SilcoTek Coating Properties

A Comprehensive Analysis of Coating Characteristics and Properties

An eBook by SilcoTek Corporation

Game-Changing Coatings

This E-book is dedicated to all SilcoTek coating technicians, scientists, and advocates.

Table of Contents

Chapter 1
Introduction to SilcoTek® and Our Coatings

About this E-Book

Customers frequently ask us about how our coatings perform under their environmental or process conditions. We've done blog posts, summary sheets, web pages and reference guides to address customer questions, but never have we combined all of our material performance data into one easy to read e-book. In this e-book we'll discuss how SilcoTek coatings perform under extreme conditions and highlight basic material characteristics so that our customers can better understand how our coatings will perform in their application.

At SilcoTek, we believe an informed customer is the happiest customer. If our coatings are not appropriate for your application, we'll tell you! To best fulfill our customer needs we need to work with the customer to understand how the coating will be used. There are a lot of variables that affect how a coating will perform. Environmental conditions, physical stress, material compatibility, chemical compatibility, process conditions, and much more. That's why we want to offer as much performance data as possible to assure your coated product performs at its best.

We also want to make selecting a coating easy. To help the customer manage all the factors that go into a superior coating, we offer several tools to make coating selection fast and easy. We offer an online coating selector tool, online chat with a live SilcoTek expert, informative coating blogs, application briefs, an easy to navigate website, webinars, and old-fashioned great customer service. We also offer a SilcoTek Coating Material Property Reference Guide so you don't have to read through this e-book! If you have a question about your application or need help with a coating selection, contact us anytime. We're here to make your coating experience easy and profitable for your company!

Before we wade into coating performance data, let's get to know SilcoTek a little more.

About SilcoTek

SilcoTek® is the world's leading provider of high-performance coatings applied by chemical vapor deposition, or CVD. We became a coatings company because we have a passion for helping people and businesses conquer their most difficult material challenges.

By improving the surface properties of the materials they use, our customers can run their machines longer, manufacture complex products more efficiently, and continue to develop innovations that push the scientific and industrial world forward. We don't sell coated products because we're solely focused on offering coating services that make your product better. Watch our video and see how SilcoTek can improve your products.

Our Mission and ZIP Code

SilcoTek's mission is to provide game-changing coatings for our customers.

What does this mean for you? It means you are doing business with a company where "employees enjoy coming to work as much as going home" and where employees are passionate, enjoy working with each other, and work in an atmosphere based on mutual respect and trust. You'll see the SilcoTek difference in every order you place.

Our ZIP Code guides the conduct we follow each-and-every day. It creates a culture of success for SilcoTek® and our customers.

What does Z.I.P. mean?

Zero disappointments
We strive for a perfect coating process from quote to shipping, every time.

Integrity in all we do:
We are open, honest, and admit mistakes.

Plus 1 customer service:
We aim to go above and beyond every time you interact with us.

You'll find working with SilcoTek staff easy, helpful, and informative. It's our goal to delight our customers with game changing service and coatings!

Now that you've gotten to know us, let's give you a quick overview of our products.

SilcoTek Coatings

SilcoTek® coatings are uniquely tailored to solve tough material problems in a variety of industries and applications. We offer over 20 custom coatings for challenging flow path problems. Our patented process eliminates interactions between the flow path and active compounds to enhance surface performance in a broad variety of applications. Since 1987, SilcoTek has provided surface coating technology solutions to process, analytical, gas & oil, semiconductor, and corrosion applications worldwide. From prototype to production, SilcoTek offers patented and custom surface coating technologies that allow the user to improve the performance of their process and products.

Our coatings:
- SilcoNert®
- Silcolloy®
- Dursan®
- SilcoGuard®
- SilcoKlean®
- Notak®
- Dursox®

We also offer specialized coating processes for specific materials or applications. Contact us to learn more.

Buying and Using our Coatings

When you send parts to SilcoTek for CVD coating application, we'll discuss the purchasing process in detail but here's a summary of the process for buying and using our coatings. You can go to our web page to learn more.

Buying and using our coatings involves the following basic steps:

1. Learn- You can learn more about our coatings by going to our website or reviewing this handy guide.

2. Discuss- Contact us to discuss your application, or you can go to our FAQ page to get quick answers to your product questions, you can use our online chat feature to reach out to a coating expert.

3. Select- After you've done some research, you can use our product selector to help pick the best coating for your application or ask us for a recommendation.

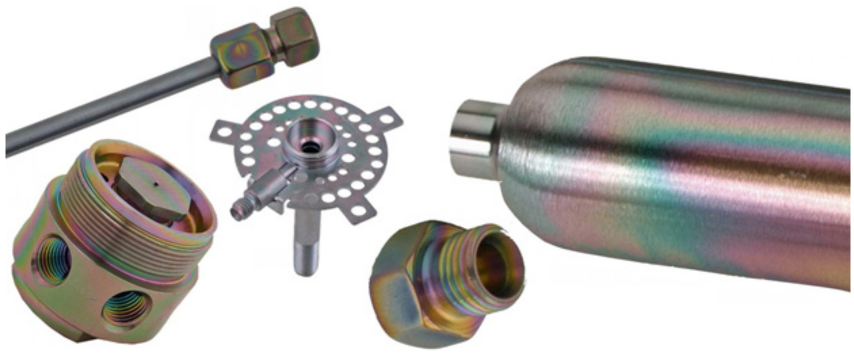
4. Quote- Our Customer Service Team is here to help you through the quote and order process. You can go online to submit a quote request (either through our chat feature or by using our online quote form). You can also send us an email, we'll get you a quote for coating application within a day.

5. Send- Send us your parts and we'll coat and return them to you in about 10 days. Learn more about sending in parts by reading our Shipping Guide.

6. Use- After the coated parts are returned, you'll want to get the most out of the coating. Read our Coating Care Guide to learn more.

And that's it! Making your process and products perform better has never been easier!
In chapter 2 we'll discuss the physical characteristics of our coatings and coating material compatibility.

Chapter 2
Coating Characteristics and Appearance



Before we discuss the characteristics of chemical vapor deposition (CVD) coatings, let's discuss how the coatings are made, coating composition, their benefits, and coating material compatibility.

About CVD Coatings

What is a CVD Coating? A CVD coating is a material applied by a process called chemical vapor deposition (CVD). The application process usually involves bonding of a material in a gas form (or vapor) to a surface under some combination of heat, pressure, or vacuum (or a combination of the three). The process may involve surface pretreatment or some level of surface preparation to prepare the base material substrate for coating application.

CVD coatings are prevalent throughout industry and can be found in many consumer products ranging from smart phones and personal computers to drill bits. They're known as being an environmentally friendly durable thin film surface. CVD products can be found in applications ranging from machine tools, wear components, analytical flow path components, instrumentation and many other areas demanding a high-performance thin film.

There are lots of thin films out there, so what is it about the chemical vapor deposition process that makes a superior coating for high performance precision applications? Chemical vapor deposition is often a non-line-of-sight process that allows coating of interior and exterior of part surfaces. This results in the entire part being treated. Additionally, the process often yields a superior coating-to-surface bond, especially when compared to plating, painting, or dipping processes.

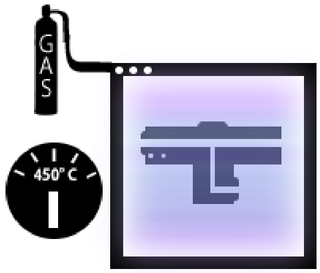
SilcoTek's CVD process involves the reaction of a volatile precursor which is injected into a chamber. The chamber is heated to a reaction temperature that causes the precursor gas to react or break down into the desired coating and bond to the material surface. Over time the coating material builds on the surface and creates a coating throughout the exposed part surface. SilcoTek's process diffuses the CVD material into the substrate, resulting in excellent coating adhesion.

Let's go into the coating process in more detail. If we wanted to bond silicon to a surface, we may want to use a trichlorosilane precursor for example (shown in the reaction below as SiHCL3). When the trichlorosilane is heated in the coating chamber the decomposition and coating reaction may look like this:

$$\mathbf{SiHCl3 \rightarrow Si + Cl2 + HCl}$$

The silicon (Si) will bond to any exposed surfaces (both internal and external) while the chlorine (Cl2) and hydrochloric acid (HCl) gas will be vented from the chamber and scrubbed according to appropriate regulatory requirements.

The CVD coating system may look something like the diagram below. In this example the desired coating material is injected in gas form into a chamber that is heated to the reaction temperature. Want to learn more about our coating process? Go to our Coating Technology and Quality page.



Characteristics of a CVD coating process

- Applied at elevated temperature to facilitate reaction.
- May involve application under pressure or vacuum.
- Contaminants must be removed from the part surface before coating application.
- Process may limit the base materials that can be coated. i.e. temperature limitations or reactivity limitations.
- Process may limit the ability to mask specific target areas.
- Unlike most PVD (physical vapor deposition) processes, the CVD Process is not limited to line-of-sight application. Coating gas will coat all areas of a part including threads, blind holes, and interior surface.
- Film thickness is limited due to coating stress.
- Coating is bonded to the surface during the reaction which creates superior adhesion when compared to typical PVD or low temperature applied spray coatings.

CVD Coating Benefits

- Can be applied to a wide variety of base materials including ceramics, glass, metals, and metal alloys.
- Can coat precision surfaces and intricate surfaces including seal areas and internal surfaces.
- Can withstand exposure to low and high temperature and extreme temperature variation.
- Remains bonded in high stress environments and when the surface flexes due to high adhesion characteristics.
- The coating process can be optimized for wear resistance, high lubricity, corrosion resistance, fouling resistance, high purity, or chemical inertness.

Application Geometry

SilcoTek® can coat most parts including intricate precision components. However, we do have material and part size limitations. SilcoTek is growing and we are constantly expanding our processing capabilities. Even if your parts exceed the capabilities and dimensions noted below, please contact our team to discuss possibilities for your application.

Part Size

- Largest overall part size: 1.63m x .76m ID (64.17in x 29.92in ID)
- Smallest part size: Approximately 1mm (0.039in). Call us to discuss.

Tubing Capabilities

SilcoTek can coat both coiled and straight tubes. Straight tubes are coated in a reactor and the current processes can accommodate lengths up to 80 inches. Straight tubing surfaces are coated both internally and externally. For coiled tubing, the maximum continuous length varies by tubing interior diameter. Coiled tubing is coated internally only per the chart below. Maximum continuous length seen to the right.

Other coating limitations may apply, go to our Frequently Asked Questions page for more details on coating capabilities and geometry limitations.

Tubing OD (in.)	Tubing ID (in.)	Maximum Coil Length (ft.)
1/16	0.010	1000
1/16	0.020	1500
1/16	0.030	1500
1/16	0.040	1500
1/8	0.055	2000
1/8	0.069	2000
1/8	0.085	2000
Larger Diameters		2500

Appearance and Coating Thickness

Most of our coatings are made of silicon and are very thin. So thin in fact that light can be transmitted through the coating and refracted (bent) back through the coating. The result is often a multi-color appearance. Because our coatings are so thin, small variations in thickness can make a big difference in the color of the coating. The different colors observed on SilcoTek treated parts indicate different layer thicknesses.

Colors associated with layer thickness are:

Dursan's light refraction properties (seen above) correlate with a coating thickness between 400 and 1600 nm. The refraction properties of the Dursan coating process are more subtle than SilcoNert, making it easy to distinguish between the two.

SilcoNert's light refraction properties above correlate with a coating thickness between 100 to 500 nm (from right to left: thin to thick). The light spectrum produced by the SilcoNert coating process is more vibrant than Dursan and includes deep blues, purple, green, and gray. The coupons shown above are highly polished, resulting in a bright color spectrum. Rough and unpolished steel surfaces will subdue the colors.

As you can see, a few nanometers change in thickness will result in a dramatic change in the color of the part.

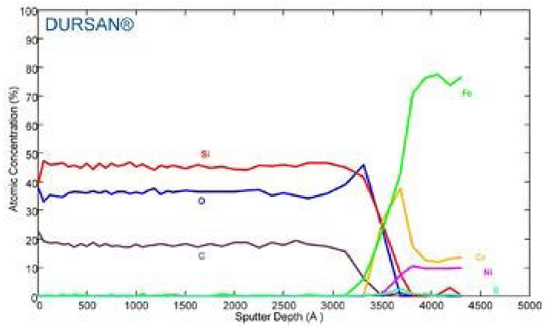
General thickness ranges for our coatings are:

Product	Coating Thickness	Color
SilcoNert® 1000	100-500nm	Rainbow
SilcoNert® 2000		
SilcoKlean®		
Silcolloy®	180-800nm	Gray
SilcoGuard®	180-600nm	Gray
Dursan®	400-1600nm	Rainbow
Dursox®		

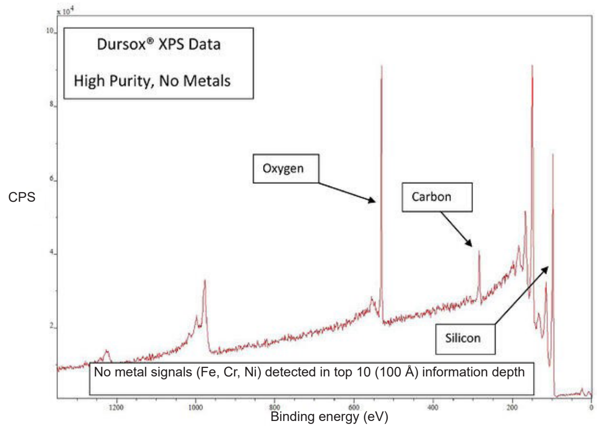
Our coatings are colorful because they are thin. Why do we make the coating thin? Because a thin amorphous silicon coating does not impact part tolerance significantly. Our coatings are also highly inert and durable, so they don't need to be thick.

Coating Composition

SilcoTek coatings are primarily composed of silicon. Depending on the coating, surfaces may contain carbon, oxides of silicon or oxygen and other proprietary compounds. The exception is our Notak® coating which contains a fluoro-derived surface chemistry. To better understand the composition of our coatings we evaluated surfaces under Auger Spectroscopy analysis to understand the coating thickness (sputter depth) and composition of the coating surface. The Dursan® Auger plot below shows the coating consists of silicon, oxygen, and carbon. Note the coating substrate interface at 3500 angstroms. The interface shows a mix of iron and the Dursan coating. Indicating the coating is bonded to the surface.



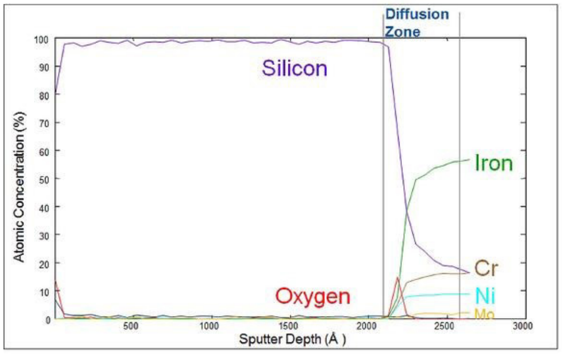
Dursox® is similar to Dursan in that it contains oxygen, carbon and silicon, although concentrations are different. The elemental concentration of Dursox continues to offer impressive corrosion resistance and inertness but is more hydrophilic (wettable) than Dursan. Like Dursan, the Dursox surface is not functionalized or dopped with other materials. This makes the performance characteristics of Dursox and Dursan consistent throughout the coating. Dursox contains no metals which can leach into high purity processes. The X-ray Photoelectron Spectroscopy (XPS) data below shows no metal signals in the coating.



