NASF SURFACE TECHNOLOGY WHITE PAPERS
82 (4), 15-20 (January 2018)

Electrodeposited Inconel and Stellite-like Coatings for Improved Corrosion Resistance in Biocombustors

A Synopsis of a Presentation given at SUR/FIN 2017 (Atlanta, Georgia)*
by
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Editor's Note: The following is an updated synopsis of a presentation given at NASF SUR/FIN 2017, in Atlanta, Georgia on June 19, 2017 in Session 2, Advances in Surface Finishing Technology I.

ABSTRACT

A scalable and economic process is required to apply coatings on low-cost stainless steel substrates for enhanced high temperature corrosion resistance specifically targeted towards biomass combustion apparatus. Cost effective, scalable, and flexible electrodeposition-based coating of various alloys [Ni/Co]-Cr-[Mo/Fe] system, that are able to withstand high temperature corrosion and improve the functional lifetime of existing and next generation bio-combustors components is a desirable technological advancement. Within this context, a wide array of electrolytes and processing parameters were evaluated to develop an ideal alloy coating. Specifically, NiCr and NiCoCr binary alloy coatings demonstrated enhanced corrosion resistance when exposed to an aggressive environment (~700°C, 1000 hr, coating surface salted with ~3 mg/cm^2 every 100 hours) on different SS substrates. When compared to the SS base material the NiCr and NiCoCr coating exhibited a 70% weight loss and 3.4 times lifetime improvement over its base material.

Introduction

This particular work is laudable in that it deals with problems in the Third World – namely improving the safety and efficiency of cookstoves used by people around the world. According to the Global Alliance for Clean Cookstoves:

"*The use of open fires and traditional cookstoves and fuels is one of the world's most pressing health and environmental problems. Globally, three billion people rely on solid fuels to cook, causing serious environmental and health impacts that disproportionally affect women and children. According to the World Health Organization, household air pollution from cooking kills over 4 million people every year and sickens millions more*" (Fig. 1).

With this work, Dr. Vijapur has worked to create more efficient, longer lasting, cleaner and cost effective cookstoves for use in burning biomaterials. Biomass combustion reactors are subjected to various corrosive attacks due to the wide range of potential materials that will be burned in them, including gasoline, grass and other carbon-based waste, which give off prodigious amounts of CO, CO_2 and other carcinogens. To meet these problems, it is necessary to increase burning efficiency, burn at high temperatures and design low cost material systems to durably perform in these environments. To address the latter problem, Dr. Vijapur's approach was to apply a high value coating to existing bio-combustors or lower cost steels.

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*Compiled by James H. Lindsay, NASF Technical Editor

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Figure 1 – Typical cookstoves.

The objective was to develop a cost effective, scalable, and flexible electrodeposition-based coating process that could be applied to the corrosion sensitive regions of existing and next generation bio-combustors. The coating could consist of corrosion-resistant alloys such as Stellite 21 (Co-base, Ni-3%, Cr-29%, Mo-6%) or Inconel 740 (Ni-base, Co-20%, Cr-25%, Mo-0.5%). Considering possible alloy coatings:

- Nickel- and cobalt-based alloys have been shown to possess excellent alkali/halide attack resistance.
- Cobalt-based alloys have been shown to possess sulfidation resistance.
- Molybdenum additions into the metal alloys also seem to improve corrosion resistance and high temperature stability.
- Chromium improves temperature stability and corrosion resistance in high temperature systems.

Electrolyte development

Keeping in mind that costs were a major consideration in of any modification of a bio-combustor, low cost ferritic or austenitic steels were used as test substrates. A Hull cell was used to determine the solution composition and processing conditions which would deposit binary and ternary alloys of the family [Ni-Co]-Cr-[Mo-Fe]. A standard trivalent chromium electrolyte was used with varying amounts of the other metals. X-ray fluorescence was used to determine the deposit composition through the current density range along the Hull cell panel.

