Plasma Electrolytic Oxidation (PEO): A High-Performance Coating for Light Metal Alloys

by
G.C. Kulkarni, S. Bolan, P. Jarosz, R. Motyka and S. Berman*
IBC Materials & Technologies
Lebanon, Indiana, USA

Technical Editor's Note*:** The following is a paper** based on a presentation given at NASF SUR/FIN 2024, in Atlanta, Georgia on June 5, 2024 in Session 3, Corrosion Protection and Wear Resistance. A pdf of this paper can be accessed and printed ***HERE.

Abstract

Plasma Electrolytic Oxidation (PEO) offers an innovative approach to high-performance coatings for light metal alloys, providing superior alternatives to traditional hard anodizing. This process transforms the surface of metals like aluminum, magnesium, and titanium into a robust oxide layer with customizable properties, tailored for demanding applications in aerospace, semiconductor, and industrial manufacturing. PEO is distinguished by its inward diffusion process, which forms a highly adhesive bond between the substrate and the coating without significantly altering the dimensions of the part. This results in unmatched wear resistance, corrosion protection, and thermal stability, even under extreme conditions like thermal shock. PEO also excels in versatility. Its non-line-of-sight process enables precise coating of intricate shapes, including sharp corners and internal features, and masking can be used for selective coating of specific areas. The process is environmentally friendly, utilizing a non-toxic electrolyte and an advanced power supply to generate micro-plasma discharges, which are key to forming the coating. By adjusting process parameters, the properties of the coating can be finely tuned. Additional enhancements, such as sealers, can be applied to the coating to further improve corrosion resistance and dielectric strength. PEO represents a major leap forward in material performance, offering an efficient, scalable, and eco-friendly solution for industries demanding durability, reliability, and advanced thermal management.

PEO Overview

Plasma Electrolytic Oxidation (PEO) offers a cutting-edge coating technology that transforms the surface of light metals like aluminum, magnesium, and titanium into a durable, oxide layer with customizable properties. Unlike traditional anodizing, PEO relies on inward diffusion rather than outward growth, creating an exceptionally strong bond between the coating and substrate while preserving the part's dimensions. This innovative process delivers enhanced wear and corrosion resistance, compatibility with sealers and topcoats, and tunable thermal conductivity. PEO coatings also exhibit remarkable high-temperature durability, withstanding thermal shock and degradation. Additionally, its non-line-of-sight deposition capability makes it ideal for coating complex shapes and intricate geometries, offering a versatile solution across industries.

During the PEO process, workpieces are submerged in an eco-friendly, proprietary electrolyte, and a programmable pulsed power supply delivers electrical power to the parts. The high voltage initiates and sustains surface micro-plasma discharges that form the PEO coating (Figure 1). By adjusting various process parameters such as the composition and pH of the electrolyte, as well as electrical factors like duty cycle and frequency, coating properties can be precisely controlled, allowing for optimal performance tailored to specific applications. The process results in the transformation of the surface of the light metal into a durable, oxide layer. PEO coatings offer a number of advantages over hard anodizing, as shown in Table 1 and Figure 2.

* Corresponding Author:
Gajanan Kulkarni
IBC Materials & Technologies
Electrochemical Engineer
823 Hendricks Drive
Lebanon, IN 46052
Phone: (765) 481-2900
E-mail: gkulkarni@ibcmaterials.com
Website: www.ibcmaterials.com

** Compiled by Dr. James H. Lindsay, NASF Technical Editor

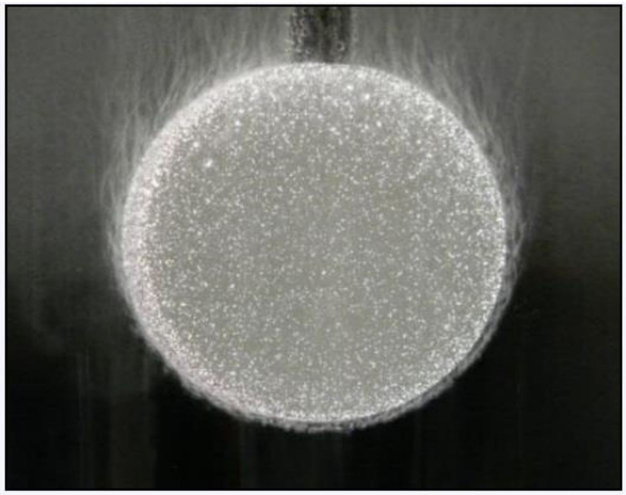


Figure 1. Micro-plasma discharges on the surface of a sample during the PEO process

Table 1. Comparison of plasma electrolytic oxidation (PEO) on aluminum as a general replacement for hard anodizing.