SilcoNert, SilcoGuard, SilcoKlean and Silcolloy Coating Composition

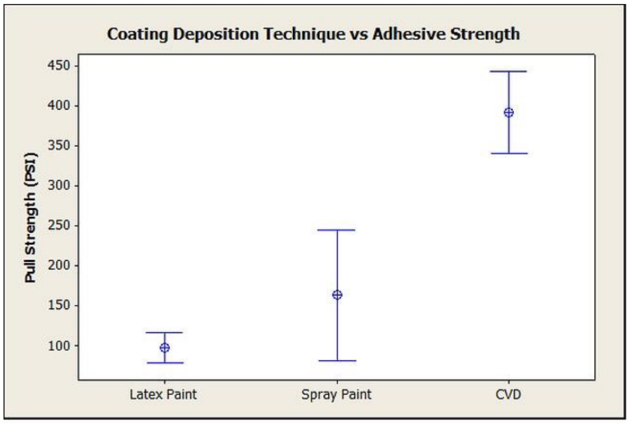
As we stated previously, most of our coatings (like SilcoNert®, SilcoGuard®, and SilcoKlean®) contain silicon and carbon with a small amount of oxygen (mostly from oxide layers on the surface). We functionalize (or "dope") the surface for specific inertness performance for these coatings. Our Silcolloy® and SilcoNert 1000 coatings are made of silicon with a native oxide surface only.

Non-reactive silicon makes an excellent barrier which prevents contamination from the base metal, glass, or ceramic surface. The Auger Electron Spectroscopy (AES) diagram on the next page of a SilcoNert® surface shows the coating contains silicon and oxygen. Note the diffusion zone where the silicon is bonded to the stainless steel substrate.



Coating Adhesion

Because SilcoTek coatings are applied by chemical vapor deposition, the coating surface is bonded to the substrate material. The Auger diagrams above show a significant diffusion zone between the coating and substrate (in this case stainless steel). Because coating diffusion promotes superior bonding, the coating adhesion strength is superior to paints or other common coatings. Pull strength testing (below) indicates significantly improved adhesion compared to common coatings.



About Coating Material Compatibility

SilcoTek can coat steel alloys as well as glass, ceramics, and many other materials that are compatible and able to withstand our process temperature. We're even able to coat some types of aluminum! But there are some materials, like copper, copper alloys, nickel, and some nickel alloys that are not compatible with our process (read our blog post to learn more about coating nickel and nickel alloys). Other materials may not be compatible because high process temperatures may increase corrosion or cracking potential, while other incompatible materials will melt during processing (think plastic for example).

To make it easy for customers to determine if their material is compatible with our process, we developed a quick Material Compatibility Reference Guide. Click the link below to read our guide.

Read our Material Compatibility Guide

Now that we understand the application and composition of our coatings, in chapter 3 we'll learn about the physical characteristics of our coatings and how they perform under extreme physical test conditions.

Chapter 3
Coating Physical Properties and Performance

Now that we've explored the application process and basic composition of our coatings, we're ready to dive into how the CVD coatings perform under physical stress. In this chapter we'll learn about how coatings perform under hardness and wear resistance testing. We'll also learn about the bend resistance, workability, welding capability, compressive, and tensile strength characteristics of our coatings.

About Hardness and Wear Testing

First let's discuss some basics about what hardness, toughness, and wear resistance mean.
Hardness refers to a material's resistance to permanent deformation and applies to a material's ability to resist indentation, scratching, cutting or bending. Wear resistance refers to a material's ability to resist material loss by some mechanical action. A material can be wear resistant and tough but not particularly hard, and a hard material can be wear resistant but not particularly tough. Let's explain the difference a bit further.

Toughness is a material's ability to absorb energy and deform (elastically and plastically) without fracturing. Think of car tires for example. Tires are not particularly hard. You can stick your fingernail in some tires, but the tire bounces right back even after extreme deformation (elastic deformation). Even if a tire is permanently deformed (plastic deformation), it rarely tears or breaks. Yet those tires take a long time to wear out despite rolling on much harder surfaces like concrete. (Yes, a fast car doing a burnout can go through a tire quickly but you get my point.) They also withstand extreme temperatures and shock. Tires are tough, they deform, can absorb a lot of energy before failure and are wear resistant, but they are not very hard.

A hard material like glass will have a very high resistance to deformation but can be highly brittle, susceptible to shock, or damaged when exposed to high temperature gradients. Glass is hard and wear resistant but not "tough". Some hard materials, like carbide and nitride materials, are better at resisting stress and shock than others. So simply asking for a hard material may not be the most appropriate criteria to base your material selection on. You may end up getting glass when what you really want is rubber.

So, is it better to have a super hard coating or a wear resistant "tough" coating? That depends on the application

3.1 Hardness Testing

To evaluate our coatings for hardness, we tested and compared uncoated stainless steel and three SilcoTek coatings applied to stainless steel, Silcolloy, Dursan, and an experimental R&D coating. We also compared the wear resistance of silicon coatings vs. stainless steel. After processing the data, we found that "softer" coatings can be wear resistant.

Hardness Test Conditions

Test coupon samples were submitted to Penn State University's Materials Characterization Lab for nanoindentation testing. The lab subjected the samples to nanoindentation hardness testing to obtain the coating hardness and elastic modulus properties.

A total of eight 316 stainless steel sample coupons were analyzed, including two for each coating and two uncoated samples as baseline reference. The coupons all have a mechanically mirror-polished side and a standard machine-finished side. The polished side is used for the nanoindentation test for consistency of readings.

Example of Dursan coated test coupons

The eight test coupons consist of three coatings, two coupons per coating, Silcolloy® 1000 (SL1000), Dursan® and an experimental coating we'll call RD5. In addition, two uncoated 316 stainless steel coupons were tested as baseline samples.

The nanoindentation test reports hardness and elastic modulus values for each sample. In the case of the coated samples, the mechanical properties of each individual coating were measured and reported.

In the case of the uncoated samples, the mechanical properties of the stainless-steel substrate were measured and reported. Silcolloy 1000 was found to have the highest hardness and elastic modulus values among the three coatings.

Experimental:

Samples were tested using a Bruker Hysitron TI-900 nanoindenter with a standard Berkovich tip made of diamond. The Berkovich indenter is a three-sided pyramid with a half angle of 65.3°, measured from the indentation vertical axis to one of the pyramid flats, as shown in Figure 1.2

The shape of the indentation left by a Berkovich tip is also shown in Figure 1. In order to exclude substrate interference, the indentation depth was controlled to be no more than 10% of the coating thickness. The coating thicknesses for the six coated samples varied between 700-900 nm, so test indents were performed first to determine the corresponding load value for each sample type to reach about 70 nm of indentation depth (including the uncoated control samples to be consistent).

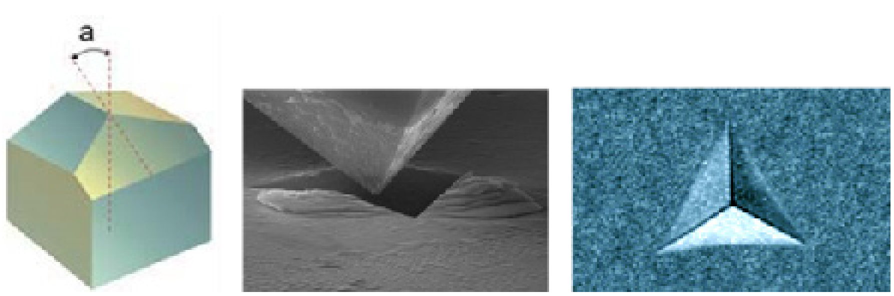


Figure 1: A Berkovich tip with "a" denoting the half angle,2 and the indentation shape it leaves on the surface of the testing specimen3,4

Each sample was indented on the polished side in 2 areas near the center, in a 5x5 XPM load function (a matrix that takes 25 individual measurements), giving 50 data points per sample, and a total of 100 data points per coating type including the bare stainless steel.

In nanoindentation, the hardness of the testing specimen is defined as peak load / contact area, where the contact area (Apml) is the projected area of contact at the maximum load, as illustrated in Figure 2 below. This area can be calculated from the load-unload curve using an analytical model developed by Oliver and Pharr, without the need to directly measure the area with a microscope.6

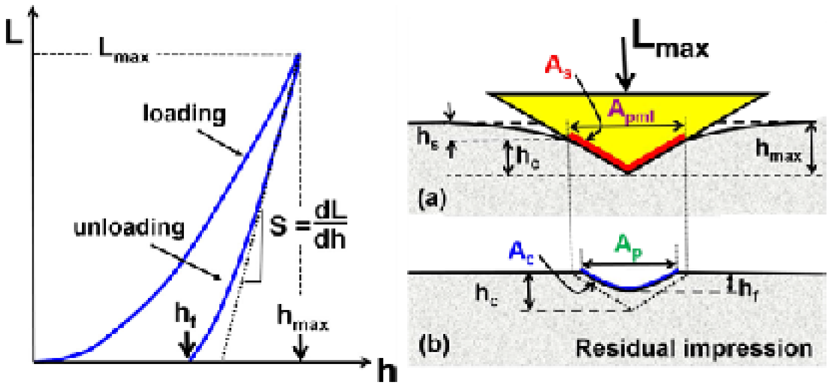


Figure 2: left - The load (L) vs. displacement (h) curve during the load-unload stage of a nanoindentation test, where hf is the final residual penetration depth when a zero load is reached during unloading. The slope of the upper portion of the unloading curve can be used to determine Young's modulus; right (a) specimen deformation at the maximum applied load Lmax and (b) residual plastic deformation after complete unloading6

Results and Discussion

The load vs. displacement nanoindentation curves for the eight samples were plotted. The example of a nanoindentation curves for 2 Silcolloy coated stainless steel coupons in Figure 3 below shows the plotted nanoindentation curves for each of the 50 data points per coupon sample.

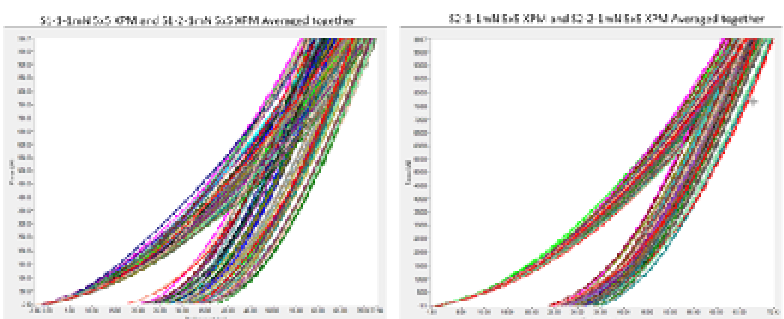


Figure 5: The load (L) vs. displacement (h) curve during the load-unload stage of the nanoindentation test for the two Silcolloy-coated coupons, S1 and S2

Hardness and reduced modulus values, as well as each specimen's Young's modulus (i.e. elastic modulus) calculated from the reduced modulus using the equation below are reported in Table 1 (below).

$$E_r^{-1} = \underbrace{\frac{1-\nu_i^2}{E_i}}_{\text{Indenter}} + \underbrace{\frac{1-\nu_s^2}{E_s}}_{\text{Sample}}$$

Poisson's Ratio

Sample's Elastic Modulus

The elastic modulus (Ei) value of 1140 GPa and Poisson's ratio (ni) value of 0.07 are used for the diamond indenter.6 The Poisson's ratios for uncoated stainless-steel (0.27), Silcolloy (0.22), Dursan (0.25) and RD5 (0.23) are used based on literature reported values for 316 stainless steel,7 hydrogenated amorphous silicon film,8,9 organosilicate glass coating10 and silicon oxynitride film,11 as RD5 is essentially a silicon oxynitride coating.

Sample	Uncoated SS	Silcolloy	Dursan	RD5
Hardness (GPa)	4-6	12-13	4.3-4.4	10
Reduced modulus (GPa)	205-209	135	30-31	98.5
Sample's Young's modulus (GPa)	231-237	145.6	28.9-29.9	102

Table 1: Hardness, reduced modulus and corresponding Young's modulus calculated from the reduced modulus for the three SilcoTek CVD coatings and the bare SS substrate

Table 2 (below) summarizes a comparison of the three SilcoTek CVD coatings with a number of literature-reported hard coatings. It shows that SilcoTek's CVD coatings are generally lower in hardness and modulus values, meaning they are softer and less stiff, than the commonly used hard engineering coatings such as DLC (diamond-like carbon) or titanium-based coatings. Those coatings are usually used in mechanically demanding applications such as metal cutting, tooling, automotive and aerospace where they can help reduce abrasive wear and improve lifetime of the components.

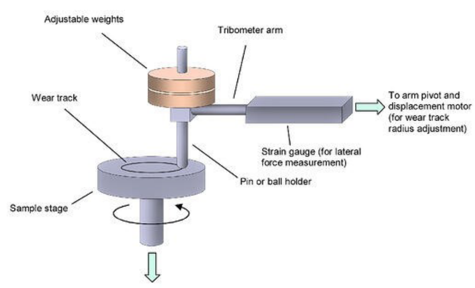
Sample	Uncoated SS	Silcolloy	Dursan	RD5	PECVD silicon oxynitride[11]	PVD TiO_2 film[13]	PVD DLC[14]	PVD TiN film[16]	Titanium carbide film[17]	Diamond film[14]
Hardness (GPa)	4-6	12-13	4.3-4.4	10	4.7-9.7	4.8-16.1	12-30	22	23-29	80 - 100
Young's modulus (GPa)	231-237	145.6	28.9-29.9	102	76.8-89.2	114.4-139.3	62-213	426	600	500 - 533

Table 2: Hardness and Young's modulus value comparison with a number of literature-reported hard coatings. The broad range of values for some coatings highlight the impact of deposition conditions on coating's mechanical properties.

One interesting finding from this study is that Silcolloy®, our hydrogenated amorphous silicon coating, appears to be the hardest coating offered by SilcoTek. This is contradictory to the notion that Dursan® is our most wear-resistant coating.

3.2 Wear Resistance Testing

Pin-on-disc tests were conducted to learn about the wear resistance and lubricity of stainless steel, Silcolloy®, and Dursan®. Pin-on-disc measurement involves engaging an indenter or pin (usually flat or sphere shaped) on to a test sample. The engagement mechanism applies a precise force to the indenter as the test sample is rotated.

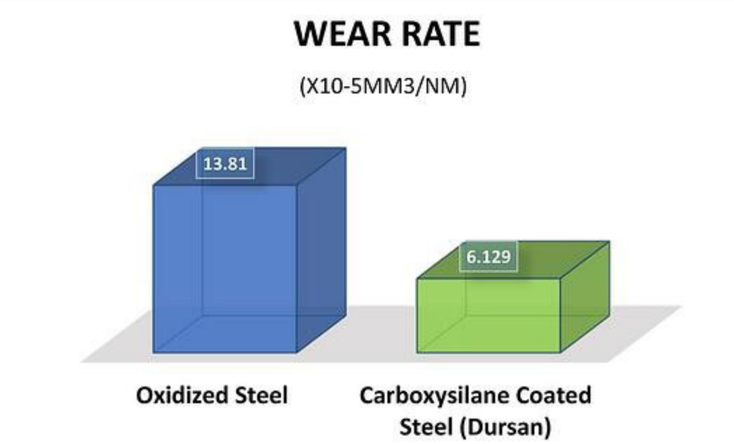


The resulting friction forces are measured using a strain gage sensor. Wear coefficients for the pin and sample are calculated based on material lost during the test. Pin-on-disc can help determine a coating's wear resistance and give an indication of the surface's coefficient of friction, lubricity, and adhesion properties.

A low coefficient of friction surface with high lubricity will enable the pin to roll more easily on the surface which would reduce material loss and improve wear resistance. Conversely a coating with poor adhesion would be stressed by the pin, resulting in coating bond failure and coating loss. This would indicate poor wear resistance, even if the coating were hard.

