

# Investigation of Aluminum Surface Cleaning Using a Novel Capillary Non-Thermal Ambient Pressure Plasma

G. Korfiatis<sup>1</sup>, L. Moskwinski<sup>2</sup>, N. Abramzon<sup>2,3</sup>, K. Becker<sup>2</sup>, C. Christodoulatos<sup>1</sup>,  
E. Kunhardt<sup>2</sup>, R. Crowe<sup>3</sup>, and L. Wieserman<sup>4</sup>

<sup>1</sup> Center for Environmental Engineering, Stevens Institute of Technology, Hoboken, NJ 07030, USA

<sup>2</sup> Department of Physics, Stevens Institute of Technology, Hoboken, NJ 07030, USA

<sup>3</sup> PlasmaSol Corporation, Hoboken, NJ 07030, USA

<sup>4</sup> ALCOA Technical Center, Alcoa Center, PA 15069, USA

## Abstract

It is the objective of this project to investigate the interaction of a novel capillary non-thermal ambient pressure plasma with contaminated Al surfaces and to develop a new technology based on this concept that is suitable for the destruction and removal of organic contaminants from Al surfaces for industrial applications. Our new approach, which is intended to replace the current solvent-based cleaning process, offers three important advantages over other existing plasma-based methods: (i) a more efficient energy utilization, (ii) ambient-pressure operation, and (iii) easy scalability from laboratory scale to in-line industrial scale.

## 1. Introduction

The cleaning of metal surfaces such as aluminum (or stainless steel) surfaces, both during manufacturing and prior to their use in specific applications has been a significant environmental challenge for industry. The main contaminants on Al surfaces are volatile and non-volatile hydrocarbons and residual hydraulic fluids from leaks. Chemically, the contaminants are primarily aliphatic hydrocarbons, branch-chain hydrocarbons, and ester-compounds. Vapor cleaning using chlorinated or chloro-fluoro compounds, though effective, has become undesirable as are processes using aqueous cleaning baths of acids or bases, since the compounds and/or some of the by-products represent serious environmental hazards. The industry has generally welcomed research and development on more advanced cleaning techniques that eliminate or minimize undesirable and/or environmentally harmful by-products.

Industry experiments in the past with plasma-based Al surface cleaning methods utilized for the most part low-pressure discharge plasmas. The effort was terminated because of concerns relating to the prohibitive costs of vacuum enclosures for any production-line plasma-based cleaning reactor. Recent progress in the generation and maintenance of atmospheric-pressure discharge plasmas in ambient air make it desirable to re-visit the possibility of using plasma-based Al surface (and more generally speaking, metal surface) cleaning methods on an industrial scale. Researchers at Stevens Institute of Technology have achieved a novel method to generate and maintain stable, large volume, uniform atmospheric-pressure discharge plasmas by employing a novel capillary electrode structure [1]. This capillary dielectric electrode structure provides dynamic feedback stabilization of the current density in the cathode region of the discharge reactor and thus prevents the non-uniform growth of the current density, which is the precursor to discharge instabilities that eventually result in a glow-to-arc transition and the termination of the discharge.

## 2. Project Goals

The current project, which is carried out as a collaborative effort between Stevens Institute of Technology, PlasmaSol Corporation, and ALCOA has five main objectives:

- Characterization of the discharge plasma used in the present application
- Development of a laboratory-scale experimental system
- Investigation of plasma jets firing against conductive and non-conductive surfaces
- Investigation of an atmospheric-pressure plasma discharge system for controlled cleaning of Al surfaces contaminated with selected hydrocarbons
- Consideration scale-up of experimental system for in-line industrial use.

Consistent with the objectives of the project the following tasks were executed up to now and the pertinent results will be reported at the Conference :

- Construction of a discharge plasma reactor that fires the atmospheric-pressure plasma jets on non-conductive surfaces
- Characterization of the plasma jets
- Assessment of destruction of oils and volatile organics on non-conducting surfaces
- Modification of plasma jet reactor for firing against conducting surfaces
- Preliminary assessment of destruction of oils on conducting surfaces

## 3. The Capillary Electrode Plasma at Atmospheric Pressure

The basis for the atmospheric-pressure operation of the capillary electrode plasma is a novel electrode design that uses dielectric capillaries that cover one or both electrodes of the discharge reactor. The capillaries, with diameters in the range from 0.01 to 1 mm and length-to-diameter ratios of the order of 10:1, serve as plasma sources which produce jets of high-intensity plasma at atmospheric pressure under the right operating conditions. The plasma jets emerge from the end of the capillary and form a “plasma electrode” for the main discharge plasma. The field inside the capillary does not collapse after the formation of the streamer discharge due to the fact that the high electron-ion recombination at the wall of the capillary requires a large ion production rate along the axis of the capillary in order to sustain the current. Under the right combination of capillary geometry, dielectric material, and exciting electric field, a steady state can be achieved. Run-away into the arc is prevented by the fact that the current through the capillaries is self-limiting, i.e. the gas density inside the capillary decreases with time due to gas heating which puts an upper limit to the conductivity as a result of gas starvation. Compared to other atmospheric-pressure discharge plasmas, the capillary plasma requires a lower sustaining voltage, lower energy input per cm<sup>3</sup> of plasma generated, and achieves a higher average energy of the plasma electrons (up to 6 eV) at a lower gas temperature (approximately 350 - 400 K) and higher electron densities (up to 10<sup>14</sup> cm<sup>-3</sup>). These parameters were obtained from optical emission spectroscopic studies and from other standard plasma diagnostic techniques applied to a prototype laboratory capillary electrode discharge plasma.