Aspect	Current state - Hard Anodizing	New solution – PEO coating
Applicable alloys	• Applicable to Al6XXX, Al7XXX. Difficulty in coating Al2XXX, Al3XX and cast alloys.	• Applicable to all Aluminum alloys including Al2XXX, Al3XX, and cast alloys
Protection	• Inherent cracking in corners and sharp edges.	• Uniform coating coverage even in corners and sharp edges.
Dimensional accuracy	• Hard anodizing typically results in 50% outward growth and 50% inward diffusion • Results in dimensional changes to the part.	• Near 100% inward diffusion. • No dimensional changes to the part/component.
Hardness	• 600 HV	• 1200-2000 HV (Up 2-2.5x improvement)
Corrosion resistance	• ASTM B117 neutral salt fog up to 264 hours	• ASTM B117 neutral salt fog up to 1848+ hours (7x or more improvement)
Wear resistance		• PEO has demonstrated 2-80x improvement depending on the alloy.
Environmental impact	• Requires harsh acids (e.g. sulfuric acid) • Require toxic chromium sealers	• Eco-friendly solution (Water based) • Chrome-free

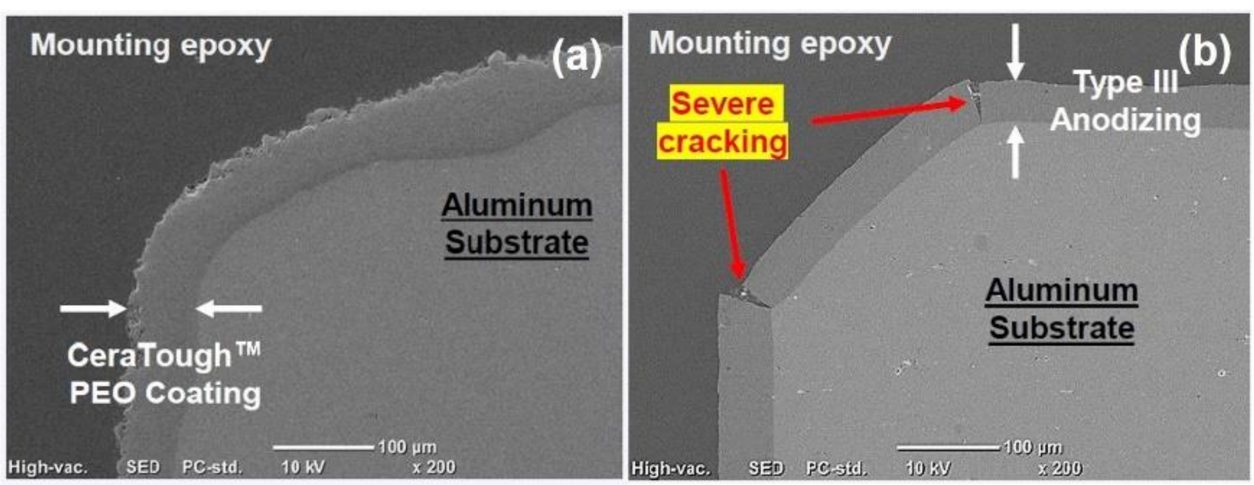


Figure 2. Cross-sections of (a) PEO coating vs. (b) Type III anodizing. The PEO process results in uniform coating, even on corners. The inherent columnar structure of Type III anodizing leads to severe cracking on the corners of the substrate.

Wear resistance

Wear tests comparing PEO and Type III anodizing were conducted in accordance with ASTM G133, the Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear. As illustrated in Figure 3, PEO exhibited significantly lower wear rates across various aluminum alloys compared to Type III anodizing. Although Type III hard coat is engineered for wear resistance, PEO on Al-7075 outperformed it, showing no measurable wear. The tests utilized a 10 mm 440C steel ball with a Rockwell Hardness of 60 HRC, applying a 5N load at a frequency of 5 Hz for 1000 seconds. All tests were conducted dry, without lubrication. These results align with the performance of PEO-coated customer parts that have been in service for over seven years, showing no detectable wear.