Pin-on-disc Test Results

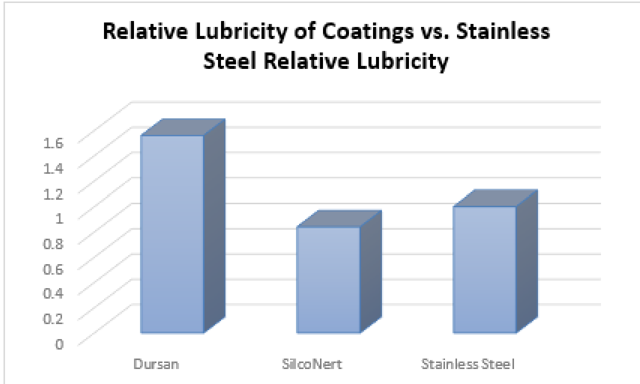
Testing indicated that Silcolloy had similar wear rate as the bare stainless-steel (oxidized steel shown below), Dursan reduced the wear rate by half.12 This indicates that a Dursan coated stainless steel surface is wear resistant, tough, and durable, but not as hard and wear resistant as DLC or other coatings.



A possible explanation for this may be that in a nanoindentation test, the force is perpendicular to the surface of the coating and the indenter penetrates directly through the coating material. In a pin-on-disc test, although the force is applied on the pin which is in contact with the coating surface perpendicularly, the coating sample is mounted on a moving stage that creates wear not only in the vertical but also parallel directions to the coating surface. So, there are more contributing factors to a pin-on-disc test, such as coating adhesion and coefficient of friction (COF), that are not evaluated in a nanoindentation test.

Sample	Minimum Coefficient of Friction	Maximum Coefficient of Friction	Average Coefficient of Friction	Wear Rate [$x10^{-5}$ mm^3/Nm]
Oxidized Steel	0.000	0.927	0.589	13.810
Carboxysilane Coated Steel	0.000	0.725	0.378	6.129

Dursan's better wear resistance properties therefore may have more to do with stronger coating adhesion and lower coefficient of friction and surface lubricity (perhaps better elasticity too) than Silcolloy and SilcoNert.



Despite that, Dursan has lower hardness and Young's modulus values. Ideally, a coating that combines both high hardness/modulus and strong adhesion/lubrication (such as some DLC coatings) will deliver the best overall anti-wear performance.

Currently we do not have any pin-on-disc data on the research coating RD5, but the SilcoTek Research and Development team plans to conduct more tribological tests on our coatings to better understand the mechanical properties that are most needed by SilcoTek's customers.

High hardness and Young's modulus are recognized and desirable characteristics for coatings used in mechanically demanding applications. On the other hand, we learned from this study that hardness and Young's modulus alone do not translate to better wear resistance. Other factors such as coating adhesion and coefficient of friction also play important roles. In some applications, a soft but flexible coating material like rubber may fit the needs better than a hard but brittle material like glass.

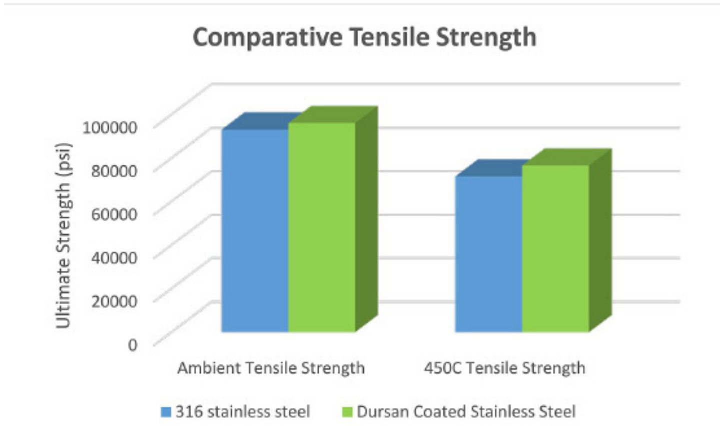
3.3 Mechanical Properties, Tensile Strength

We tested a coated 316 stainless steel rod to determine if our coating process changed the ultimate tensile strength of stainless steel. SilcoTek contracted an independent material test laboratory, Massachusetts Materials Research, Inc (MMR) to conduct comparative tensile strength tests. The lab ran standard tensile strength tests per ASTM E8-16A at ambient and elevated temperatures. As a baseline, MMR first tested the tensile strength of an uncoated 316 stainless steel 1inch diameter rod, then tested a Dursan coated 316 stainless steel rod. You can read more about the tensile test by reading the entire test report.

We chose the Dursan process as a representative SilcoTek process but any of our coatings would have been an acceptable representative of our process. That's because all of our CVD processes involve similar overall process steps. They generally include:

- Surface preparation, usually involving an aqueous ultrasonic cleaning process.
- Exposure of the part to heat and vacuum to prepare the part for coating application.
- Application of the coating materials (they vary with the desired coating).
- Post cleaning of parts and shipment.

Tensile test results showed the Dursan coating performed at or above the uncoated coupon in ultimate tensile performance, failing at 96,000 psi at ambient temperature.



We tested uncoated and coated rods again at 450ºC to see if the relative tensile test changed. The ultimate tensile strength dropped as expected, but the Dursan coated rod fared a bit better, with a 20% drop compared to a 23% drop for the uncoated rod.

Comparative tensile strength		
Material	Ambient Tensile Strength	450C Tensile Strength
316 stainless steel	93000	71500
Dursan® Coated Stainless Steel	96000	76500

The results indicate the SilcoTek coating process does not significantly alter the tensile strength of 316 stainless steel. Our other coating processes are similar to the Dursan process and would have similar performance characteristics. The specific materials used may differ and application temperatures may be slightly different, but the overall impact to 316 stainless steel would be about the same.

3.4 Impact Resistance

MMR also conducted charpy impact tests of our Dursan coated stainless steel surface per ASTM E23-12C at ambient temperature (70°F). The samples were subjected to rupture energy as noted in the table below. All samples did not break.

Sample I.D.	Energy of Rupture (Ft/lbs)
1	264
2	264
3	264
Average	264

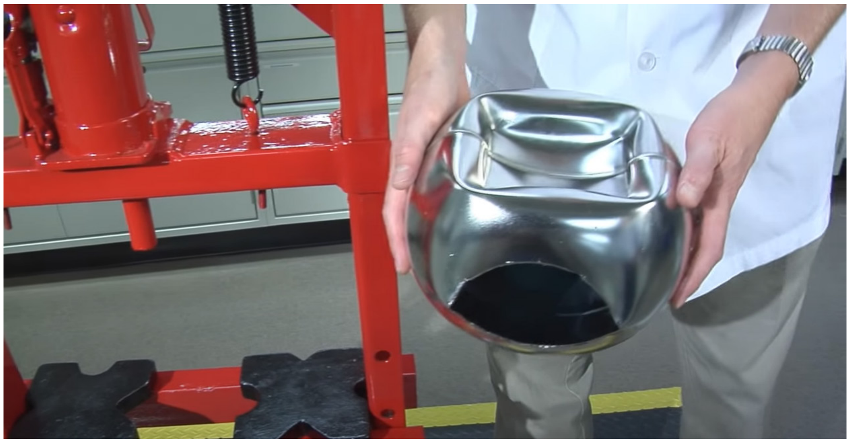
The test indicated a hardness of 94 RBW.

3.5 The Crush Test

The SilcoTek Research and Development Team wanted to know how a coated part would perform under deformation. We devised 2 simple tests to determine how a coated surface would perform under extreme deformation. First, we coated a thin stainless steel foil sheet with our SilcoNert coating. We also coated another thin stainless foil sheet with common spray-on paint. Then we crushed and compared the coated foil samples to see if any coating flaked or failed.

The painted foil on the left (below) has lost some of its coating. You can see paint flakes on the white table below the foil. The SilcoNert coated foil on the right does not show any flaking or failure

In another test we coated the interior of a stainless steel ball. Then we placed the ball in a press to see how the coating would perform under extreme deformation stress. The interior coated surface deformed with the stainless steel and did not flake.



Watch our Durability Video to see our coatings in action.

3.6 Coating Joined Parts

Are Brazed, soldered, or welded joints able to be coated? Are there compatibility problems with the coating? Let's discuss each of these questions in detail.

First let's discuss brazing and soldering. Customers usually have 3 concerns about processing solder and braze joints in customer-supplied parts:

1. Will the joint physically survive the heat exposure of our process?
2. Will the solder/braze material contaminate SilcoTek processing systems (vessels / lines / other customer parts)?
3. Will the joint area pass SilcoTek's visual inspection criteria?

Let's discuss the third concern. It is common for the coated solder/ braze joint area to appear "hazy" after processing. Though the coating performance should not be negatively affected, the customer can expect a different visual appearance in the brazed or soldered areas

Brazing and Process Contamination Concerns

Brazing is a joining process where metals are bonded together using a filler metal with a lower melting point than the base material. Heat, via torch or furnace, is used to liquefy and allow the flow of filler metal (via capillary action), which then cools, solidifies, and joins the base material. Additional materials, such as flux, may be used to prevent the accumulation of oxides and other undesirable contaminants in the filler metal.

Brazing and soldering are typically defined by the melting temperature of the filler material, with brazing joints rated to withstand temperatures over 450°C whereby solder joints can fail above 370°C. Most braze joints will survive our process, however it's our experience that vacuum nickel brazing yields the best coating appearance.

Recommendations for braze joints:
- Most braze joints are compatible with our process temperatures
- Most braze joints will not cause contamination issues
- The most preferred braze method is Vacuum Nickel Brazing. This joining method is highly compatible with our process and does not show cosmetic hazing. Titanium brazing, although not as popular, also coats well.
- For high copper-containing filler material, a general recommendation is to follow our current existing guidelines on copper-containing base materials.

Soldering and Process Contamination Concerns

Solder filler material may have some of the same components as found in braze materials, such as silver and copper, but it is also alloyed with metals such as tin, bismuth, indium, zinc, antimony, and gold. Solder is applied at a lower temperature than brazing and typically contains metals with a lower melting temperature. The lower application temperature of solder means that the joint will likely fail when exposed to our elevated process temperature. The resulting joint failure may also contaminate the process and result in compromised coating quality.

Recommendations for solder joints:
- Because of their low melting temperature, it is not recommended to process parts with soldered areas, especially those with high percentages of tin, lead, and zinc.
- However, the presence of the above materials may not disqualify the use of a specific solder. It is best to know the specific temperature limitations of the solder material and contact our Technical Service Team to discuss the application.

A note about silver soldering. Silver soldered components are typically not soldered, but rather brazed. Most "silver solder" joints will survive SilcoTek's processing but may appear hazy after the coating deposition.

Welding

Welding is a high temperature joining of 2 parts. The process usually involves using a welding stick composed of various alloys to join 2 components. The extreme temperature associated with welding will remove the SilcoTek coating approximately 2-4mm in all directions from the heat affected zone. When possible, it is recommended to first weld parts, then send them to SilcoTek for coating. Go to our FAQ Page to learn more about coating capability and part size.
SilcoTek can coat over high-quality welds, such as those listed in our material compatibility guide, without process contamination and with excellent coating appearance.

Joining Summary

SilcoTek is able to coat over welded and brazed parts if the joining process involves a TIG/ MIG weld, vacuum-nickel brazing, or a silver solder that can withstand up to 450°C. Please see our Technical Insight, "Recommendations for Coating Components with Braze and Solder Joints" to learn more.

Now that we've learned about the material properties and workability of our coatings, we'll next explore the electrical properties of our coatings.

References:

1. Fischer-Cripps, A. C. "Nanoindentation" 3rd edition, 2011.
2. https://en.wikipedia.org/wiki/Berkovich_tip
3. https://www.bruker.com/products/surface-and-dimensional-analysis/nanomechanical-test-instruments/nanomechanical-upgrade-options/test-probes.html
4. https://www.nanoscience.com/products/nanoindenters/
5. Hess, A. E. "Integration of process-incompatible materials for microfabricated polymer-based neural interfaces" Ph.D. thesis, Case Western Reserve University 2011
6. Broitman, E. "Indentation hardness measurements at macro-, micro-, and nanoscale: a critical overview" Tribol. Lett. 2017, 65:23
7. https://www.azom.com/properties.aspx?ArticleID=863
8. Kuschnereit, R. et al. "Mechanical and elastic properties of amorphous hydrogenated silicon films studied by broadband surface acoustic wave spectroscopy" Appl. Phys. A 1995, 61, 269.
9. Guo, S. et al. "Internal stress, thermal expansion coefficient and bi-elastic modulus of photochemically vapor deposited hydrogenated amor phous silicon films" Thin Solid Films 1992, 219, 135.
10. Li, H. et al. "Determining the elastic modulus and hardness of an ultra-thin film on a substrate using nanoindentation" J. Mater. Res. 2009, 24 (3), 1114.
11. Gan, Z. et al. "Material structure and mechanical properties of silicon nitride and silicon oxynitride thin films deposited by plasma enhanced chemical vapor deposition" Surfaces 2018, 1, 59.
12. https://www.silcotek.com/blog/wear-resistant-cvd-coating-tests-put-dursan-on-top
13. Wiatrowski, A. et al. "Comparison of the physicochemical properties of TiO2 thin films obtained by magnetron sputtering with continuous and pulsed gas flow" Coatings 2018, 8, 412.
14. Savvides, N. et al. "Hardness and elastic modulus of diamond and diamond-like carbon films" Thin Solid Films 1993, 228, 289.
15. https://www.entegris.com/shop/en/USD/Products/Specialty-Materials/Coatings/Plasma-Enhanced-Chemical-Vapor-Deposition-%28PECVD%29-Coatings/c/plasmaenhancedchemicalvapordepositionpecvdcoatings
16. Wu, S. et al. "Hardness and elastic modulus of titanium nitride coatings prepared by PIRAC method" Surface Review and Letters 2018, 25 (4), 1850040.
17. Fieandt, L. V. "Cutting edge titianum-based CVD hard coatings" Ph. D. thesis, Uppsala University 2018.

Chapter 4
Electrical and Thermal Characteristics of SilcoTek Coatings

4.1 Electrical Properties of SilcoTek Coatings

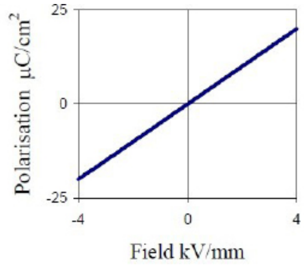
Our customers have asked about the electrical properties of SilcoTek® coatings and if our coatings would be a good fit for their application. Because our coatings are in general poor electrical conductors, we have not performed any systematic study to quantify the electrical properties of our coatings. To gain a better understanding of our coatings' electrical properties and to offer our customers relevant test data, we tested our coatings by polarization field measurements to characterize electrical performance.

4.2 About our Test

Samples to be characterized include various SilcoTek commercial coatings. Measurements were carried out at the Electrical Characterization Lab of Penn State University. The Electrical Characterization Lab identified the dielectric vs. resistor nature of the coatings (a resistor allows electric current to flow through it, whereas a dielectric is an electrical insulator that gets polarized by an applied electric field and through the polarization stores electric energy).
The lab utilized the polarization vs. field measurement (P-E loop) to characterize the coating. This test is conducted under low applied voltages and it serves as a quick screening method to check whether a coating's response to applied electric field is "capacitor-like" or "resistor-like".