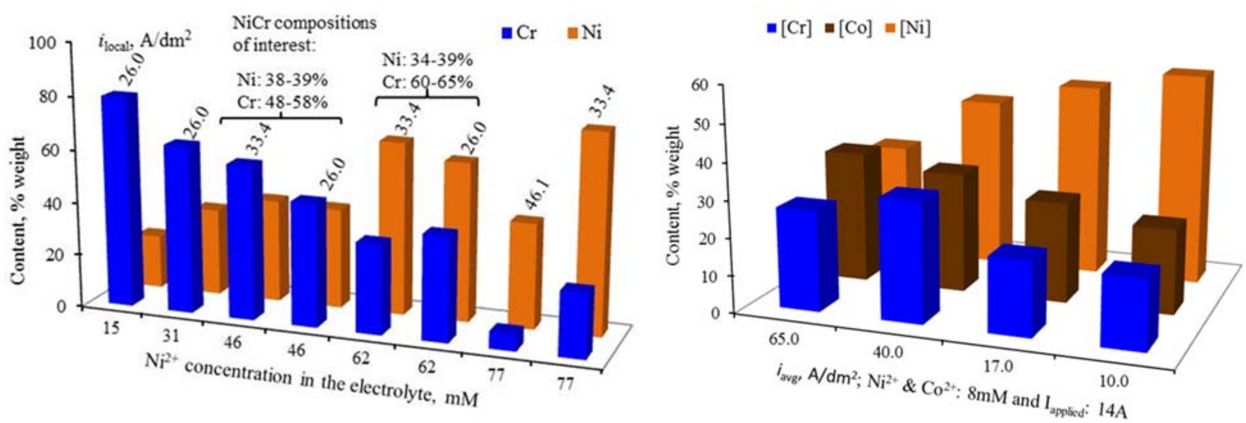

Figure 2 – Ni-Cr (L) and Ni-Co-Cr (R) alloy content versus nickel concentration in solution at various local current densities on the Hull cell specimens.

Commonly used in production control, the venerable Hull cell remains an invaluable tool in electrodeposition science and engineering. In this case compositional screening of Ni-Cr and Ni-Co-Cr alloys showed that a wide range of potential deposit composition could be obtained by controlling the nickel concentration (Fig. 2). Similar results are shown for Ni-Cr-Fe ternary deposits, both with DC and pulse waveforms (Fig. 3). Adding molybdenum, it was found that alloys approaching the compositions of Inconel 740 and Stellite® 21 could be produced (Fig. 4).

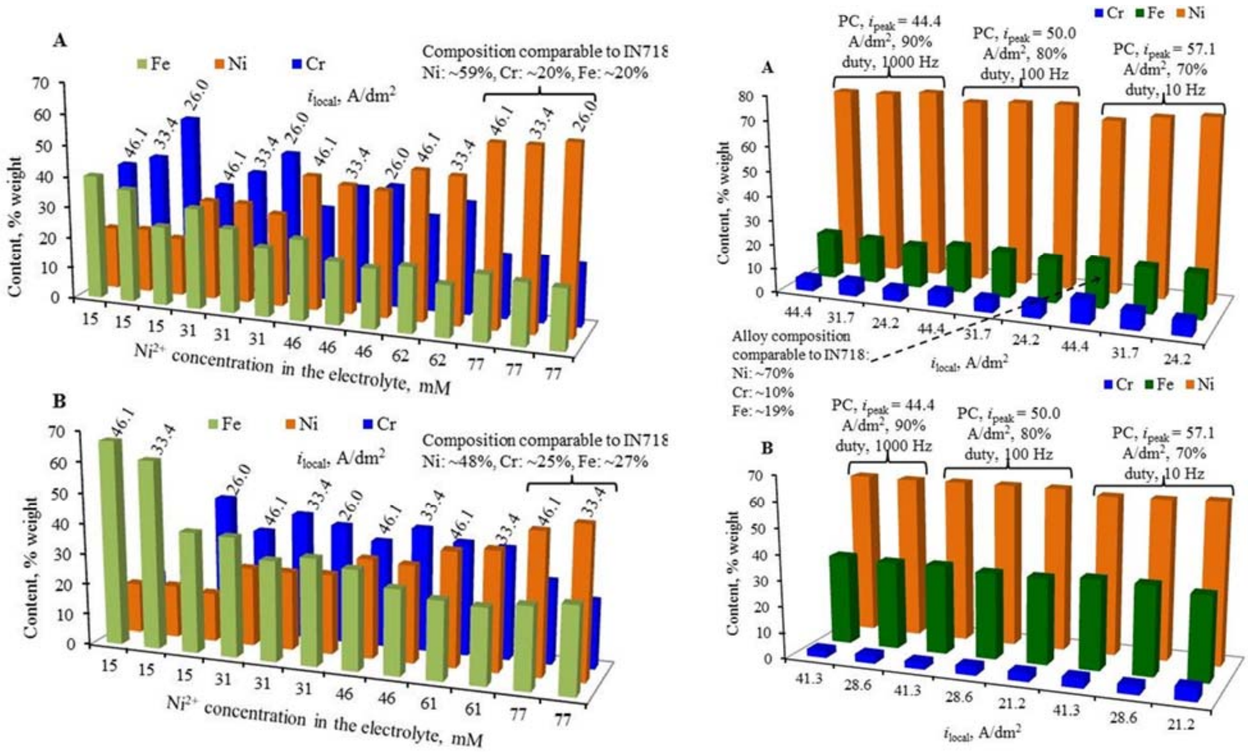

Figure 3 – (L) Ni-Cr-Fe alloy content versus nickel concentration in solution at various local current densities on the Hull cell specimens; (R) results with pulse waveforms.