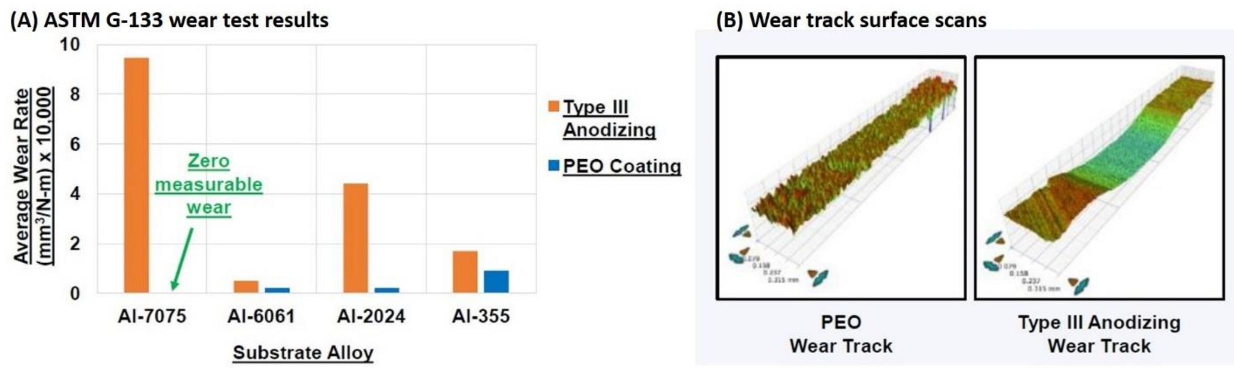


Figure 3. Results of wear resistance studies: (a) Typical ASTM G133 wear results for anodizing vs PEO; (b) typical optical surface scans of wear tracks showing significant wear trough for anodizing, but negligible wear for PEO.

Corrosion resistance

PEO-coated specimens underwent corrosion testing and were compared to Type III anodized samples. The corrosion tests were carried out in a neutral salt fog environment according to ASTM B117, the Standard Practice for Operating Salt Spray (Fog) Testing. Aluminum 7075 samples (sealed PEO and sealed Type III anodizing) were exposed to a salt fog with pH range of 6.5-7.2. The results show pitting failure in the Type III anodized samples after 264 hours. In contrast, PEO-coated samples remained unaffected, with testing halted at 1848 hours due to the absence of pitting even after prolonged exposure (Figure 4).

Figure 4. Results for PEO and Type III anodizing in corrosion testing per ASTM B117 (Neutral Salt Fog)

Corrosion testing of PEO-coated samples was also conducted in an acid rain environment, following ASTM G85, the Standard Practice for Modified Salt Spray (Fog) Testing. Aluminum 7050 samples (sealed PEO and sealed Type III anodizing) were exposed to a salt fog with SO_2 gas, resulting in an acid pH range of 2.5-3.2. As depicted in Figure 5, the Type III anodized samples exhibited severe corrosion and pitting, along with the formation of white corrosion products and visible discoloration. In contrast, the PEO-coated samples showed minimal corrosion on the aluminum, with the corrosion primarily affecting the steel components, resulting in red rust.

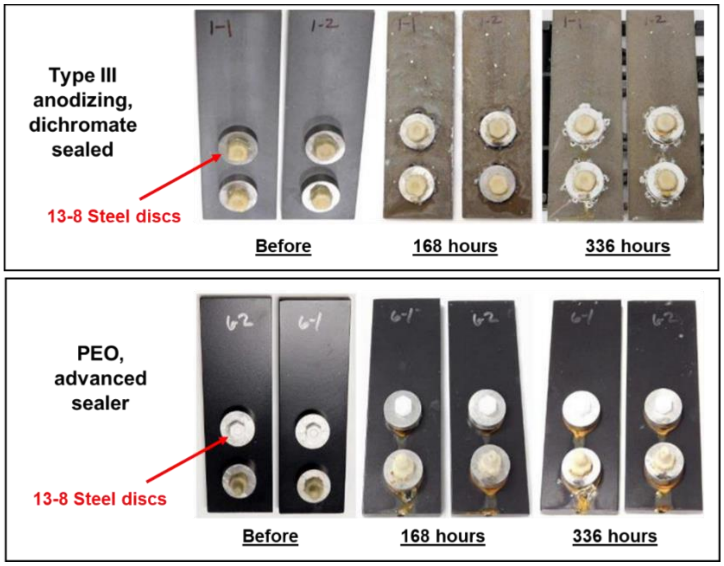


Figure 5. PEO and Type III Corrosion Testing per ASTM G85:A4 (Salt Fog + SO_2)

