by 1% or greater).

technical content

In fabrication of piping and vessels in power plants, carbon steel is the preferred material of construction given its relatively high strength and relatively low cost. However, in applications for corrosive environments (e.g., acid gas-containing flue gas streams, amine solutions in capture systems, and wet CO_2 captured by amine systems), carbon steel may not provide suitable corrosion resistance. Stainless steel provides high corrosion resistance, but it is expensive. Conventional organic-

program area:
Point Source Carbon Capture

ending scale:
Laboratory Scale

application:
Post-Combustion Power Generation PSC

key technology:
Enabling Technologies

project focus:
Corrosion-Resistant Coated Carbon Steel Components

participant:
LumiShield Technologies Inc.

project number:
FE0031659

predecessor projects:
N/A

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partners:
N/A

start date:
10.01.2018

percent complete:
100%

coated steel initially confers corrosion resistance but tends to develop defects though which diffusion of water and gas species can occur, leading to corrosion of the substrate and delamination of the coating (as illustrated in Figure 1). Therefore, better anti-corrosion coatings are needed in applications such as corrosive solvent-containing carbon capture systems.

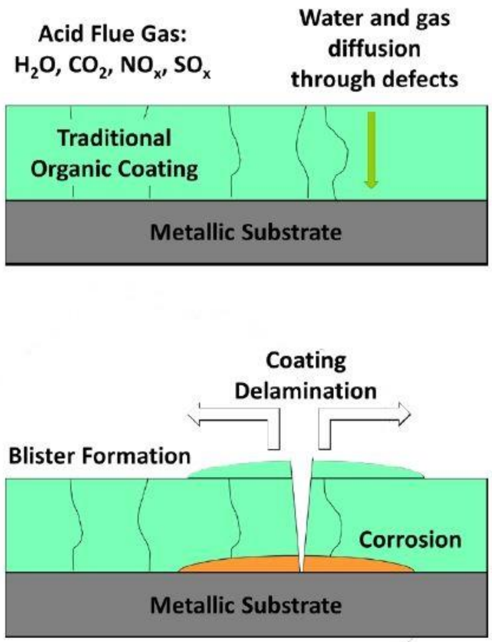

Figure 1: Mechanism for corrosion of coated metallic substrates.

The approach to this problem involves utilization of previously developed LumiShield metal oxide coating technology to establish a base metal oxide layer on carbon steel, on which organic coatings tailored for resistance to amine solutions could be applied. The basic geometry of the dual coating concept is depicted in Figure 2. The presence of the LumiShield coating improves the adhesion of the organic coating, preventing the coating from being undermined and considerably increasing the overall coating performance. The LumiShield coating was initially developed as a stand-alone anti-corrosion coating to replace toxic metal coatings like chromium and cadmium. However, realization occurred that the metal oxide surface would allow excellent adherence of organic coating molecules and that the resulting composite coating could make use of a thinner organic layer with fewer defects, improving corrosion resistance performance and reducing cost. The metal oxide layer itself may be applied in a single step using equipment and expertise well-known to the industry. These characteristics allow competitive or even lower costs than conventional primed steel coatings, which sometimes require multiple layers at increased cost.

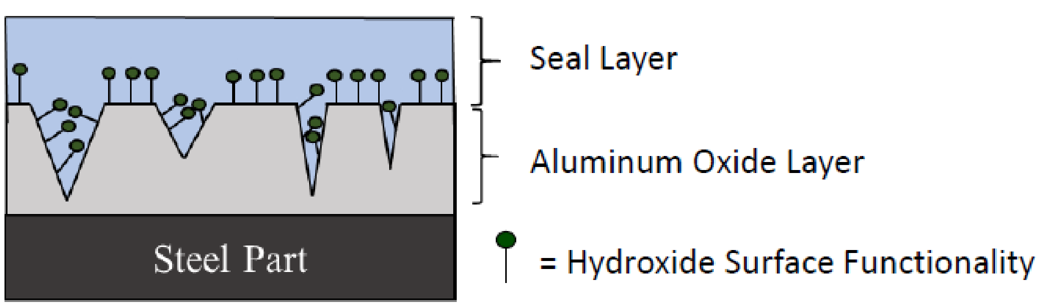

Figure 2: Coating structure.

Metal Oxide Base Layer

The metal oxide layer consists mainly of aluminum oxide applied via electroplating, utilizing water-stable aluminum complexes (with proprietary additions) in the electroplating bath, which form a coherent and highly adherent aluminum oxide layer on steel via a proprietary cathodic electroplating process. It has been observed that the aluminum oxide layer formation allows for some degree of metal-to-metal bonding between aluminum centers and the steel substrate, giving the coating excellent adhesion. The LumiShield alumina electrodeposition process takes place in an aqueous system, offering significant cost advantages over non-aqueous methods of alumina deposition that require processes to be free of atmospheric water and oxygen. The process is analogous to the electroplating of common metals like zinc and can be applied using standard equipment present in every electroplating facility.