## 4. Interaction of Plasma Jets with Conductive Surfaces

A significant challenge of this project was the development of a working system that can fire an array of plasma jets against a conductive surface consistently in a non-destructive manner. This is a much more challenging task than constructing a working plasma reactor that fires an array of jets against an insulating surface where shorting and arcing are not a problem. A prototype of such a device was recently constructed that overcomes the

difficulties associated with maintaining an array of stable plasma jets firing against conductive surfaces. This device, which is a modified version of PlasmaSol's patented "plasma shower" reactor, ensure repeatable and reliable operation when firing against conductive surfaces. Figure 1 shows a prototype of the actual capillary electrode plasma reactor firing against a conductive surface (here a stainless steel surface). As the plasma strikes the surface, it diffuses more or less uniformly across the treated surface. In an initial proof-of-principle experiment, we demonstrated that the plasma depicted in fig. 1 can completely remove a layer of pump oil from a stainless steel surface with an exposure time of less than 1 minute. Additional preliminary results indicate that this new device has the ability to operate at different plasma intensities and the ability to tailor the plasma jet intensity to a given application.

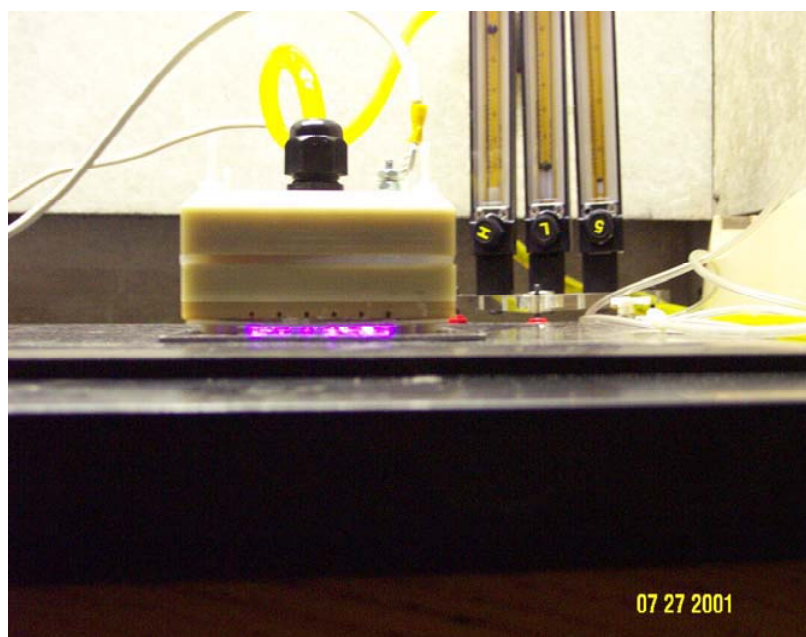


Fig. 1: Capillary electrode discharge plasma reactor firing against a conducting surface.

We characterized the hydrocarbon removal process from various surfaces by standard surface characterization studies supported by a detailed mass balance. These studies were carried out for both conductive and non-conductive. The macroscopic properties and the spatial distribution of the capillary plasma were examined for conductive and non-conductive surfaces in order to determine the effects of the treated material on the characteristics of the plasma (back-diffusion of volatile surface reaction products into the plasma !). Plasma generation was achieved using He, air, and various combinations of He and air as carrier gases. The experiments were performed by inserting uncontaminated surfaces into the plasma region and by subsequently monitoring the pertinent parameters (plasma distribution, plasma stability, current, voltage, etc). This assisted in determining distances between the treated surface and the electrodes that maximize surface exposure under a given set of operating conditions (power input, carrier gas, etc).

In order to characterize the effect of the plasma on a treated surface, we used an SEM analysis of the surface. Several samples of Al alloy 6061 were prepared for testing. A control sample was prepared and was always compared to the treated samples. The samples were subjected to the following conditions:

- Sample 1: control – no plasma; one hour elapsed - ambient air oxidation
- Sample 2: Plasma treated for two minutes at high power.

- Sample 3: Plasma treated for five minutes at low power.
- Sample 4: Plasma treated for five minutes at high power.
- Sample 5: Plasma treated for twenty minutes at high power.

The surfaces were analyzed using energy dispersive x-ray spectroscopy (EDXS) to determine the “before” and “after” effects of the plasma. We measured the electron ejection rate of a sample treated with a plasma for twenty minutes at high plasma density versus the control surface. This sample as well as other samples exposed for a shorter time and a lower power had no appreciable difference in the surface characteristics.

## **5. Summary**

We have developed a prototype atmospheric-pressure plasma reactor based on the novel capillary dielectric electrode discharge concept [1] that is capable of firing an array of high-density plasma jets against a conductive surface such as Al in a reliable, reproducible, non-destructive manner. This reactor was subsequently used in a series of preliminary experiments aimed at the determination of the optimum operating conditions for the destruction and removal of hydrocarbon contaminants on Al surfaces. We have so far demonstrated that our method is capable of removing hydrocarbon contaminants efficiently without affecting the underlying Al surface. Further experiments are currently underway.

## **6. Acknowledgment**

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## **References**

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- [1] E.E. Kunhardt and K. Becker, US Patent No. 5,872,426; US Patent No. 6,005,349; US Patent No. 6,147,452