Thermal barrier coatings (TBC)

Thermal barrier coatings (TBCs) are essential for protecting components exposed to extreme heat, such as those in gas turbines, jet engines, piston crowns, hypersonic systems, and space propulsion or re-entry vehicles. Effective TBCs must provide critical thermal insulation, protect against oxidation, and resist thermal shock, ensuring durability in high-temperature environments. PEO coatings have been specifically developed for these demanding applications, achieving rapid growth rates (>10 µm/min) and high thicknesses (>100 µm) as shown in Figure 6. The amorphous/nanocrystalline structure of PEO offers superior thermal insulation, with thermal conductivity as low as 0.2 W/m-K, significantly lower than traditional plasma spray coatings, which range from 0.5 to 1.5 W/m-K. Heat flow testing results, presented in Table 2, demonstrate heat rejection rates as high as 60%, making PEO coatings an effective solution for extreme thermal environments.

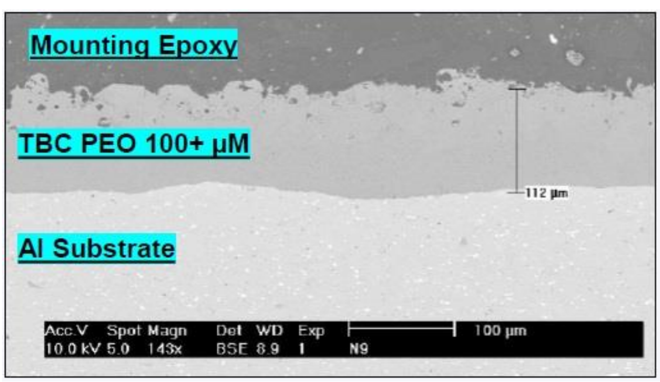


Figure 6. High thickness (>100 µm) PEO thermal barrier coating (TBC) in cross-section.

Table 2. Heat flow results for Al 4032 with and without PEO TBC.

Temperature (°C)	80	120	160	200
Heat Flow Through Uncoated 4032 (W)	64.4	96.6	210.6	270
Heat Flow Through PEO Coating (W)	33.6	52.4	88.9	108.1
Heat Rejection Rate	48%	46%	58%	60%

Building on the successful application of PEO as a thermal barrier coating, its thermal cycling performance was evaluated (Figure 7). PEO-coated samples were subjected to surface temperatures of 1000-1400°F using a gas torch for 30 seconds, followed by immediate quenching in water. This cycle was repeated 200 times without any delamination, spallation or degradation in coating performance. Temperature measurements revealed an average temperature drop of 660°F between the front and back of the coupons, demonstrating the PEO coating's excellent thermal protection and durability under extreme thermal cycling conditions. Other TBCs like plasma spray typically suffer severe delamination from thermal shock in such conditions.

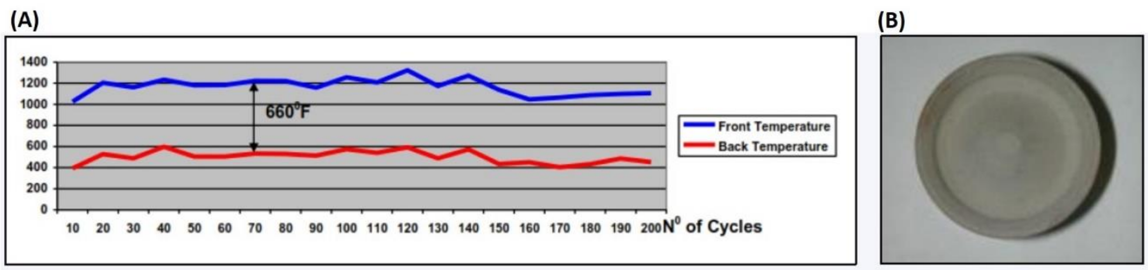


Figure 7. Thermal cycling study: (a) Temperature measurements of PEO-Coated Samples subjected to thermal cycling; (b) PEO-coated coupon sample after thermal cycling.

Additionally, samples were exposed to an oxy-acetylene torch for under 5 seconds at close cutting distance (4000-6000°F), as shown in Figure 8a. Bare aluminum coupons (Figure 8b) melted under the intense heat, while PEO-coated aluminum (Figure 8c) remained undamaged by the torch exposure, demonstrating the exceptional thermal resistance of the PEO coating under extreme conditions.

Figure 8 – Torch testing study: (a) torch exposure at cutting distance; (b) Uncoated Al 4032; (c) PEO-coated Al 4032.