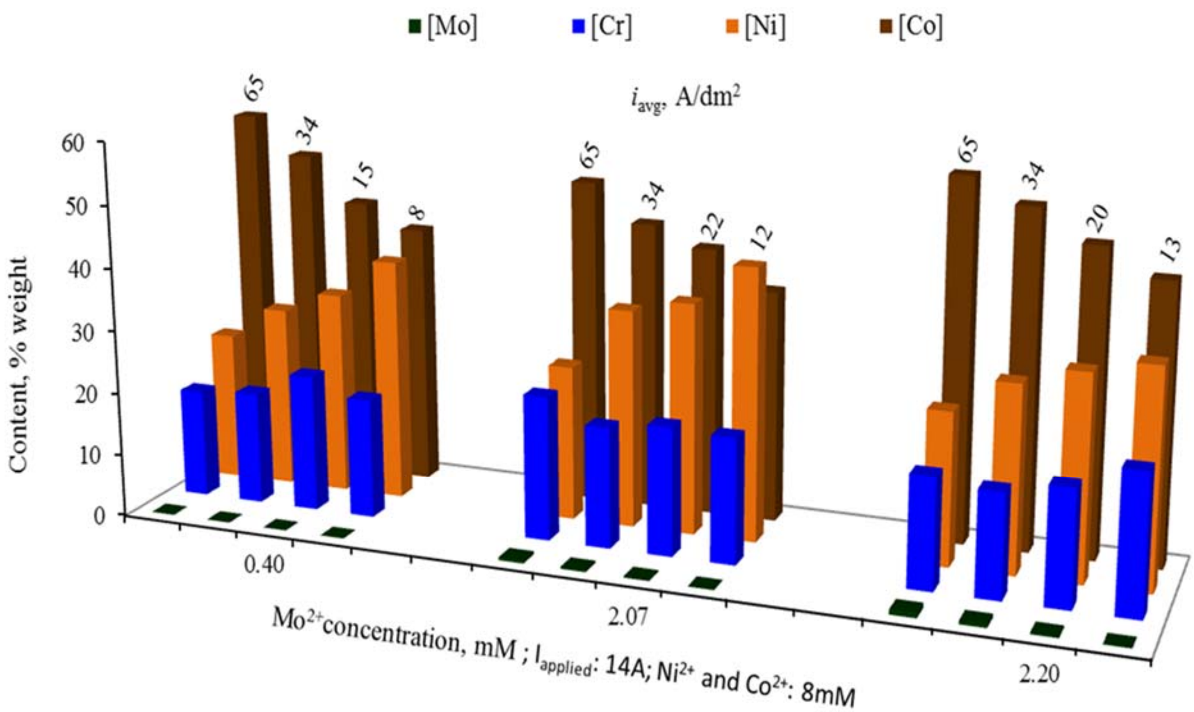

Figure 4 – Results of compositional Hull cell screening of quaternary Ni-Co-Cr-Mo alloys.

Coupon studies

Using the electrolyte designed within the Hull Cell study and approximate applicable current densities we transitioned to coupon studies. 1” × 4” samples were plated with different deposits in a Faradayaic® flow chamber, providing uniform laminar solution flow. Pure nickel, pure chromium, Ni-Cr, Ni-Cr-Fe, Ni-Co-Cr and Co-Cr deposits were studied at varying thicknesses and, in the case of nickel, varying nickel concentrations in solution. The results are shown in Fig. 5.