The LumiShield approach makes use of pulse-plating methods (in which electrical field strength is varied to improve control over electroplating processes). By adopting a pulsed-plating procedure (example illustrated in Figure 3), the LumiShield coating is further improved in adhesion and density. Also, the nature of the coating process allows a large degree of control of the morphology of the coating. By adjusting the electroplating conditions of pulse, pH, temperature, and solution composition and concentrations, it is possible to create morphologies ranging from plate-like growth with a so-called cracked glass appearance under magnification (Figure 4, left side) to granular growth structures (Figure 4, right side). The cracked glass morphology is valuable because its high surface area will improve the adhesion of organic layers deposited on top of it.

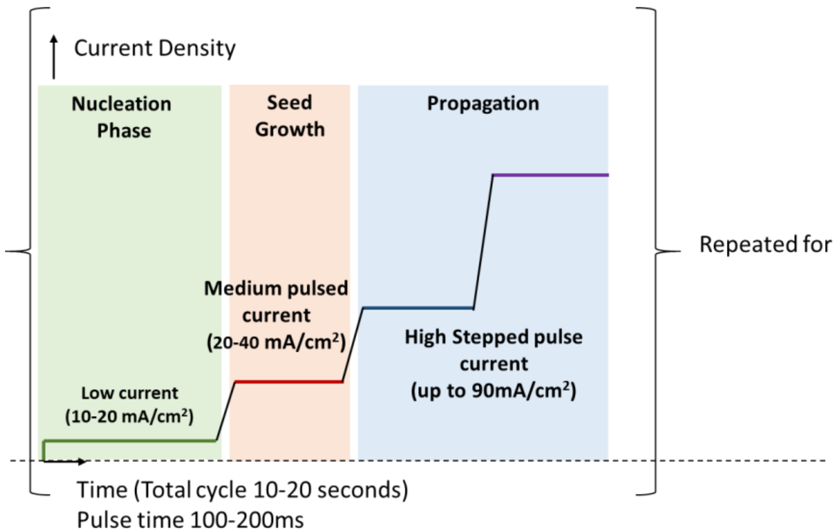

Figure 3: Complex electroplating pulse scheme.

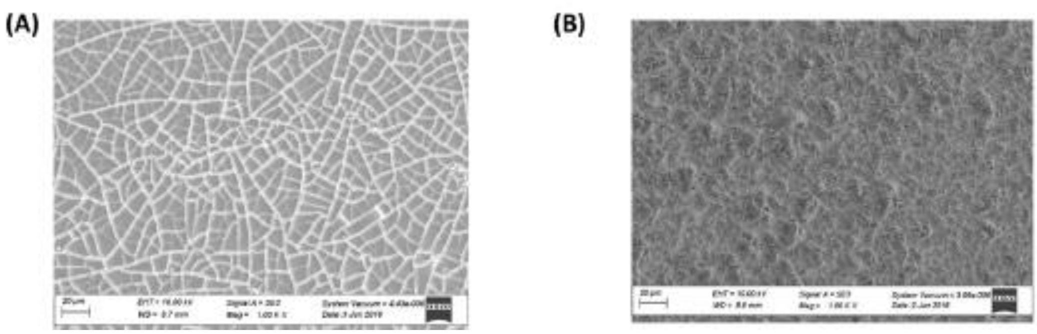

Figure 4: Variation in metal oxide coating morphology.

A major focus at the start of the project was optimization of the LumiShield metal oxide base layer. This was accomplished by varying process and electroplating solution conditions in forming the metal oxide coatings, which were then characterized for morphology and adhesion through physical and optical methods. Polarization testing to determine corrosion rates, electrochemical impedance spectroscopy to determine corrosion mechanisms, and salt spray exposure testing were conducted. LumiShield has identified plating solution parameters (temperature, pH, concentrations), as well as electrochemical process variables (pulse scheme, current density, timing), which result in thin, rough, adherent metal oxide coatings that will promote organic top-layer adhesion.

Organic Top Layer

For the essential organic top layer, LumiShield has surveyed existing/available organic anti-corrosion coating materials and identified epoxy resins, phenolic resins, and fluoropolymer resins as the three types for consideration for applications involving amine solutions, flue gas, and wet CO_2, given their formulation flexibility, robustness at elevated temperatures (as high as 180–250ºC for epoxy coatings and 120–200ºC for phenolic coatings), chemical resistance, and physical characteristics. Project work has involved testing of these three types with and without the LumiShield base coat to establish baselines for each polymer class for corrosion resistance, adhesion and scribe creep, and measure improvement of corrosion resistance in salt spray tests. Testing has shown significant improvement in corrosion performance with both epoxy and phenolic coatings, both of which likely have enhanced adhesion on the LumiShield metal oxide base layer that is improving corrosion protection. Specifically, epoxy coatings appear to be the best candidate for modification and further work to improve performance as the project progresses. On the other hand, it has been concluded that fluoropolymer coatings (which show poor adhesion to many materials) will probably not meet performance goals. Figure 5 shows interim results on these evaluations for the more promising epoxy and phenolic coating choices.