PEO coating as a dielectric layer

PEO on aluminum can be tailored for various applications beyond thermal barrier coatings, including dielectric layers for electronic applications. The PEO layer creates a uniform, durable electrical insulator (~500V/mil) with relatively high thermal conductivity (e.g., 7 W/mK). This thermal conductivity can help with heat dissipation in some cases, such as metal core printed circuit boards (MCPCBs). The PEO coating also retains its dielectric performance at high temperature and, with high resistance to thermal cycling, PEO coating is suitable as a dielectric layer for challenging environments in defense, electronics, and semiconductor industries.

PEO-coating on magnesium

Magnesium is one of the lightest structural metals, making it highly valuable for weight-sensitive applications in aerospace, automotive, and electronics. However, its low density comes with a major drawback, which is high susceptibility to corrosion, especially in harsh environments like marine settings or areas with high humidity. This vulnerability limits its broader use. Traditionally, magnesium is protected with a chemical conversion coating, followed by a primer and topcoat. However, Plasma Electrolytic Oxidation (PEO) offers a superior alternative, providing enhanced corrosion resistance and durability for high-value magnesium parts in demanding environments (Table 3).

Table 3. Comparison of PEO coating performance on magnesium versus commercial conversion coating.

Aspect	Conversion Coating	PEO Coating
Corrosion resistance	Inferior corrosion protection. Requires primer-paint layers for added protection.	Superior corrosion protection.
Durability	Fragile, thin layer (e.g., <5 μm). Susceptible to scratch damage.	Robust layer (e.g., 15-20 μm) with exceptional adhesion to substrate. Resistant to scratch damage.
Scratch-corrosion resistance	Highly susceptible to scratch-induced corrosion. Scratches easily compromise primer-paint layers, resulting in severe corrosion propagation.	Highly resistant to scratch-induced corrosion. No corrosion propagation even when scratched.
Environmental impact	Use of hazardous materials: Conversion coatings are often chromium-based.	Environmentally friendly (chromium-free).

Corrosion testing of PEO on Magnesium

PEO-coated magnesium specimens, both with and without primer and topcoat, were evaluated against chemical conversion-coated magnesium in a salt fog corrosion test, conducted per ASTM B117. Testing results indicate that PEO on magnesium is vastly superior in corrosion resistance, compared to the incumbent chemical conversion coating, as highlighted in Figure 9. Both specimens were deliberately scratched through the epoxy primer to the substrate in order to simulate field conditions in which the paint and coating system are compromised. As shown, the PEO exhibits little to no corrosion and suffers no corrosion propagation. In contrast, the baseline chemical conversion coated specimen is severely damaged by corrosion that initiated at the scratches and propagated underneath the epoxy to the entire specimen.

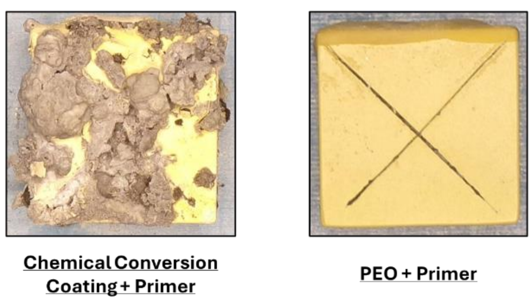
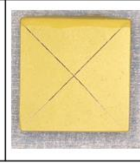


Figure 9. Baseline chemical conversion coating + primer with scratch (left) and PEO + primer with scratch (right) after 336 hours of ASTM B117.

Table 4 illustrates similar analysis of the corrosion resistance of various other coating stack ups after deliberate scratching. Specimens with chemical conversion coating alone show extensive corrosion, setting the worst-case baseline. Chemical conversion coating + primer + paint also exhibits significant corrosion due to insufficient protection from the exposed chemical conversion coating. In contrast, sealed PEO shows minimal corrosion, confined to scratches with minor salt deposits, highlighting its superior resistance. The PEO + chemical conversion coating + primer system demonstrates the best performance, with minimal corrosion and propagation, far outperforming the chemical conversion coating + primer + topcoat combination.

Table 4. Corrosion performance of PEO-coated magnesium versus conversion-coated magnesium (ASTM B117 salt fog, samples as-processed, **scratched**).