4.3 Introduction to P-E Measurement

A P-E loop for a material/device is a plot of the charge or polarization (P) developed, against the field (E) applied to that device at a given frequency. The P-E loop for an ideal linear capacitor is a straight line whose gradient is proportional to the capacitance (figure 1a). For an ideal resistor, the current and voltage are in phase and so the P-E loop is a circle with the center at the origin (figure 1b). If these two components are combined in parallel, we get the P-E loop shown in figure 1c. The combination is in effect a lossy capacitor, meaning there is resistive leakage in the device. The equivalent circuit would be a resistor with a linear capacitor in parallel. If we consider less ideal devices, such as non-linear ferroelectric materials, we would get a P-E loop such as in figure 1d.2



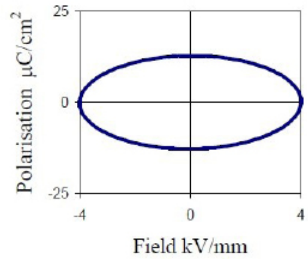
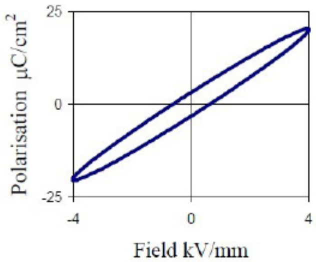


Figure 1a): Ideal linear capacitor response Figure 1b) Ideal resistor response



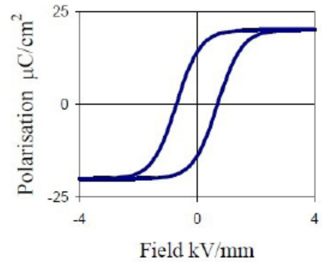


Figure 1c): Lossy capacitor response Figure 1d): Non-linear ferroelectric response

4.4 Electrical Characterization Results

P-E measurements were performed on SilcoTek commercial coatings by the Penn State Electrical Characterization Lab. We selected the PSU lab because of the superior facilities and test team. We also wanted an independent verification of coating performance. The results are shown below.

Two of our silicon-based coatings (Silcolloy® and SilcoNert® 2000) were characterized and their P-E responses are shown below in figures 2a and 2b, respectively (below). These measurements indicate that our silicon-based coatings exhibit large resistive leakage and are more “resistor-like” than “capacitor-like”. This may be expected as silicon is a semiconductor and known to be a lossy material.3 Our other two silicon-based coatings SilcoKlean® and SilcoGuard® were not measured but are expected to possess similar properties due to similar chemistry.

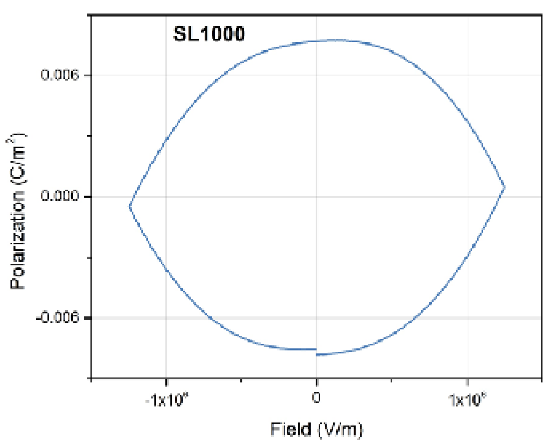


Figure 2a): P-E response of Silcolloy 1000 coating

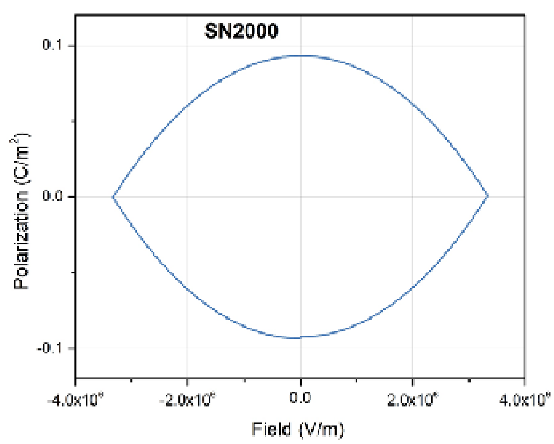


Figure 2b): P-E response of SilcoNert 2000 coating

Dursan exhibits improved dielectric properties (i.e., better electrical insulating properties with minimal loss). The P-E response of the Dursan coating is shown in figure 4 below.

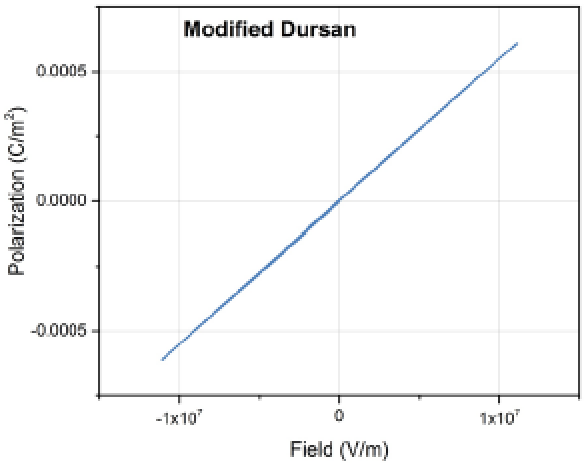


Figure 4): P-E response of the current Dursan coating

The linear P-E response is characteristic of a low loss capacitor. The improvement on the loss factor of Dursan compared to silicon-based coatings is due to the oxidized nature of Dursan.

Silicon dioxide (SiO2) is a good dielectric material with low loss and high breakdown strength on the order of 10MV/cm.4,5 Dursan, however, contains carbon and is not a pure SiO2 film so actual breakdown strength will not be exactly the same as SiO2 but will be similar.

The summary table below compares the electrical properties of Silcolloy (a corrosion resistant silicon coating), Dursan (a corrosion resistant silicon oxide coating), and an experimental silicon nitride coating.

	Bulk resistivity (Ω · cm)	Relative permittivity (error)	Dielectric loss tan δ (error)	Breakdown field 1 (MV/cm)	Breakdown field 2 (MV/cm)	Weibull Modulus
Silcolloy	10^{8}	18.9 (2.3)	0.4 (0.04)	0.09 - 0.1	0.15 - 0.2	4.3
Dursan	10^{12}	6.9 (1.2)	0.6 (0.6)	N.A.	5.9 - 9.6	4.6
SiN	10^{13}	8.3 (0.6)	0.04 (0.05)	4.2	5.6 - 7.7	14.6

Next, we'll explore the thermal performance of our coatings.

4.5 Thermal Performance

Open any materials handbook and you'll find information relating to the thermal performance of silicon. Because our coatings are basically silicon or oxides of silicon, we'll use basic silicon thermal properties for the purposes of our discussion.

Thermal properties are:

Bulk modulus	$9.8 \cdot 10^{11}$ dyn/cm^2
Melting point	1412 °C
Specific heat	0.7 J g^{-1}°C^{-1}
Thermal conductivity	1.3 W cm^{-1}°C^{-1}
Thermal diffusivity	0.8 cm^2/s
Thermal expansion, linear	$2.6 \cdot 10^{-6}$°C $^{-1}$

Does all this data mean that our coatings make good thermal insulators? Well, no. Why? Because our coatings are thin and on the order of a few microns thick. Even coatings with low thermal conductivity will not offer significant thermal protection if they're extremely thin. The other issue regarding thermal performance is that our coatings are designed for specific performance/benefits to the user. Some coatings are hydrophobic, some are inert or non-reactive, others are corrosion resistant, etc. Because the coatings are designed for specific performance parameters, the coating formulation or additives will vary. The variation in formulations can limit the thermal performance of our coatings. The recommended maximum temperature for each of our coatings is:

SilcoNert® 2000	450 °C; 400 °C (oxidative atmosphere)
SilcoNert® 1000	1410 °C
Silcolloy®	1410 °C
SilcoGuard®	1410 °C
SilcoKlean®	450 °C (functionalization loss), 400 °C (oxidative atmosphere), 1410 °C (melting)
Dursan®	500 °C; 450 °C (oxidative atmosphere)
Dursox®	500 °C

(Note: The values above reflect limits of the coating material itself and assume that the base substrate is stable at these temperatures.)

In general, temperatures should not exceed the recommendations. This will assure consistent coating performance. However, some coatings can be used at higher temperatures under certain conditions.

Heat treatment of the part prior to coating, at the application's temperature, will ensure the highest possible coating adhesion. Thermal pretreatment of the part will reduce the potential of coating failure when exposed to elevated temperatures. Coating failure can occur when carbon migrates to the stainless steel surface during heating. Carbon will displace the coating, resulting in failure. Preheating the part will get all that carbon precipitation over with and prevent the coating from being pushed off the stainless steel surface during high temperature exposure. To learn more about the mechanics of heating stainless steel and it's effects, read our blog post.

If the application will exceed the suggested temperature limit, please contact technical support at 814-353-1778 or by clicking here for additional information or to discuss your application.

Low Temperature Performance

SilcoTek coatings are essentially amorphous silicon. An amorphous structure enables the coating to bend or deform to some extent. This allows our coatings to flex, bend, expand, and contract with the substrate surface. That means during extreme changes in temperature, the coating remains intact and bonded to the substrate. Thermal shock, heat cycling, and low temperature cryogenic exposure won't cause the coating to fail as long as the substrate remains intact. Watch the video below to see how our coatings perform under extreme low temperature conditions.

4.6 Steam Exposure

An autoclave is often used to sterilize surfaces by exposing those surfaces to saturated steam over a period of time. Understanding the effect of steam exposure on SilcoTek® surfaces is important since many customers and potential customers may use steam for cleaning and sterilization purposes.

It's also important to note that the following steam evaluation was conducted under high purity, controlled steam environments. Exposing a sample flow path to process steam or steam that contains contaminants or particulates may contaminate the flow path surface or damage the surface. We recommend contacting SilcoTek to discuss your application before exposing your flow path to steam.

We tested our coatings by exposing our coatings to steam in a laboratory autoclave environment. We compared the surfaces by measuring before and after exposure conditions. We utilized surface contact angle, coating thickness, and Fourier-transform infrared spectroscopy (FTIR) techniques as characterization methods to determine how the surface performs under steam exposure. Coated 316 stainless steel coupon samples were used for these characterization methods.

The coatings/treatments evaluated for autoclave exposure were:

- Notak®
- RD5 (an experimental coating)
- Silcolloy® 1000
- Dursox®
- Dursan®
- SilcoNert® 2000
- SilcoKlean® 1000

6 Coupons of each treatment were prepared per SilcoTek standard processes (or per the latest optimized processes per Research and Development for Notak and RD5).

Tests were conducted using SilcoTek coated 316L stainless steel coupons for a total of 42 samples.

After treatment, the following baseline measurements were made on all coupons: DI water contact angle, hexadecane contact angle (for Notak coupons only), thickness (via Filmetrics F40 spectrometer) at the general center of the coupon, and FTIR spectroscopy.

After our baseline testing, half of the coupons were sent to Namsa in Northwood, Ohio for autoclave exposure. All coupons were treated simultaneously in one chamber with the following conditions of exposure:

- Cycle Type: Gravity
- Exposure Pressure Range: 16.4-17.8 psig
- Conditioning Time: 10 minutes, 7 seconds
- Exposure Temperature Range: 121.0-123.2°C
- Exposure Time: 60 minutes
- Total Cycle Time: 1 hour 10 minutes 40 seconds

The treated coupons were returned to SilcoTek and re-characterized using the same measurement evaluation techniques prior to autoclave exposure.

Contact Angle Evaluation

Table 1 illustrates changes in contact angles of seven different SilcoTek surfaces after exposure to standard autoclave conditions. Silcolloy, which is an unfunctionalized amorphous silicon deposition had the most dramatic change, with a water contact angle before exposure of 70° to a post exposure contact angle of 29°. The degree of change is not surprising, since Silcolloy has silicon hydrides at the surface that can be surface oxidized to create Si-O-Si hydrophilic functional groups (moieties), as confirmed in the FTIR data discussed below (Silcolloy, however, is very stable against bulk oxidation).

Table 1: Average contact angle differences, before and after autoclave exposure, with deionized water and hexadecane (Notak only).

Surface	DI Water before	DI Water after	Decrease	Hxdcn before	Hxdcn after
Notak	120°	120°	0°	83°	82°
Silcolloy	70°	29°	41°		
Dursox	51°	40°	11°		
Dursan	88°	78°	10°		
SN2000	82°	70°	12°		
SK1000	84°	75°	9°		
RD5	25°	22°	3°		

On the other end of the scale is Notak. Notak is not a silicon deposition, but a direct functionalization of the substrate surface (316 stainless steel in this case) with organofluoro molecules to provide a stable, low-energy surface which is hydrophobic and oleophobic. (No other SilcoTek surfaces are oleophobic and therefore only Notak was analyzed for hexadecane contact angles.)

For hydrophobicity, the Notak coupons showed no change in contact angle after autoclave exposure. For oleophobicity, the Notak coupons had an average loss of 1 degree after autoclave exposure.
The test coating, RD5, is significantly hydrophilic and showed a slight decrease in hydrophilicity after autoclave exposure. The spread of hydrophilic contact angle measurement values was rather large (13°), however, so the slight decrease after exposure is marginally significant.

The other surfaces, Dursox, Dursan, SilcoNert 2000 and SilcoKlean 1000 all showed similar decreases in water contact angle of 9-12°. For those depositions, there was a small degree of hydroxylation as illustrated in the FTIR data discussed on the next page.

Film thickness evaluation

Table 2: Average thickness (nm) differences, before and after autoclave exposure.

Surface	Thickness before	Thickness after	Variance
Silcolloy	400	380	-20
Dursox	664	667	3
Dursan	486	506	20
SN2000	215	219	4
SK1000	211	214	3
RD5	839	824	-15

The measurement of coating thicknesses was accomplished with a Filmetrics F40 instrument. The F40 measures light photon absorbance through the thin film. The absorbance data is compared to known absorbance of various substances in the coating to determine the thickness of the film. The F40 uses spectrophotometric absorbance data to non-destructively measure and compare coating thickness to a sensitivity of 4nm-40um.

The spot size of the instrument is 10um and is difficult to train on to the exact same spot with repeated measurements. Therefore, measurements before and after autoclave exposure on the exact same spot is unlikely and some variation should be expected since the coating itself may have a significant thickness variance throughout due to thermal uniformity and proximity to other parts and fixturing during deposition. Accordingly, the measurement variances in Table 2 are not considered significant. There was no visible loss under magnification during measurement and the differences listed are considered within the expected variance of the instrument and technique.

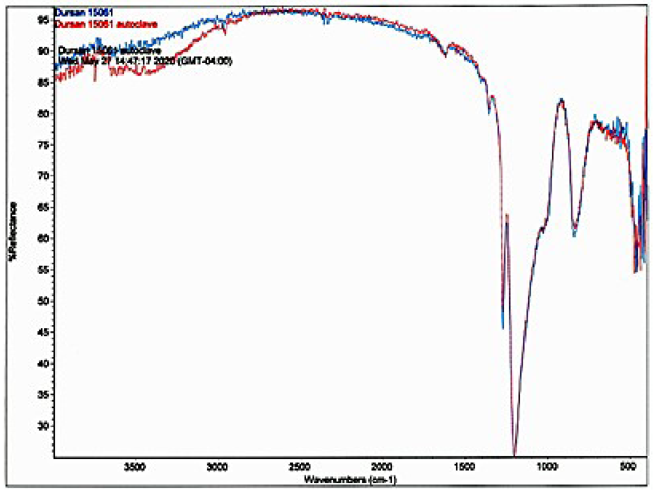
Notak was not evaluated using this technique because that surface is a functionalization of the stainless steel and not a coating. Thickness measurement of the Notak functionalization is not within the capability of this instrument.

Grazing angle FTIR evaluation

Fourier Transform Infrared Spectroscopy (FTIR) spectra were obtained with a Thermo/Nicolet 380 FTIR equipped with a Smart SAGA grazing angle attachment, allowing FTIR spectra of thin films and surfaces on reflective substrates. The following spectra provide FTIR data before and after autoclave exposure for each surface.

During the FTIR test, infrared radiation is passed through the sample. During exposure, some of the IR radiation is absorbed by the coating and other parts of the IR spectrum pass through the coating. The reflected IR spectrum is specific to each coating, making a sort of coating composition fingerprint that is unique to the coating. A change in the FTIR spectra plot from pre and post steam exposure would indicate a change in the coating composition.

A typical FTIR test on a Dursan coated sample (next page) shows the before and after plots. There was little significant change observable via FTIR between before and after autoclave exposure for the Dursan surface. There was a slight increase in Si-OH functional groups (moieties) in the broad 3400 cm-1 region, accounting for the slight decrease in water contact angle mentioned above.