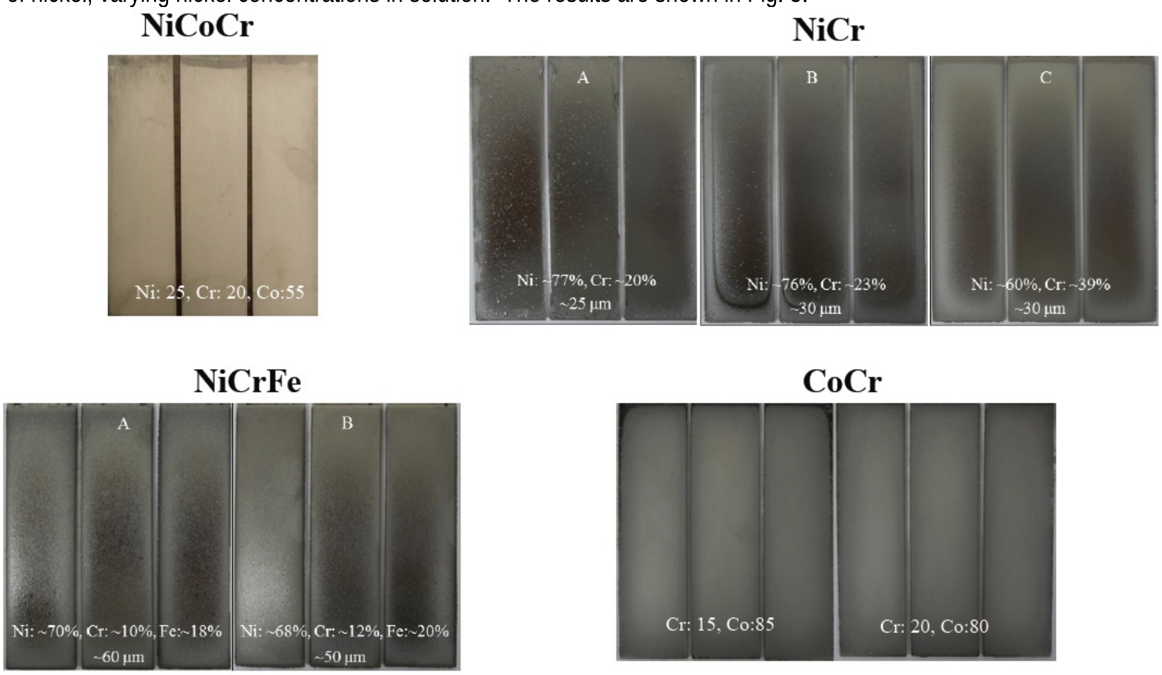

Figure 5 – Coupon samples as-plated.

Corrosion studies

Corrosion studies of the alloy deposits consisted of 100 hr of salted oxidation with high salt loading (~3 mg/cm^2). A 3.5 wt% solution of sea salt was applied to the surfaces before corrosion testing. Ten 100-hour cycles of salted oxidation, involving an initial thermal cycling regimen was used. The results for the high-level salt exposure are shown in Fig. 6.

The results of the entire study indicated that the pure chromium and nickel deposits did not maintain adhesion during the corrosion studies. However, the ~60/40 Ni-Cr and Ni25-Co55-Cr20 alloy deposits exhibited the best corrosion resistance, albeit dependent on thickness. The ternary (Ni/Cr/Fe) deposits did not maintain adhesion during the oxidation study, likely due to a mismatch of coefficients of thermal expansion (CTE).

As to suitability for their use in bio-combustors, the ~50 wt% Ni-Cr alloys improved the corrosion resistance of the base stainless-steel substrate by at least 70%, potentially leading to a 3.4-fold improvement in cook stove lifetime. An initial economic analysis indicated that a 4-mil coating unit cost declined with the number of units produced: (a) 10,000 units - $15.03; (b) 100,000 units - $2.91; (c) 1,000,000 units - $1.69.