	Hours of Exposure			
Sample Description	**0**	**23**	**167**	**336**
Chemical Conversion Coating				
Chemical Conversion Coating + Primer + Topcoat				
PEO + Sealer				
PEO + Chemical Conversion Coating + Primer				

PEO on Mg Gearbox

With proven corrosion protection, PEO coating is ideal for protecting valuable magnesium parts such as Accessory Gearboxes from harsh environments. To accommodate such large parts, IBC has scaled up the PEO on Mg process, using its PEO production facilities to successfully apply PEO to a magnesium gearbox (Figure 10).

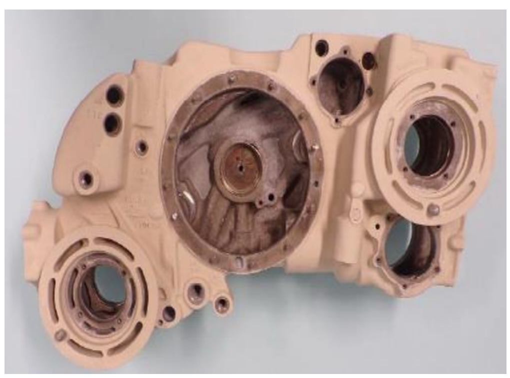


Figure 10. PEO-coated magnesium Accessory Gearbox

Summary

This discussion highlights several key benefits of Plasma Electrolytic Oxidation (PEO) coatings, including:

- Superior corrosion resistance
- Outstanding wear and scratch resistance
- Environmentally friendly process, improving safety and reducing remediation costs
- Significantly extended part lifespan
- Lower maintenance and replacement costs
- Increased part availability
- Customizable properties for various applications

PEO is a high-performance coating that offers wear resistance, corrosion resistance, electrical insulation, and thermal barrier capabilities. It enables the use of materials in extreme environments that would otherwise be unsuitable, such as aluminum in high wear applications or magnesium in corrosive conditions.

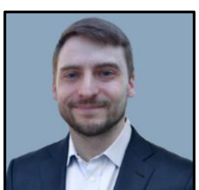
In practice, IBC Materials' PEO coatings have dramatically extended the service life of high-value parts. We have successfully scaled PEO production for high-volume industrial and aerospace applications and continue to innovate and optimize PEO technology to deliver these benefits to new customers.

About the authors

Dr. Gajanan C. Kulkarni is an Electrochemical Engineer at IBC Materials & Technologies in Lebanon, Indiana. He holds a PhD in Chemistry from Southern Illinois University and has a strong background in Organic Synthesis for battery applications. At IBC, Dr. Kulkarni focuses on plasma electrolytic processes and electropolishing, developing advanced methods for surface modification, polishing, and coating removal. His work aims to enhance the performance and durability of cutting-edge materials, making him a key contributor in the field of surface engineering.

Stephen Bolan is a chemical engineer at IBC Materials, with a B.S. in Chemical Engineering from Ohio State University. At IBC, Stephen has focused on the development, characterization, and scale up of PEO coating technology for various defense, aerospace, semiconductor, and commercial applications. Mr. Bolan has managed many projects that aim to further advance the PEO technology and tailor coatings to provide innovative solutions for IBC's many customers.

Dr. Paul Jarosz is the Director of Business Development at IBC Materials. He holds a Ph.D. in Chemistry from the University of Rochester and has extensive experience in materials science, nanomaterials, chemical engineering, and coatings. Dr. Jarosz has also served as a research scientist/technical director, transitioning novel technologies from the laboratory into new products. At IBC, Dr. Jarosz has developed and improved multiple coating processes to meet challenging requirements for customers from aerospace, defense, semiconductor, and oil & gas.



Roman Motyka is the Chief Technologist at IBC Materials. He holds a B.S. in Materials Science and Engineering from Purdue University, with 10 years of experience in the field of surface engineering, including process development, tribology, and characterization of advanced coatings. At IBC, Roman provides technical oversight for a diverse portfolio of PVD, CVD, and diffusion technologies in the pursuit of solving complex friction, wear, corrosion, and fouling problems.

Dr. Solomon Berman holds an MA in Mechanical Engineering from Kishinev Agricultural Academy in Moldova and a Ph.D. in Plasma Coatings from the Paton Welding Institute, National Academy of Sciences of Ukraine. Since 1996, he has served as the President & CEO of IBC Coatings Technologies, ltd. and IBC Materials & Technologies, LLC., leading the companies to consistent growth in surface engineering services for wide variety of customers in many different industries. He has extensive research experience in plasma coatings and surface modification. He has authored over 30 scientific papers and holding 7 patents on metallurgical coatings.