Here's a summary of FTIR performance for the coatings tested. Go to our Steam Exposure Blog Post to review all the FTIR results for our study.

Table 3: Summary of Comparative FTIR Spectroscopy Results

	Notak	RD5	Dursan	SilcoNert	SilcoKlean	Dursox	Silcolloy
Before/After Steam Exposure FTIR Result	No change in FTIR spectra	No change in FTIR spectra	Slight change in silicon hydroxides	Slight change in silicon hydroxides	Slight change in silicon hydroxides	Slight change in silicon hydroxides	Increase in oxidation of surface

The exposure of several SilcoTek® surfaces to autoclave steam conditions revealed the following:

- Notak® surface energy measurements and FTIR spectra were unaffected, signifying excellent resilience to autoclave conditions.
- The test coating, RD5, surface energy measurements and FTIR spectra were unaffected, signifying excellent resilience to autoclave conditions.
- Dursan®, SilcoNert® 2000, SilcoKlean® and Dursox® showed some sign of surface hydroxylation via autoclave exposure via slight decreases in water contact angle and slight increases in Si-OH functionality via FTIR.
- Silcolloy® 1000 was significantly surface-oxidized by autoclave exposure, with a substantial decrease in water contact angle and a measurable increase in Si-O-Si absorbance via FTIR data.
- None of the SilcoTek depositions revealed any significant loss of coating thickness after autoclave exposure.

Conclusion

Most of our coatings (SilcoNert®, Silcolloy®, SilcoGuard®, SilcoKlean®) are characterized as more resistor-like rather than capacitor-like. Dursan®, on the other hand, is best characterized as more of a low loss capacitor. None of the coatings are designed or intended for use in electric or electronic applications, however the electrical performance data above will be helpful to customers who need an inert or corrosion resistant coating with known electric properties.
Thermal performance of our coatings varies but all can withstand relatively high temperatures. All coatings are also able to endure low temperature environments found in cryogenic applications as well as temperature cycling conditions. The coating bond strength and amorphous nature of the CVD coating structure will remain intact during wide temperature changes, allowing the coatings to be used in extreme thermal environments.

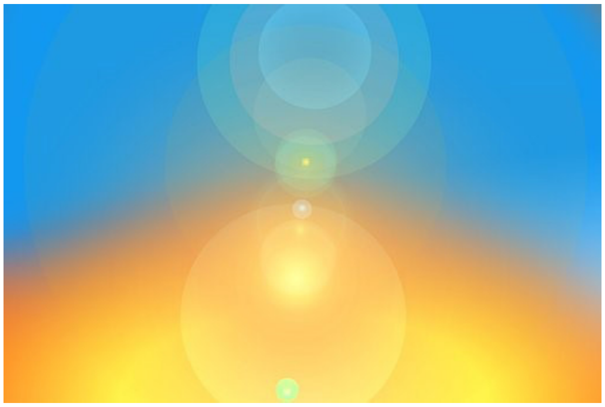
Under steam exposure conditions, testing showed some slight oxidation of the coating surfaces but no significant loss of coating thickness. Additional steam cycle testing is needed to confirm long term durability when exposed to steam environments.

In our next chapter we'll discuss the optical and light transmission properties of silicon coatings.

REFERENCES

1. Chung, T. C., “Functionalization of Polypropylene with High Dielectric Properties: Applications in Electric Energy Storage”, Green and Sustain able Chemistry 2012, 2, 29-37.
2. Stewart, M., Cain, M. G., Hall, D. A., “Ferroelectric Hysteresis Measurement & Analysis”, National Physical Laboratory Report CMMT (A) 152, 1999.
3. Frye, R. C., Liu, K., Badakere, G., Lin, Y., “A Hybrid Coupled-Resonator Bandpass Filter Topology Implemented on Lossy Semiconductor Substrates”, IEEE Microwave Symposium 2007, pp. 1757- 1760.
4. Sze, S.M., “Physics of Semiconductor Devices”, 2nd edition, John Wiley & Sons 1981.
5. Lim, J. W., Yun, S. J., Lee, J. H., “Low-Temperature Growth of SiO2 Films by Plasma-Enhanced Atomic Layer Deposition”, ETRI Journal 2005, 27, 118-121.

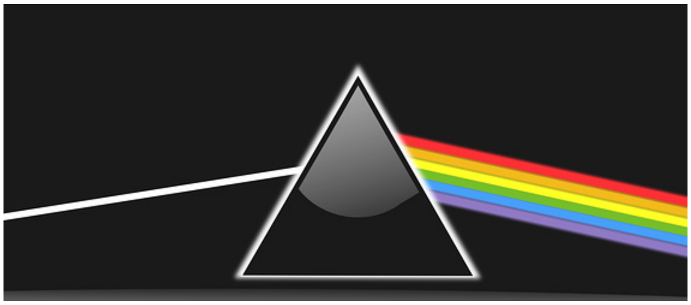
Chapter 5
Light Transmission Properties of SilcoTek Coatings



Finding a coating that has a specific light spectrum transmission can be critical to the success of a research project. In this chapter we'll discuss light, why SilcoTek coatings look the way they do, and how super-thin silicon CVD coatings perform under light spectra analysis.

5.1 Background

Light is basically electromagnetic waves that are all around us. Some can be seen (visible light with wavelength ranging from 400-700 nm) while some cannot such as infrared's longer wavelength and ultraviolet with shorter wavelengths. Transmission is basically that "light" moving through something. Reflection is the light that is bounced back from the object the light hits, such as a mirror. Absorption accounts for what light is not bounced back or taken up by the body. Light can also be spread into interference patterns which makes those cool prisms so fun to use.



5.2 Coating Color and Light Transmission

Most coatings, like paint, absorb some visible light waves and reflect a portion of that light back in the form of color. For example, the color red looks red because red pigment reflects light in the visible red color spectrum. The color white reflects most of the visible light spectrum back, representing white light. The color black is absent of visible light spectra because virtually all visible white light is absorbed, so no light is reflected back.

Conversely, SilcoTek coatings do not contain pigments like paint does. Pigments get their color because they absorb most of the white light and reflect only the color you see. Our coatings are made primarily of silicon which, in natural form, looks like a shiny gray rock. So how does a gray rock become a shiny rainbow i.e. adsorb minimal color? The answer comes down to light refraction, absorption, and interference with super-thin films like SilcoTek's coatings.

Want to learn more about CVD coating material properties? Go to our Coating Material Property and Specifications Website Page.

5.3 The CVD Process and How it Creates Colorful Coatings

We bond silicon to metals, glass, or ceramics through a process called chemical vapor deposition (CVD). This process builds a silicon layer on the surface one Angstrom (0.1 nanometer) at a time, resulting in a coating anywhere between 1,000 and 16,000 Angstroms depending on the coating process and parts being treated. A super-thin layer of silicon is pretty clear, in fact you can see through a thin silicon layer. As the silicon thickness increases on say a stainless steel surface, light which travels through the silicon is bent. The light then reflects off the stainless surface and is bent again. All of this light bending causes some wavelengths of light to cancel each other out while other wavelengths are reinforced. The canceled (or interference) wavelengths aren't seen by your eye while you see the reinforced wavelengths as color. Changing the color of a thin silicon surface is easy; a few nanometer change in silicon thickness can have a big impact on the colors you see. Go back to chapter 2 to learn more about coating thickness and how it affects color.

5.4 Light Transmission of CVD Silicon Coatings

At times, research teams require an inert surface that absorbs minimal light, usually at a particular target wavelength. For longer wavelengths, our silicon coatings (basically hydrogenated amorphous silicon) would have minimal effect on light transmission.

SilcoTek has not measured optical transparency directly. However, a graduate school colleague at The Pennsylvania State University did his graduate work on depositing materials very similar to our SilcoNert coating (hydrogenated amorphous silicon) for optical waveguides in telecommunication applications.

For reference, the common telecommunication wavelength is 1550 nm, so this was the wavelength of interest for their measurements. Transmission loss is measured in dB. A 0.001dB loss equates to 99.98% transmission. The lower the dB loss value the higher the transmission.

For example, when comparing to a specific wavelength (say the 1550 nm wavelength used in waveguides), the thickest hydrogenated amorphous silicon coating we have (Silcolloy®) is only 800 nm thick. That would translate to ~0.00104 dB, or 99.98% transparent.

In that graduate dissertation mentioned above, the researcher measured optical losses anywhere from 0.8 dB/cm up to 13 dB/cm. Our SilcoNert coating for example is about 500 nm thick, that would translate to a transmission loss of a minimal 0.00004-0.00065 dB.

Due to the very thin nature of SilcoNert® 2000 and its optical transparency at the 1550 nm wavelength, it will not absorb an appreciable amount of light if in the 90-95% transmission range. For other wavelengths, this loss may be more significant, as can be seen when comparing coated sample FTIR spectra in the UV range.

5.5 FTIR Light Transmission Data

In chapter 4 we tested our coatings using a technique called Fourier Transform Infrared Spectroscopy (FTIR). We used FTIR to assess changes in our coatings after exposure to steam. In this chapter we'll again use FTIR, but in this case we'll use the data to show how each of our coatings transmit light at different wavelengths.

During the FTIR test, infrared radiation at various wavelengths (or wavenumbers) is passed through the sample. The reflectance data is processed in the FTIR computer to produce a percent reflectance plot at various wavelengths. During exposure, some of the IR radiation is absorbed by the coating and other parts of the IR spectrum passes through the coating and is specified as a percent reflectance. The reflected IR spectrum is specific to each coating.

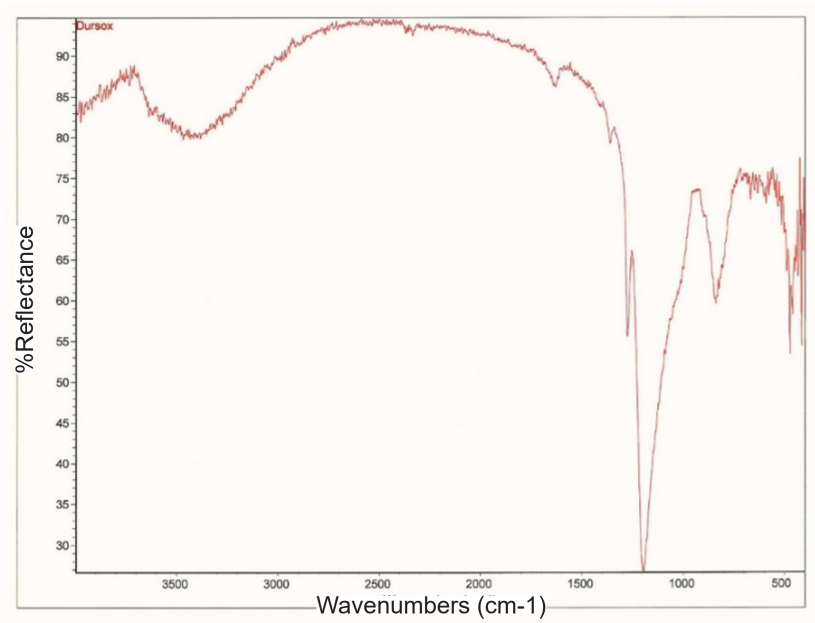
The FTIR test measures transmission as a percent of reflectance for wavenumbers ranging from 400 to over 3500 cm-1. Wavenumbers are used in the physical sciences to measure the number of waves per unit distance (in this case per centimeter, cm-1). IR spectroscopy devices can measure a wide infrared spectrum from 40 to 13,000 cm-1.

To give a perspective, the IR light wavenumbers used in this test range from 400 to over 3500cm-1. Visible light wavenumber range from approximately 14,000 to 25,000 cm-1. Infrared light range from about 10 to 12,800 cm-1 and ultraviolet light range from wavenumbers between about 25,000 to 50,000 cm-1.

With that review and perspective, let's review the FTIR data for each coating.

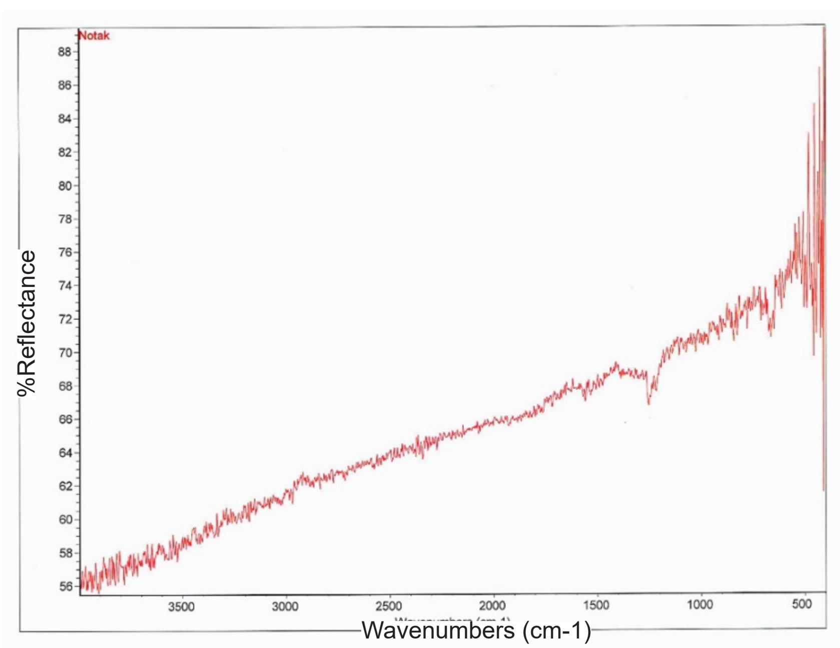
Dursox

Dursox is a thin primarily silicon oxide (SiO) coating with a small amount of carbon. The FTIR result below shows the percent reflectance of the Dursox surface at various frequencies. The reflectance, y axis, shows the amount of IR energy that the surface reflects to the instrument. Low reflectance translates into more energy absorbed at that wavenumber.



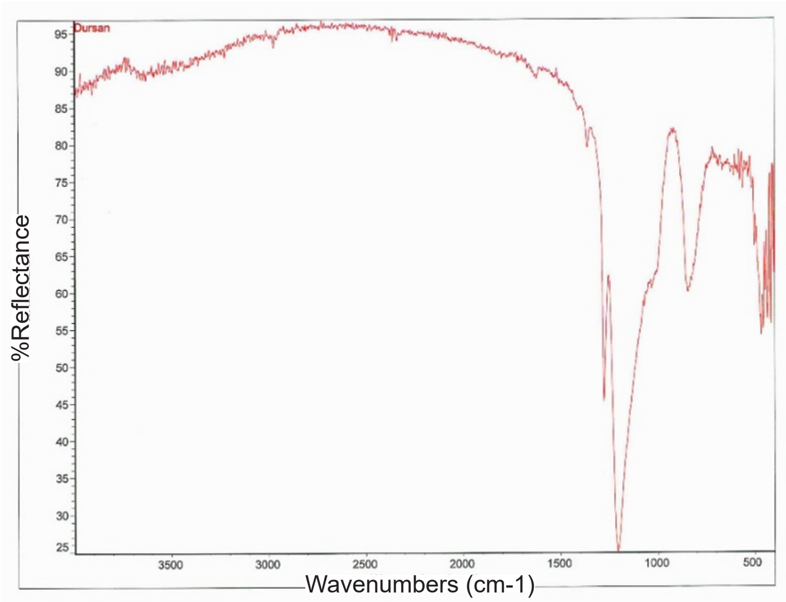
Notak

Notak® is SilcoTek's newest and most hydrophobic and oleophobic surface treatment. Applied via chemical vapor deposition (CVD), Notak is a patented organo fluoro surface treatment that improves surface repelling properties to resist unwanted build-up of water, oils, sticky hydrocarbons, and other foulants.



