NASF SURFACE TECHNOLOGY WHITE PAPERS
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The 55th William Blum Lecture
Presented at NASF SUR/FIN 2021
in Detroit, Michigan
November 2, 2021

Additive Manufacturing and Surface Finishing

by
Dr. Keith Legg
Recipient of the 2019 William Blum
NASF Scientific Achievement Award

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Modeling and Simulation for the Finishing Industry

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EXTENDED ABSTRACT[*]

As Dr. Legg watched the changes in industry over the past decade or so, he has seen modeling and simulation move from one industry to another. Seeing how and where it is used elsewhere, he concludes that modeling could be more widely and profitably used in the surface finishing industry.

Models are not reality, but they are tools to make reality more comprehensible and predictable. They can be used to improve the performance of jet aircraft and racecars, to design new alloys in weeks rather than years, to predict the transmission of Covid-laden droplets, but they can also be used to improve the performance of items as prosaic as dishwashers. Models give us a way to predict the behavior of complex systems and find ways to improve their performance. Models often give us insight into how complex systems work, allowing us to rapidly find ways of improving them. Even when they provide little insight into mechanisms it is possible to use modeling to “test” materials, coatings and equipment far faster and at far less expense than the old Edisonian method of finding a thousand ways not to make a lightbulb.

However, a model is only as good as what goes into it. A model must include all the critical processes and have good quality data. This does not mean it must be all-encompassing to be useful, but one needs to know what its limitations are, where it is valid and where it will break down. For example, if your product contains dissimilar materials, a galvanic corrosion model may be fine, but if you have overlapping components, you probably need a crevice corrosion model as well. If your product is used on a ship, you need seawater corrosion data, but if it is used in a chemical plant, you may need acid corrosion data.

How does one determine whether a model is accurate or useful? One also needs to know how accurate it must be to get useful answers and what are the consequences of a wrong answer. It may look impressive but is it validated again solid, reliable data? Can it predict accurately over the ranges of time, temperature, distance, etc. relevant to your application? In particular, can it hindcast? That is, does it predict known data – quantitatively or even qualitatively? If not, it is missing something important. The complexity of the system to be modeled is critical. The more complex it is, the harder it is to be sure it includes all the critical variables. Climate models are a prime example – the earth’s climate is an extremely complex system, depending as it does on solar output, atmospheric chemistry, polar reflectivity, cloud cover, and myriad other variables. Climate models cannot be directly validated against solid, reliable temperature records, but only against proxies for temperature (tree rings, pollen, isotope ratios, etc.), which may or may not accurately reflect the temperature itself.

The most important benefit that modeling provides is the insight to improve processes and handle change efficiently, and with more certainty. It is almost always far faster and cheaper to develop and optimize materials and processes using modeling than using formulation and testing. This is particularly important for developing and optimizing coatings, where modeling can be used to short-circuit the multiple reformulation and retesting cycles that coating development usually entails. Models do not have to be complicated (or even necessarily complete) to be useful, but they do have to be correct. Getting it right means you must define the way the model is made, where it is valid, and how to take the data that go into it.

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[*] Compiled by Dr. James H. Lindsay, NASF Technical Editor, with the edits and approval of Dr. Legg.

When your product or process has to change, you may need to redesign a component. A model lets you quickly check how the redesign will affect system performance. If regulations such as REACH ban yet another of your critical chemicals or coatings, you must first get the materials data from the alternatives. Then, you can quickly rerun your models with all the alternatives to see how performance changes (Cr^6 > Cr^3 > non-Cr). If you want to enter a new market, a good model can predict performance directly for all manner of stresses or environments. You can reduce risk by evaluating any number of what-ifs – far more than you could possibly test. This includes checking for possible, but unusual, scenarios that would not happen in normal service testing – or that would be disastrous if they did.

Modeling is used in automotive component plating Both Ford and GM both encourage or require computational modeling to ensure coating thickness uniformity for plating-on-plastic parts. In fact, some companies always carry out computational modeling whether the customer requires it or not, (1) to meet specifications for thickness uniformity across components and across the plating rack and (2) to optimize the loading on the rack for maximum throughput consistent with coating quality. Some companies that design, mold and plate also use CFD to optimize mold filling, ensure part quality, platability and plating quality.

So, why use modeling in surface finishing and corrosion? While stress engineers, heat transfer engineers and vibration engineers all have models showing why their solutions will work, the corrosion/coatings engineer cannot prove (even to himself) that his solution will work. Without quantitative modeling, the corrosion/coatings engineer is severely handicapped, resulting in corrosion concerns often not being adequately taken into account in design.

In the galvanic corrosion control standard MIL-STD-889D (released in 2021), NAVAIR improved the original *Best Practices for Data Acquisition - Polarization Data for Galvanic Corrosion Protection* developed by a Navy Research Lab Sea-based Aviation Team and incorporated them into MIL-STD-8809D. Many Naval aircraft operate from aircraft carriers – the world's most corrosive environment.