	Scribe creep at 1000 Hours of Salt Spray				
	Industry Standard		Aluminum Oxide Coated Steel		
	Average creep / mm	max creep / mm	Average creep / mm	max creep / mm	Improvement
Epoxy	1.08	1.6	0.77	1.1	**29%**
Phenolic	1.12	1.8	0.89	1.3	**21%**

	Salt Spray Hours Initial Testing to Failure		
	Industry Standard	**Aluminum Oxide Coated Steel**	Improvement
Epoxy	500	1500	**300%**
Phenolic	500	1000	**200%**

Figure 5: Comparisons of performance of epoxy and phenolic top coats with and without LumiShield metal oxide base coat.

To facilitate the attachment of top layer to the aluminum oxide base coating, several organic treatments have been considered based on silane treatment (silane is an inorganic compound with the chemical formula SiR_4). Silanes are used in a large variety of high-performance coatings as a binding agent between organic resins and inorganic substrates. The aim is to bind silanes to the pendant hydroxide functionality of the aluminum oxide layer (refer to Figure 2 depicting this idea) to create a synthetic handle for incorporation of the silane into the polymer top layer. To this end, several silane candidates will be investigated.

Non-Capture Applications

Although LumiShield's project focus has been application of the coatings for carbon capture systems, it has two customers that are interested in piloting LumiShield technology with specific modifications to their specific paints:

- An automotive company interested in high-temperature paint adhesion for heat shields.
- Expansion of an oil and gas program toward other markets and corrosion sites using heavy brine solutions.

There is also interest in corrosion resistance to other corrosive amines to serve the needs of the broader chemical industry.

Cost-Benefit Analysis

The LumiShield team includes AECOM, who performed a preliminary cost-benefit analysis of LumiShield's coating technology. An initial objective was to determine the highest value targets in the carbon capture system for materials replacement with the developed aluminum oxide coating over incumbent construction methods. Initial analysis has found that stainless steel currently used for fabrication of both the absorber and stripper could be replaced by LumiShield-coated mild steel with powder-coating at a capital cost saving of 13% and 17%, respectively. They also note that the replacement of stainless steel parts with mild steel may have additional nonquantifiable benefits (e.g., improved materials of construction may allow a wider range of operating conditions or allow use of amine species previously ruled out due to their effects on the stainless steel construction materials). Furthermore, cost savings might be improved significantly based on increasing part lifetime by using a new coating system.

technology advantages

- Coated mild steel can cost-effectively replace stainless steel constructions.

- Coatings can be made acid- and amine-resistant with suitable top coats.
- Coatings can be readily fabricated using straightforwardly implemented aqueous electroplating methods.
- Coatings of the type being developed are non-toxic and can replace heavy metal-based processes.
- May be used to avoid chloride stress cracking of stainless steel in some services.

R&D challenges

- Achieving a dense base metal oxide coating layer with high roughness suitable for securely attaching the upper coating layer, and the general difficulties of controlling results in utilization of electroplating methods.
- Achieving chemical and physical compatibility between the metal oxide base layer and upper organic layer.
- Attaining substantially improved performance of prototype organic coatings on the metal oxide base layer.
- Developing surface repair technique for coatings when damaged during shipping or installation.

status

LumiShield techno-economic analysis (TEA) of the fabrication of dense metal oxide-based coatings led to a 1.5% decrease in cost per tonne CO_2, and the coating predicted cost was \$0.06/ft^2. The fabricated coatings led to a 15% decrease in capital expenditure (CAPEX) for absorber and stripper. The native aluminum oxide and epoxy silane were identified as the best binder conditions. Aluminum oxides show improvement over industry standard pretreatments. The optimized dense, adherent aluminum oxide coating achieved by pulse deposition in 15 minutes timeframe. This study suggests replacement of 316 stainless steel with an aluminum oxide coating system could yield \$20M saving in capital costs for a reasonably sized system.

available reports/technical papers/presentations

John Watkins, "Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications," Project kickoff meeting presentation, Pittsburgh, PA, January 2019. *http://www.netl.doe.gov/projects/plp-download.aspx?id=10596&filename=Inexpensive+and+Sustainable+Anti-Corrosion+Coating+for+Power+Generation+Applications.pdf*.

John Watkins, "Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications," presented at the 2019 BP1 to BP2 Continuation Meeting Presentation, Pittsburgh, PA, August 2019. *http://www.netl.doe.gov/projects/plp-download.aspx?id=10598&filename=Inexpensive+and+Sustainable+Anti-Corrosion+Coating+for+Power+Generation+Applications.pdf*.

John Watkins, "Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications," Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, Pittsburgh, PA, September 2019. *https://netl.doe.gov/sites/default/files/netl-file/J-Watkins-LTI-Anticorrosion-Coating.pdf.*

John Watkins, "Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications," NETL Project Review Meeting - Carbon Capture, Pittsburgh, PA, October 2020. *https://netl.doe.gov/sites/default/files/netl-file/20VPRCC_Watkins.pdf.*

John Watkins, "Inexpensive and Sustainable Anti-Corrosion Coating for Power Generation Applications," Final Project Briefing, Pittsburgh, PA, March 2021. *http://www.netl.doe.gov/projects/plp-download.aspx?id=10601&filename=Inexpensive+and+Sustainable+Anti-Corrosion+Coating+for+Power+Generation+Applications.pdf*.