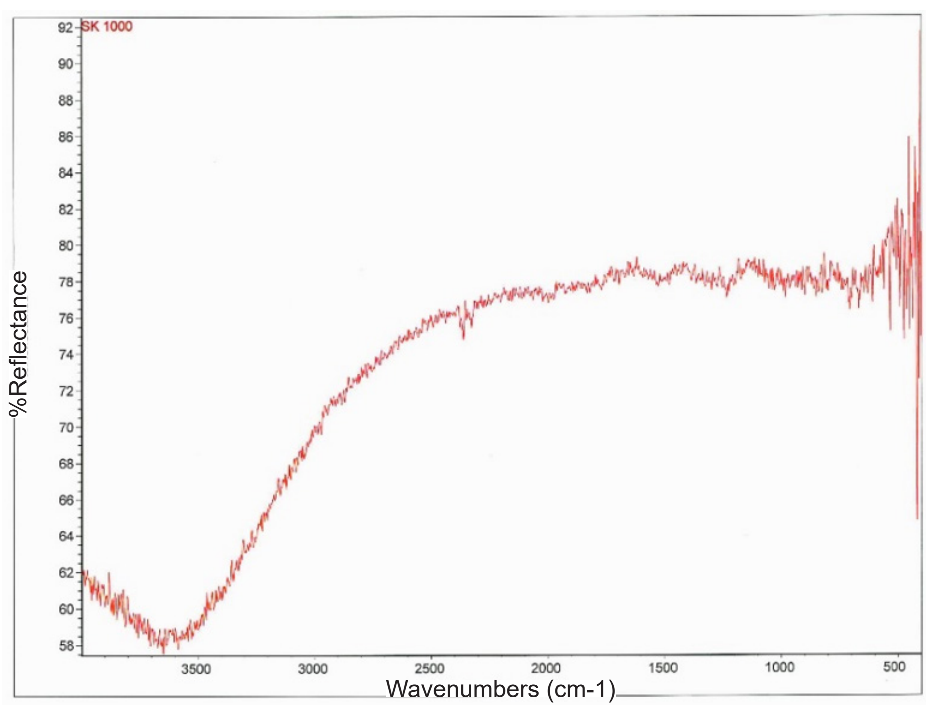
Dursan

Dursan® is a proprietary, patented, NSF certified and FDA compliant process designed to improve the inertness, durability, fouling and corrosion resistance of products ranging from precision instrumentation to severe industrial applications. Dursan is a silica-like coating that is chemically functionalized (a-SiOX;CHY) to improve inertness and corrosion resistance.



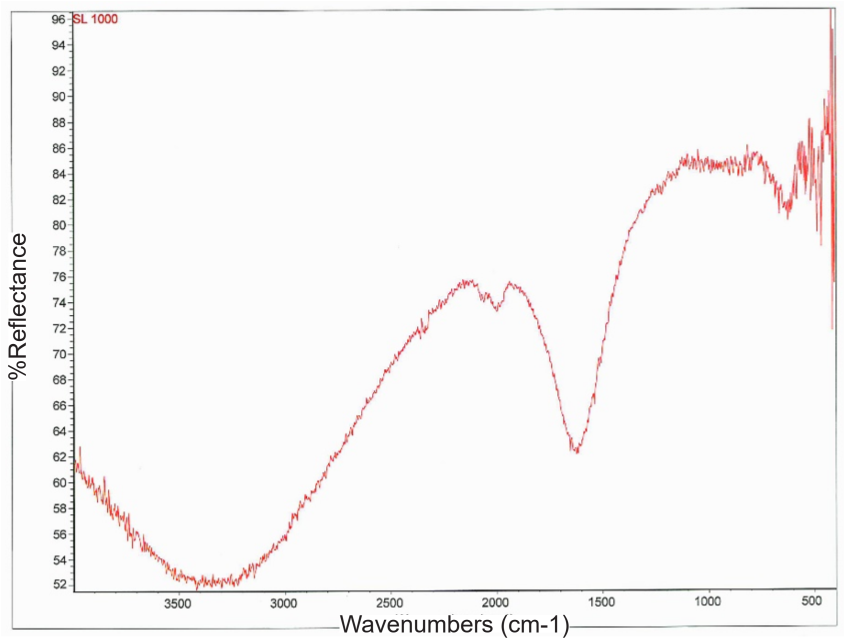
SilcoKlean

SilcoKlean® is a high temperature precision anti-coking CVD coating process, designed specifically to reduce carbon coking and improve fouling resistance on stainless steel and specialty alloy surfaces. SilcoKlean is a patented amorphous silicon coating that is surface functionalized to minimize the build-up of surface deposits.



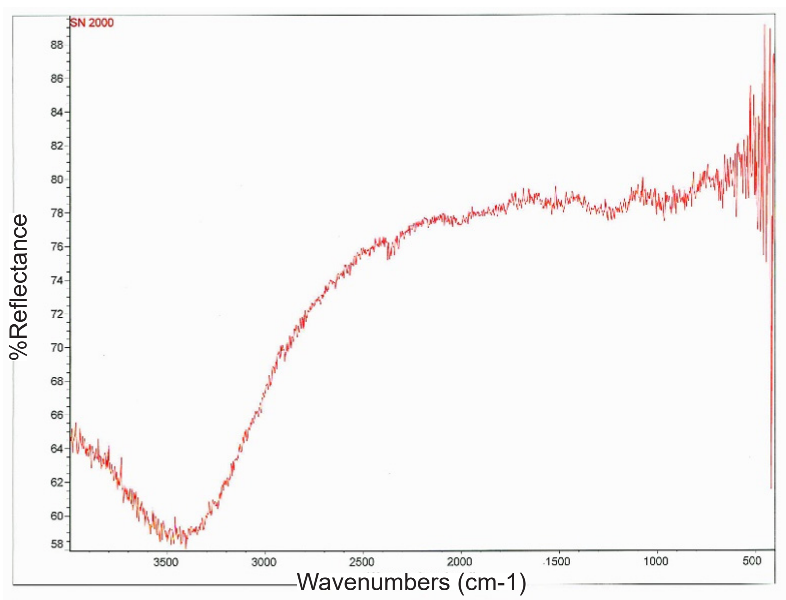
Silcolloy and SilcoGuard

Both Silcolloy and SilcoGuard are a multi layered amorphous silicon coating with a native oxide layer on the surface. The FTIR spectra for these coatings are similar



SilcoNert 2000

SilcoNert is single layer amorphous silicon deposition with a functionalization designed to enhance the inertness of the surface.



Now that we've characterized the light transmission of the coatings, in chapter 6 we'll discuss surface energy characteristics and hydrophobicity.

Emissivity Data

Emissivity is a measure of an object's ability to emit thermal radiation. SilcoTek often gets asked about our coating's impact on emissivity. Let's explore how our coatings impact elgiloy (cobalt, chrome, nickel alloy) and its emissivity to solar radiation and compare how our coatings perform.

About Emissivity

When light hits an object, there are three main mechanisms of interaction:

- Reflection: the light bounces off the surface. In this type of interaction, there is little to no change in the light or the material.
- Transmission: the light goes straight through the material. There is more interaction in this case. The light is often refracted and/or scattered as it passes through the material of interest.
- Absorption: the light is transformed to some other radiant power. Typically, it is transformed into thermal energy or heat. This heat could either be absorbed into the material causing an increase in temperature, or the heat energy could be emitted as visible or IR radiation. Emissivity is a measure of a materials effectiveness in releasing, or emitting, this energy.

Most texts will define emissivity as a number or value (ranging from 0 to 1) given to a material or coating surface when compared to a perfect "black body" at a particular wavelength (emissivity changes with wavelength). A perfect black body has a value of 1, conversely, a surface that is a perfect reflector has a value of 0. For example, if a low-e opaque material had an emissivity value of 0.05 at a particular wavelength, the material would reflect 95% of the radiant thermal energy. (Calculated as 1.0- 0.05 = 0.95)

Emissivity is an important variable when looking at heat flow and thermal calculations for materials in a wide variety of industries including aerospace, refining, and electrical work.

Background

Recently a customer was experiencing issues with an elgiloy alloy that was exposed to solar radiation. When in the direct sun, the elgiloy component absorbed much more light energy than it emitted causing it to increase in temperature. When the elgiloy material was not in direct sunlight (such as in the Earth's shadow), the part would then cool. This heating and cooling were causing expansion and contraction which interfered with the unit's performance.

Faced with this problem, the customer was left with two options: utilize a very expensive plastic designed to have a coefficient of thermal expansion of zero or find a way to cut the elgiloy's absorption to emissivity ratio to one, meaning it emits the same amount of energy it absorbs.

Glasses and silicon-based materials are known to increase emissivity due to their relatively broad infrared absorption and emission profiles. Most of SilcoTek's coatings are silicon-based and should assist in improving emissivity of materials. To confirm our assumption we enlisted Nexolve, a high performance materials provider, to perform experiments on uncoated and coated elgiloy to see the impact of SilcoNert® 1000, Silcolloy® 1000, and Dursan® on the emissivity properties of the metal. This blog will show that all three improved the emissivity of the materials, and Silcolloy was able to reach the goal of an absorption to emissivity ratio of 1.

Test Data and Discussion

Elgiloy is often heat treated to stiffen the material for use in aerospace. Nexolve provided coupons of heat treated elgiloy for coating. One was coated in SilcoNert 1000, a thin hydrogenated amorphous silicon coating, one was coated in Silcolloy 1000, a thicker hydrogenated amorphous silicon coating, and one was coated in Dursan, a hybrid silica material. The coupons were then measured for solar absorptance (absorptivity) using a Perkin Elmer Lambda 950 UV/Vis/NIR spectrometer coupled with a 150 mm Spectralon coated integration sphere and IR emittance (emissivity) using an AZ Technology TEMP 2000A portable infrared reflectometer/emissometer.

The solar absorptivity measurement was done by following ASTM E903 standards. Due to the opaque nature of elgiloy, no transmission was reported. The solar absorptance (αs) and solar reflectance (ρs) values can be found in Table 1. Note that the coated materials all showed less absorptance and higher reflectivity values.

Table 1: Solar absorptance values for bare and coated coupons

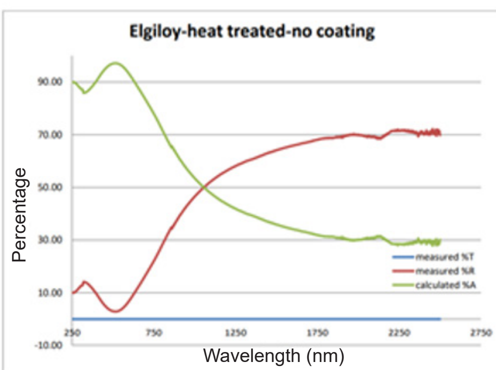
Sample identity	**Solar Absorptance (αs)**	**Solar Reflectance (ρs)**
Bare heat treated elgiloy	0.7189	0.2811
Dursan coated	0.6265	0.3735
SilcoNert 1000 coated	0.4983	0.5017
Silcolloy 1000 coated	0.6712	0.3288

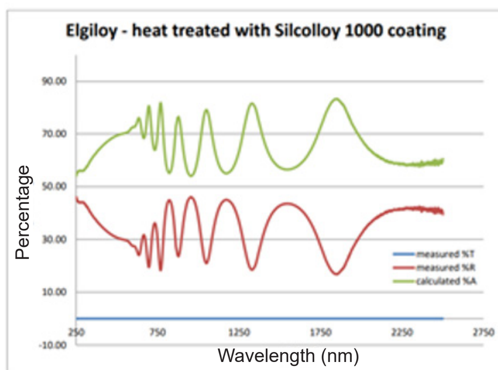
Infrared emittance was measured in relative mode to yield hemispherical IR emissivity values. The instrument used, AZ Technology TEMP 2000A, measures the total hemispherical IR emittance (ε) integrated over the spectral range of a 300K blackbody (3000nm-30000nm). The results can be found in Table 2. Note that the three coatings all resulted in higher emittance relative to the uncoated sample, but Silcolloy had the largest impact on emissivity of the sample.

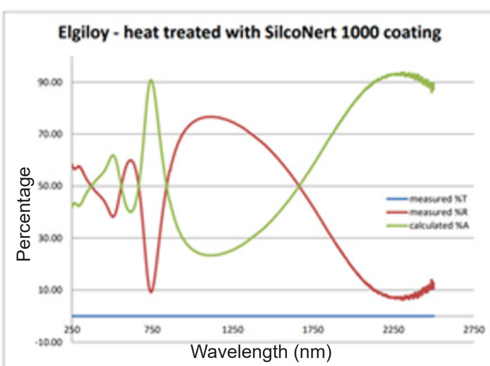
Table 2: IR emittance values for bare and coated coupons.

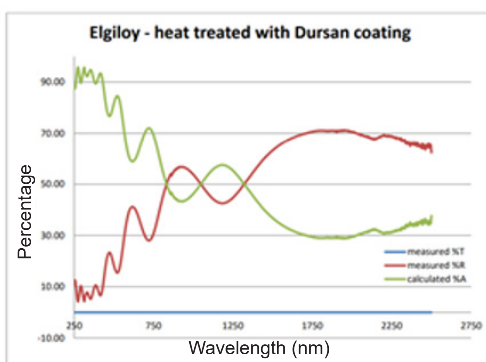
Sample Identity	Hemispherical infrared emittance (ε)
Bare heat treated elgiloy	0.123
Dursan coated	0.339
SilcoNert 1000 coated	0.159
Silcolloy 1000 coated	0.710

The four absorptivity and reflection spectra can be seen below.

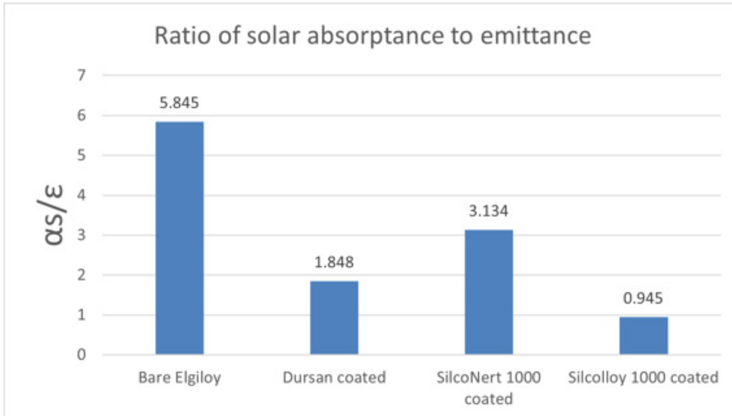








The goal of the coating was to lower the ratio of solar absorption to emittance down to 1 or less. As can be seen in Figure 1, Silcolloy achieved that goal. In any case, the coatings all provided lower absorption, higher reflectance and higher emission of solar radiation which would ease the heating and cooling process these parts might see in space applications.



All three coatings can enhance the emissivity properties of heat treated elgiloy. One thing to keep in mind when it comes to emissivity of SilcoTek coatings. The substrate they are deposited on will likely play a role in emissivity results. Since our coatings are very thin (Dursan coating was 450 nm, SilcoNert 1000 was 125 nm, and Silcolloy 1000 was 750nm) the solar radiation will penetrate the coatings and interact with the base substrate.

These results could be quite different on other metals, such as stainless steel, and it would certainly be different on a ceramic material. In the case of heat treated elgiloy, all three coatings provided a benefit, with Silcolloy 1000 providing the biggest impact to emissivity.

Chapter 6
Surface Characteristics of SilcoTek Coatings

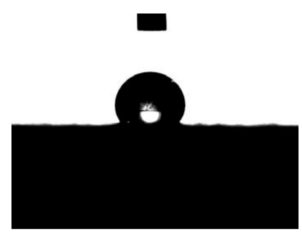
In this chapter, we'll discuss the water repelling properties (hydrophobicity) of our coatings. First, we'll review a little background theory about measuring water repelling properties and how surface contact angle measurements relate to the overall surface energy of a coating. The discussion will cover contact angle data for our coatings and highlight the performance of coatings designed for low and high surface energy. To round out our discussion, we'll also cover the oil repelling and ice repelling properties of our coatings.