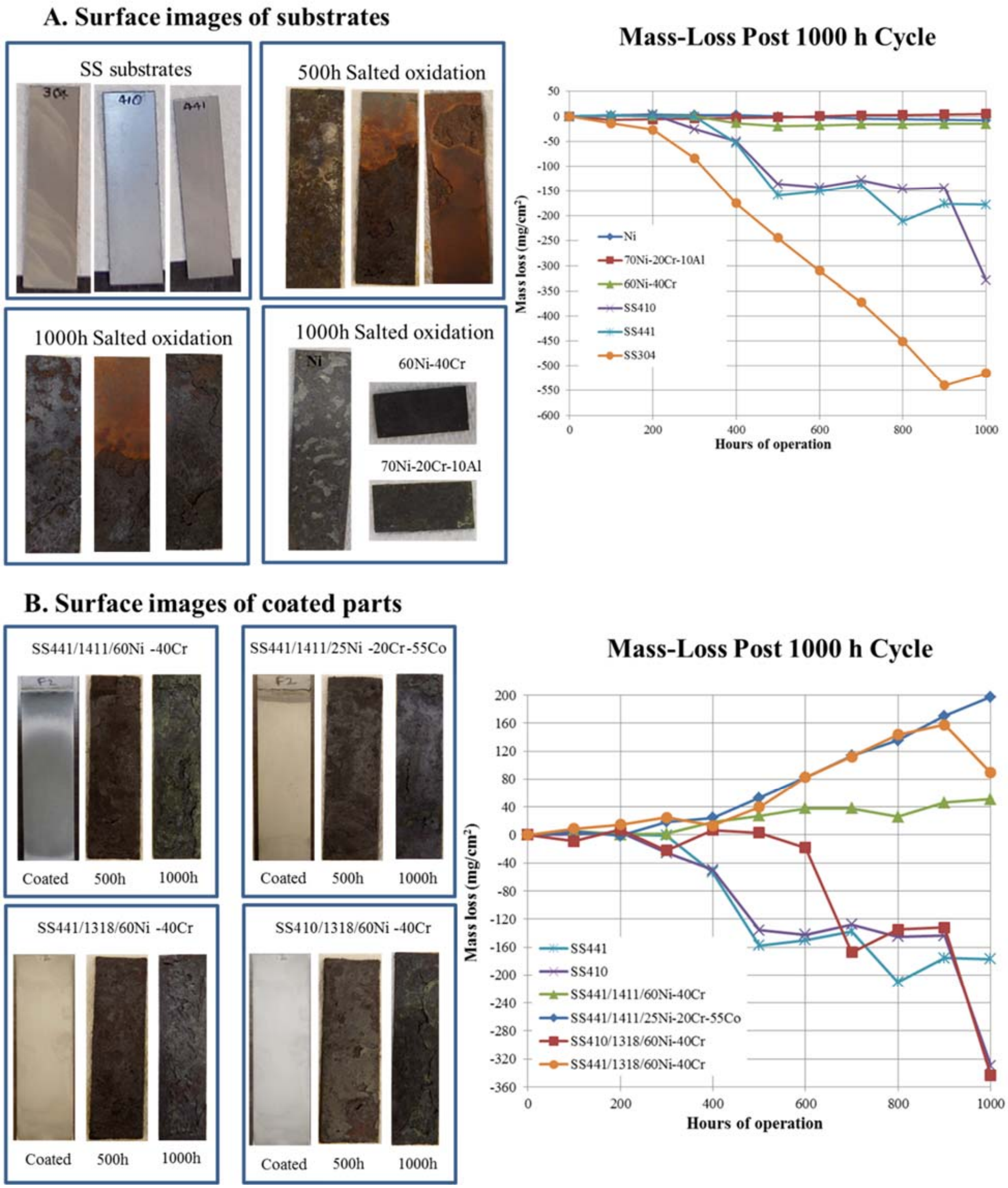

Figure 6 - Comparison between (A) substrates and (B) coated parts after 1000 hr salted oxidation trials [3 mg/cm^2].

Summary

Summing it up, this work:

- Demonstrated a wide range of [Co/Ni]–Cr–[Mo/Fe] alloy coating compositions that can be produced
- Demonstrated process scalability from a Hull Cell to flat coupons.
- Demonstrated the potential of specific coatings to surpass 1000 hours of accelerated high temperature corrosion testing.
- Showed that 50 wt% NiCr alloys improve corrosion resistance of the base stainless-steel substrate by at least 70%, potentially leading to a 3.4 fold cookstove lifetime improvement.
- Demonstrated that the process may be an economically viable approach for improving cookstove bio-combustor lifetimes.
- Showed a cost estimate that for 50 wt% NiCr coating to be $2.93/in.^{3} or $1.69 for a 4 mil coating on a 0.61 ft^2 component produced at 1,000,000 units per year, realizing an 89% cost reduction compared to base IN625 materials.

About the author / presenter

Dr. Santosh H. Vijapur is Principal Scientist at Faraday Technology Inc., Englewood, Ohio. He received his B. Tech. in Chemical Engineering from Dr. Babasaheb Ambedkar Technological University (India) in 2002, his M.S. and Ph.D. in Chemical Engineering from Ohio University (Athens, OH) in 2008 and 2015, respectively. Dr. Vijapur is currently working on plating technologies at Faraday. Prior to joining Faraday in August 2016, Dr. Vijapur worked at TE Connectivity, tasked with investigating the performance of corrosion inhibitors. Dr. Vijapur is the recipient of IEEE H.H. Dow Student Achievement Award 2015 from the Electrochemical Society. Dr. Vijapur has numerous publications and one patent application currently pending.