To minimize the galvanic interaction between fasteners, bushings, and aluminum airframes and skins in Naval aircraft steel fasteners and bushings are usually Cd-plated and wet-installed (*i.e.*, dipped in primer before installation to prevent water penetration between the aluminum and the bushing/fastener, which inevitably creates severe local galvanic corrosion. Following successes with Al-rich primer elsewhere, NAVAIR saw an opportunity to reduce galvanic corrosion in bushings and fasteners by wet-installing with Al-rich rather than standard primers. Although a bushing is a very simple device, an Al-rich primer is very complex, comprising a size distribution of passivated Al alloy particles in a polymer matrix. Optimizing such a wet-install system would be very complicated, probably involving hundreds of formulations, thousands of tests, and millions of dollars. With modeling, it did take three years to develop the model and measure the underlying electrochemical properties of its constituents, but once model was developed, CFD workflow automation took days instead of weeks. Optimization took thousands of simulations, over a few weeks, to define the optimum formulation. But this was still far less expensive and faster than the old test and reformulate approach, and it means that when a better material comes along or changes needed to the existing formulation, re-optimization be relatively quick and inexpensive.

Another example involves the replacement of Cd in aerospace and Zn in automotive with ZnNi plating. It is easy to plate an elemental coating – get the plating parameters right and Faraday's law takes care of the rest. Once you have two elements however, they do not typically deposit in the same ratio as the composition in the electrolyte, and that ratio can vary with plating voltage, current density, electrolyte flow rate, etc. This means that the coating chemistry, microstructure and performance can vary across complex components. The coating can even change between galvanically protective to galvanically corrosive in different areas. If you want to plate ZnNi for aerospace, your tooling must be designed by electrodynamic simulation and sometimes computational fluid dynamics, to get the right chemical and thickness uniformity. The Zn/Ni ratio varies with current density and current density varies over complex shapes, holes, etc., so one must model component, anodes, secondary anodes and robbers, while complex parts may also require modeling fluid flow, including eductors.

Machining turbine engine components, gun rifling and other complex parts, often involves electrochemical machining (ECM) to make non-circular holes or machine thin sections of Ni--based alloys. The ECM tool rapidly creates complex-shaped holes in very hard alloys, and, because the tool never touches the part, it can be used to machine thin sections that mechanical machining would distort. Hole dimensions, however, are a complex function of tool shape, voltage, etc. The only way to design a tool is multiple iterations of trial and error, which is very costly and uncertain. It takes many months and even then, the tolerance may be unacceptable. The solution is to develop an ECM model to calculate the required tool shape. Such a model must include many variables: electrochemical properties of the tool, workpiece alloys, and the electrolyte, the use of DC or pulsed current, the machining rate and removal of heat, debris, bubbles, etc. Ideally, we should be able to mathematically unmachine the part to determine the tool from the finished product. However, it turns out we cannot do that, but we can model hundreds of tool shape iterations to optimize the tool. Once the ECM model exists, we can quickly and reliably design tools to machine any shape.

Another example involves non-drip brush plating, where, instead of dipping the tool into electrolyte, the electrolyte is pumped through the tool, through the plating pad, and back to the electrolyte reservoir. For the tool to be non-drip, the fluid entering the pad must be balanced by air flowing in. Whenever we design a new non-drip brush plating system, we use a combination of computational fluid dynamics and electrodynamics to ensure the tool will not drip and will plate uniformly. With computational methods, a non-drip repair system to repair Al anodizing and fastener corrosion on an aircraft wing simultaneously was developed. On-aircraft processing at this scale could not be done without computational methods.

Today, modeling for surface finishing is a recognized approach. It is proving to be very useful for plating and some finishing processes. It is finding new uses as it develops, but there is a lot to learn. The aim is to make modeling a standard, integrated approach to coating development and corrosion protection.

About the author

Dr. Keith Legg, is Co-owner and CTO of Corrdesa LLC, Newnan, Georgia, a new venture started by Alan Rose and Keith Legg to bring computational galvanic corrosion prediction software to the market for design and maintenance. Corrdesa works closely with various defense organizations and aerospace companies to use the computational approach for assessing risk and correcting design.

He is also Technical Manager of the DoD SERDP-ESTCP ASETSDefense Initiative, which provides information, a public database of reports, periodic workshops, and assistance to engineers to meet ESOH requirements for the US and Europe.

Dr. Legg earned his B.A. in Physics from Lancaster University (UK)(1967-1970) and his D. Phil, in Physics from the University of York (UK)(1970-73). His expertise is in advanced coatings, and alternatives to materials and coatings with environmental and health problems, such as chromate materials and processes, chrome plating, Cd plating, etc.