6.1 Hydrophobicity Background

A hydrophobic surface is a water repelling, low energy surface that resists wetting. Moisture contact angle measurements will classify a surface as hydrophobic when the contact angle of the water droplet exceeds 90 degrees. A surface that surpasses the 150-degree contact angle mark is classified as ultrahydrophobic or superhydrophobic. Water repelling properties help analytical, chemical process, oil and gas, research, and a wide range of other users to manage moisture contamination in their operations.

Benefits of a moisture repelling surface include:

- Surface icing prevention
- Condenser & evaporator fouling prevention
- Improved corrosion resistance
- Prevent moisture contamination in heat trace tubing
- Produced water filtration & management
- Improved reliability in continuous emissions monitors (CEMS)
- Improved moisture detection instrumentation
- HPLC medical diagnostics improved separation & corrosion resistance
- Manage moisture contamination in liquid natural gas systems
- Prevent contamination in analytical sample transfer systems



The analysis of the interaction of a liquid with a surface can provide a simple but powerful understanding of surface energy characteristics and how that surface will perform in other environments. Contact angle data using liquids of known surface tensions can provide an insightful characterization of surface energy and how that substrate will interact with analytical or process streams.

For example, a high contact angle with water translates to a hydrophobic surface that may display rapid dry down properties for flow path surfaces subjected to gas streams contaminated with water vapor. This may, in turn, prevent localized corrosion as the water vapor is less likely to pool and corrode the surface over time.

6.2 Contact Angle measurement

SilcoTek utilizes two instruments for contact angle analysis, a Krüss K100 tensiometer and a Ramé-Hart Model 200 goniometer. Both systems provide valuable information when evaluating the interactive forces between a known liquid and a test surface.

The tensiometer is excellent at providing bulk analysis of a larger surface area, generating advancing and receding contact angle values. The goniometer is a fixed level stage system (i.e., no tilt) that can provide a localized equilibrium contact angle. It is also excellent at providing a visual identification of the solid/liquid/air interaction.

Tensiometer samples were tested using the Kruss liquid plate measurement method. 17 Mohm deionized water (DI water) was used as the test liquid to determine wetting. The Kruss tensiometer DI water container was raised to the test plate/water interface by a lift table. A precision balance then measured the water surface tension force interaction with the plate surface as the plate advanced into and then receded from the DI water (Figure 1).

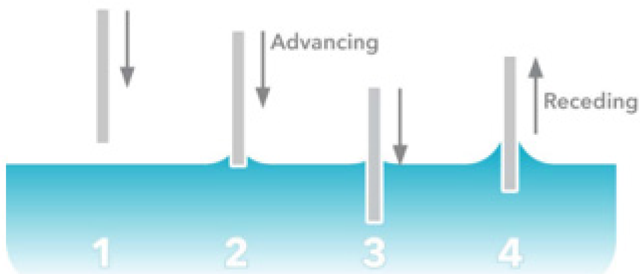


Figure 1: Advancing and receding contact angles are calculated by measuring water/ sample interface force generated when immersing the test plate into DI water. Bolin Scientific image.

As the test plate is advanced into the DI water, liquid surface tension and wetting forces act upon the test plate. Plates that interacted with the DI water wetted and exerted higher force on the plate. Plates that did not interact with the DI water did not wet and consequently, exerted low o negative force (repelling force) on the plate as it was advanced and withdrawn from the DI water (Figure 2).

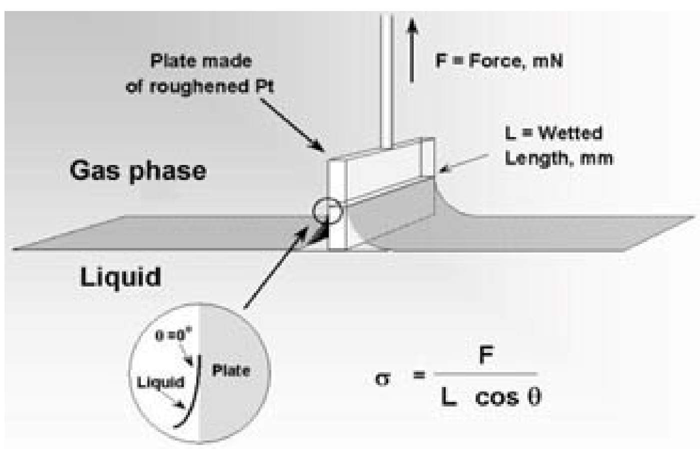


Figure 2: Wetting forces exerted by surface tension on test plates advancing and receding in DI water are used to calculate wetting contact angle. Kruss image.

As the plate is immersed in the DI water media, advancing and receding contact forces were plotted (Figure 3 below). Low downward forces or repelling forces are plotted as a negative number. Repelling forces indicate a low wetting, hydrophobic surface. As the plate enters the water, hydrophobic surfaces will repel the water, creating an upward force (shown as a negative number in the plot). Hydrophilic surfaces will create a downward, attractive force (shown as a positive number on the plot), indicating a low contact angle. As the coupon is removed from the water, receding forces pull on the plate, creating a downward force.

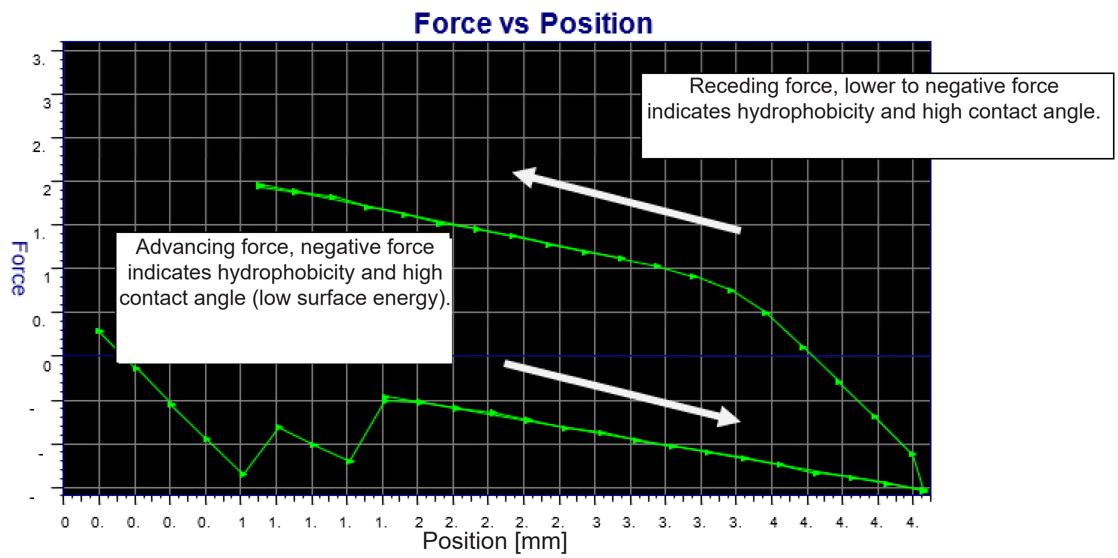


Figure 3: Advancing and receding forces are plotted; negative forces indicate repelling, non-wetting/hydrophobic, surfaces which are ideal for minimizing moisture contamination in emission monitoring systems.

Hydrophobic surfaces have low to negative receding forces indicating a high contact angle. Contact angles greater than 90 degrees indicate a hydrophobic, non-wetting surface. The advancing force indicates the lowest surface energy of the test surface and the receding force indicates highest surface energy. Advancing/receding hysteresis can be influenced by surface roughness, differences in surface heterogeneity or kinetic factors. The resulting advancing/receding hysteresis plot fully characterizes the test surface.

Tensiometric comparison of 304 stainless steel, amorphous silicon, and carbon functionalized amorphous silicon advancing/receding force show the 304 stainless steel and amorphous silicon surfaces demonstrate high positive force during advancement and receding of the plate (hydrophilic, wetting surface) (Figure 4). The carbon functionalized amorphous silicon plate exhibits relatively low advancing and receding forces (high contact angle) indicating a hydrophobic surface.

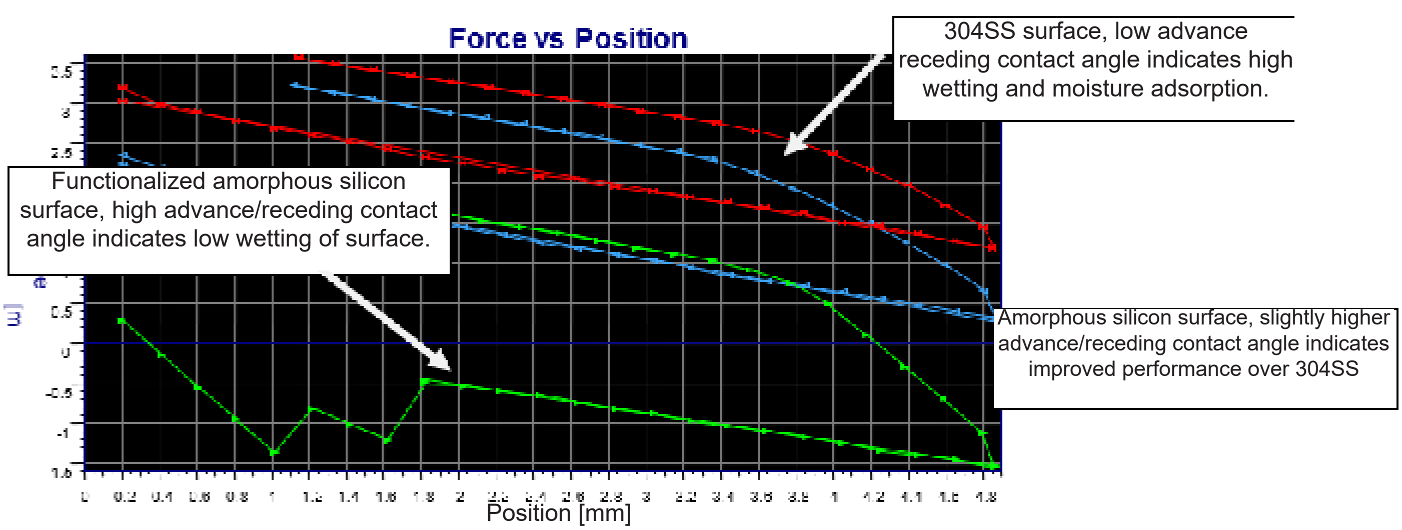


Figure 4: Contact angle comparison of 304SS amorphous and functionalized silicon surfaces.

The test utilized a test substrate of 316L stainless steel in two different surface finishes: a corrosion coupon with a 120-grit finish, and a sample coupon with a “mirror finish” surface. As you’ll see in the hydrophobicity data below, surface topology (roughness) can influence the equilibrium contact angle data when measured with a goniometer. Samples with varying roughness were used to help set the performance expectations of each coating.

6.3 Hydrophobicity Data

Contact angle data, depending on the measurement type and surface, can appear to be quite variable. The advancing and receding data obtained on the Krüss Tensiometer (Table I below) provide accurate characterization of a bulk surface for advancing and receding measurements as the test coating sample is progressively immersed into and removed from the measurement liquid.

Advancing data is acquired as the liquid is pushed into the coated coupon, and receding data is acquired as the liquid is pulled away from the coated coupon as noted above. More information on this experiment can be obtained at www.krussusa.com.

Surface roughness (i.e., smooth vs. rough) on a bulk measurement such as this did not have a significant effect on the tensiometer contact angle data, and therefore each data point in Table I is averaged from 3 rough and 2 smooth coupons.

Table I. Average rough and smooth surface tensiometer advancing and receding contact angles; DI water

	Advancing	Receding
Silcolloy 1000	28.3	0.0
SilcoNert 2000	83.0	47.0
Dursan	96.2	70.9
Notak	125.1	93.6

6.4 Water Droplet Contact Angle Measurement

Contact angle data, depending on the measurement type and surface, can appear to be variable. In this test, water droplet contact angle was measured using a Ramé-Hart Goniometer. Contact angle data (Table II and Figure 5 below) are measured from 2ul drops of water placed onto several localized coupon points. Variability in this measurement is significant when comparing a rough and smooth surface with the same surface material. The Goniometer data was averaged from each local contact area between the liquid drop and the coupon surface and segregated by smooth vs. rough. Further technical information about contact angle measurement can be found at www.ramehart.com.

Table II. Average goniometer static contact angles for rough vs. smooth; DI water

	Rough (n=9)	Smooth (n=6)
Silcolloy 1000	53.5	29.4
SilcoNert 2000	99.4	74.1
Dursan	119.3	86.0
Notak	146.7	112.1

Water droplet photographs, figure 5 below, illustrate the progression from hydrophilic to hydrophobic surfaces on the rough surface coupons. The highest contact angle for the Notak surface generated a maximum contact angle of 163° with an average of 146.7 degrees. The droplet for that coupon had to be larger than the standard 2ul size, as the drop would not release to the surface until it was large enough for its own weight to pull it away from the syringe needle tip.

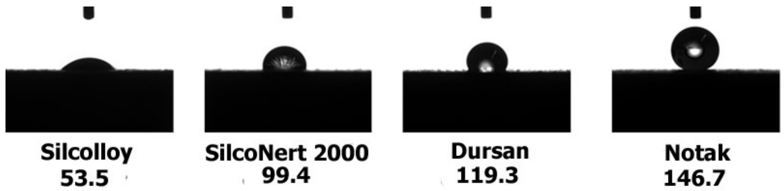


Figure 5. Goniometer contact angle (CA) photos; DI water on treated surfaces: Rough Surface

6.5 Hydrophobicity Discussion

The progressive increase of water contact angle shown in Tables I & II are the result of coating formulation through surface science and functionalization. The lowest coating contact angles measured were for the Silcolloy 1000 coating. Silcolloy 1000 is a patented multilayered amorphous silicon CVD material with a native oxide surface that is relatively hydrophilic in nature. It is best suited for anti-corrosive applications, particularly for acidic and salt media.

SilcoNert 2000 is also an amorphous silicon CVD material but is surface functionalized with a covalently bonded hydrocarbon to dramatically improve its inertness qualities and hydrophobicity. Because of its unprecedented inertness and good hydrophobicity, SilcoNert 2000 is commonly applied to analytical and sampling systems used in chromatography supplies, oil and gas sampling media, chemical processes transfer tubing, valves, and fittings.

Dursan is a carboxysilane CVD coating with a functionalized hydrocarbon surface. Dursan is highly inert, wear resistant, and is an excellent anti-corrosive barrier for acidic and basic media. It also has a narrow advancing/receding hysteresis so that it exhibits a Cassie-Baxter characteristic, even on a mirror-smooth surface. The combination of four characteristics: inertness, wear-resistance, anti-corrosion, and hydrophobicity make Dursan an excellent addition to analytical and transfer systems/components that require precise media transfer without the negative accumulative effects of humidity or moisture, or surface reactivity.

SilcoTek developed a new deposition, Notak, specifically designed to be highly hydrophobic, oleophobic, and thermally and oxidatively stable. This type of coating should find application opportunities where high hydrophobicity is necessary, and in antifouling and anticoking applications.

Notak tensiometer data showed an average advancing water contact angle of 125.1° and an average receding of 93.6°. Average equilibrium contact angle was 146.7° for a rough surface and 112.1° for a mirror surface. Free surface energy calculations for Notak (Figure 6 below) show a significant reduction in surface energy (increased contact angle) compared to aluminum or stainless steel.

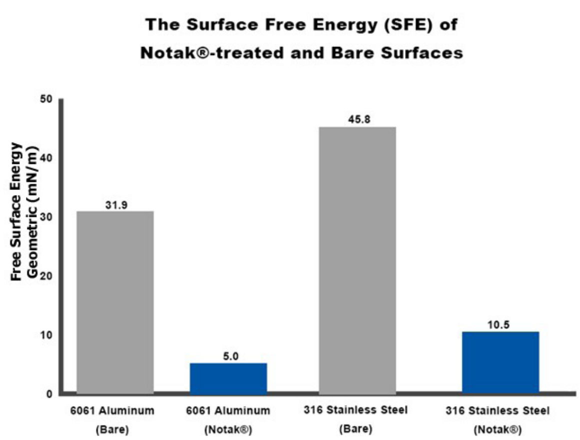


Figure 6: Comparative free surface energy of Notak, Aluminum and Stainless Steel surfaces.

6.6 Results and Discussion - Oleophobicity

A surface with a high contact angle for hexadecane translates to an oleophobic (oil repelling) surface. A highly oleophobic material may prevent the accumulation of hydrocarbon-based material in fuel delivery systems or combustive exhaust systems, thereby allowing a higher degree of performance efficiency and power output.

The need for oleophobic surfaces has grown in recent years and has become a desirable feature for many material applications, from glass used in cell phones and computer tablets to resist fingerprints, to fuel delivery and exhaust systems to resist fouling and coke accumulation.

Table III compares the advancing and receding contact angles for various coatings. Of the coatings tested, only Notak demonstrated oleophobic performance when measured with hexadecane.

Table III. Average (n=5) tensiometer advancing and receding contact angles; hexadecane

	Advancing	Receding
Silcolloy 1000	0.0	0.0
SilcoNert 2000	0.0	0.0
Dursan	0.0	0.0
Notak	52.8	20.2

The Notak surface exhibits significant oleophobic characteristics, with measurable advancing and receding tensiometer contact angles, and significant localized equilibrium contact angles of 53° (smooth) and 79° (rough) as illustrated in Figure 7.

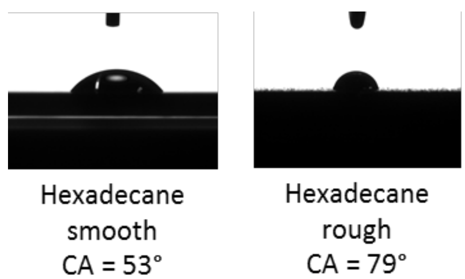


Figure 7. Goniometer drop photos for hexadecane on Notak surface

Using 10W40 motor oil as a droplet liquid (Figure 8), the Notak surface exhibited further oleophobicity with contact angles of 63° (smooth) and 82° (rough).

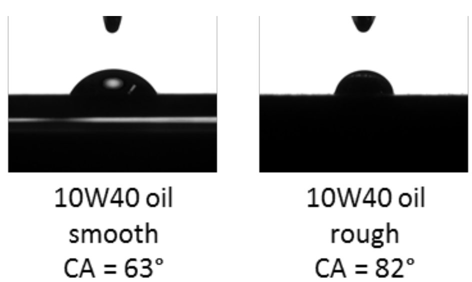


Figure 8. Goniometer drop photos for 10W40 motor oil on Notak surface.

Notak is transparent to visible light when applied to glass which may benefit analytical, research, or consumer product applications. Testing of Notak is ongoing, particularly in the characterization of inertness, wear resistance and friction coefficient. Contact angle data, however, reveal a material that may be highly applicable when hydrophobicity and/or oleophobicity characteristics are required.

6.7 Icephobic Surfaces

Like water repelling surfaces, icephobic surfaces can repel ice or minimize the formation of ice. Ice repelling properties can be attributed to the structure of the surface or low surface energy which results in low adhesion and easy removal of ice.

Low energy surfaces that prevent ice adhesion may provide substantial benefits for applications utilizing heat exchangers, as well as applications that are negatively affected by the accumulation of ice, such as aircraft or instrumentation components. SilcoTek® works with customers to solve adhesion problems; our Dursan® and Notak® coating technologies lower surface energy, increase hydrophobicity and water repelling properties.

6.8 Testing the Surface for Icephobicity

Evaluating surfaces using commercially available instrumentation is feasible but can be expensive, especially when initially screening surfaces for icephobicity. Although SilcoTek does not have specific instrumentation to quantitatively test this property, we were able to devise a simple qualitative proof of concept test.

Using a standard food storage freezer (at 0°F / -18°C), a variety of SilcoTek® surfaces and an uncoated control were evaluated. The evaluation procedure involved placing a 1-2ml droplet of deionized water to the middle of each room temperature coupon. Samples were then placed in the freezer for approximately 16 hours. After the freezing cycle the samples were removed from the freezer. A metal pick was used to laterally remove each ice ball from the coupon surfaces. The degree of removal difficulty was subjectively rated on a scale of 1-10 (1 = easy, 10 = difficult) with accompanying observations.

Notak® has a low surface energy of approximately 10.5 mN/m compared to an untreated 316 SS surface of approximately 45.8 mN/m. This low surface energy may allow ice to release from a Notak surface with little effort. Additional SilcoTek surfaces will be evaluated for comparative analysis.

6.9 Icephobic Data and Discussion

The photo below gives an empirical representation of the relative ice repelling properties of each surface. The Notak coated sample appears to repel the ice droplet more than the other samples.

Untreated 316 Silcolloy

Notak Dursox Dursan

Upon opening the freezer door (see photo), each coupon was individually removed and rapidly tested to avoid the potential impact of thawing. A metal pick inserted at the point of ice attachment to the coupon was used to laterally remove the ice. The effort required (1 = easy, 10 = difficult) to remove the ice and associated observations are listed in the table below.

316 SS Coupon Surface	Effort (1-10)	Observations
Notak	2	complete removal with little effort
Dursan	6	partial removal from surface with effort
Silcolloy 1000	7	partial removal from surface with greater effort
Dursox	8	difficult, bulk chipped with minimal surface separation
Uncoated	8	difficult, bulk chipped with minimal surface separation

Only Notak® displayed significant icephobic properties where the frozen droplet completely removed from the Notak coupon surface with relative ease, giving a rating of 2 (good). Notak® has a low surface energy of approximately 10.5 mN/m compared to an untreated 316 SS surface of approximately 45.8 mN/m. This low surface energy allows ice to release from a Notak surface with little effort.

The subjective data indicates an opportunity for the application of Notak surfaces for the prevention of ice accumulation and provide opportunities for ice release with little effort from surface.

6.10 Conclusion

The characterization of the surface energy and hydrophobicity of SilcoTek CVD depositions is a significant step in helping customers understand the performance of a coating for their application.

How do I get a surface to match my desired moisture level of moisture resistance?

The testing shows that customers don't have to make a radical material change or modify a product design in order to better manage water repelling properties. SilcoTek offers a wide range of barrier coatings with varying degrees of water management capabilities as can be seen in figure 9 below.

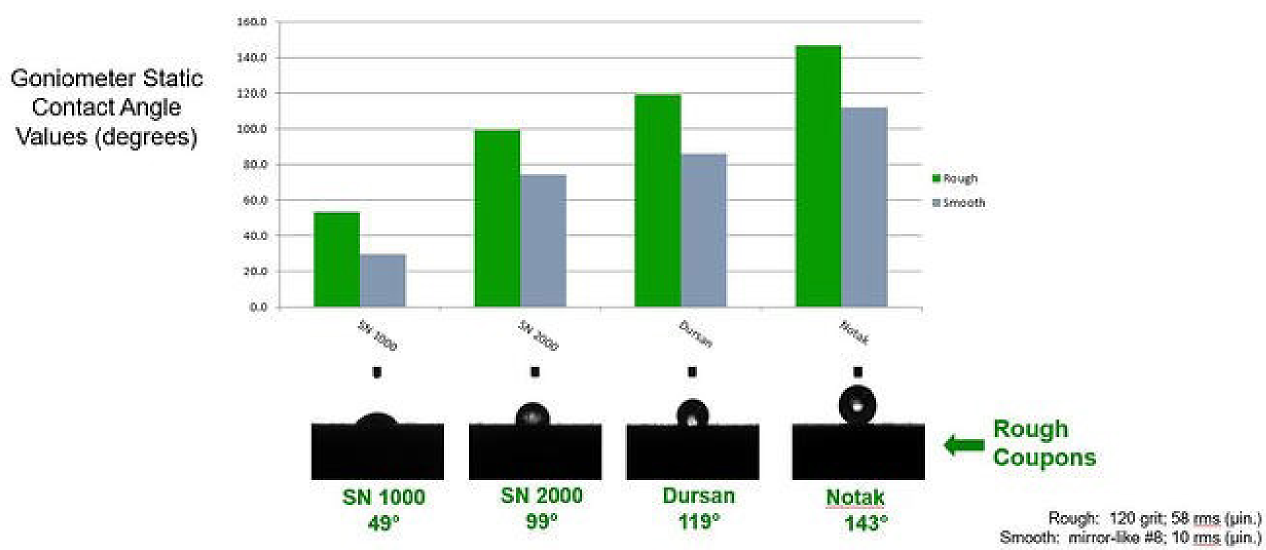


Figure 9: SilcoTek offers coatings with a range of surface energy from high energy, low contact angle, SilcoNert 1000 and Silcolloy, to low energy, high contact angle, Notak.

For applications requiring a high degree of hydrophobicity as well as inertness, corrosion resistance and wear resistance, Dursan is the coating of choice.

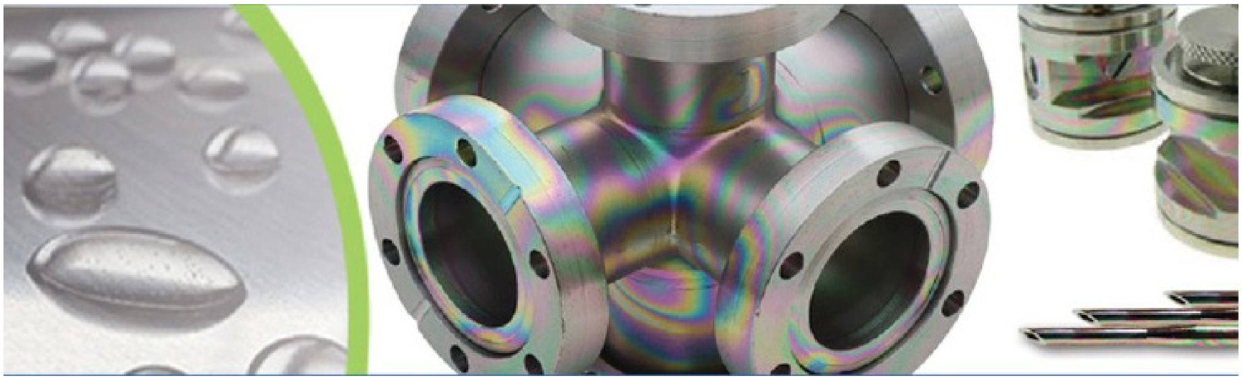
For applications that require a non-reactive surface that is slightly less hydrophobic, SilcoNert 2000 fills that need, particularly if inertness is an utmost requirement.

For applications where surface energy is not a concern or where applications require a high energy, hydrophilic surface, Silcolloy 1000 is an optimal choice where an inert, corrosion resistant surface is needed.

Finally, SilcoTek continues to develop new materials to meet customer needs. Our newest coating, Notak, is showing significant promise when hydrophobic and oleophobic qualities are required. Notak may be desirable in low surface energy applications, such as plastic mold release, or where water repelling, icephobic, or oil repelling properties are required.
Note, our Notak coating is in pre-production Beta testing so we have limited capacity for that coating. Contact our Technical Service Team to discuss your application and we'll be happy to make a coating recommendation.

In previous chapters we characterized the properties of our coatings. In chapter 7 we'll discuss chemical compatibility and how our coatings interact with corrosive and reactive compounds.

Chapter 7
Material and Chemical Compatibility



Why are we discussing material and chemical compatibility in a material property e-book? Because if a coating is expected to perform to specification and to exhibit certain desired physical properties, the substrate material and coating environmental conditions must be compatible with that coating.

Let's expand on this idea. For example, if the coating user is expecting the coating to repel water (as discussed in chapter 6) but the coating is applied to an incompatible surface, like copper, the resulting coating won't repel water as expected or the coating may not correctly bond to the surface. This will result in coating failure and certainly not the desired hydrophobicity property expected.

Not only does the substrate material play a role in the coating performance, but the environmental conditions also play a major factor in achieving the desired coating property. Using that hydrophobicity example above, if the surface is exposed to a highly abrasive environment or is exposed to an incompatible chemical such as concentrated hydrofluoric acid, the coating will be damaged and the desired water repelling property won't be achieved.

In this chapter we'll summarize the material and chemical compatibility of the coatings. We won't go into much detail on specific data; that is out of the scope of this e-book and frankly would make this e-book painfully long! If you're interested in learning more about material or chemical compatibility and how our coatings perform, go to our website or blog to get the latest information on each of our coatings.

7.1 Material Compatibility

We'll first summarize the material compatibility of our coatings by highlighting how each coating performs for select materials. SilcoTek can coat an impressive array of materials, allowing the user to benefit from an inert surface while using the same base material originally specified.

Some of the materials you may not know we can coat are:

Aluminum

There are some exceptions and limitations to coating aluminum. We don't recommend coating parts that will undergo high stress or pressure like gas cylinders, and there are some grades that are not recommended. Go to our aluminum web page to learn more.

Glass

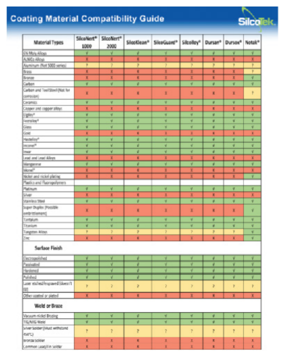
Yes, we can make glass even more inert! Glass contains contaminants that can leach into high purity processes in analytical, research or chemical process applications.

Alloys

We can coat most alloys. High performance alloys like Hastelloy® are expensive and costly to machine. Protect your investment and extend component life by preventing metal ion leaching, improving corrosion resistance, durability, and inertness.

Ceramics and Quartz

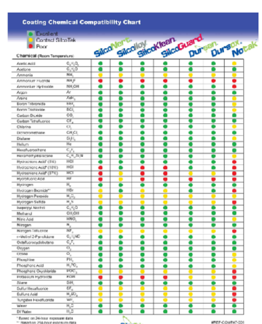
We can make ceramics and quartz more inert, even in high temperature applications. SilcoTek® coatings conform to porous ceramic surfaces, making even high surface area components inert.
Read through the more detailed summary of material compatibility below. The green highlighted areas indicate compatibility for a coating. Red indicates not recommended. The yellow highlighted areas indicate areas under current review or those that have mixed results. Contact our technical service team for more information on the compatibility of our coatings with your materials.



Click here to view our updated, easy-to-use, Material Compatibility Chart.

7.2 Chemical Compatibility

Generally, our coatings are non-reactive to most chemicals. In fact, our coatings are frequently used in analytical, process, and environmental testing of trace chemicals that normally react with relatively stable materials like stainless steel, glass, and ceramics. However, some strong acids and bases can damage or erode our coatings. The chemical compatibility guide below highlights chemical exposure recommendations for each of our coatings. Contact our Technical Service Team to discuss chemicals not listed in our guide.



Click here to view our updated, easy-to-use, Chemical Compatibility Chart.

For a more application-oriented determination of which coating is best for your application, just click through our coating selector guide on our website. The guide will ask a few simple questions to assess which coating is right for your application. The selector will account for any potential environmental compatibility issues and suggest a coating for the application and your desired performance level. As always, our Technical Service Team is here to help with any coating questions.

In our final chapter we'll tie everything together with a summary of our coating properties and discuss key takeaways from our e-book.

Chapter 8
Tying It All Together

Congratulations, you made it! You've tackled some pretty difficult subject matter ranging from CVD coating technology all the way to light transmission theory and surface energy water droplet contact angle measurement. Along the way we hope you gained an understanding of the material properties and limitations of our coatings. It's important to understand the properties of our coatings in order to achieve the highest coating performance and to avoid a disappointing coating failure or, more importantly, a failure to achieve your expectations.

Now that you've made it through all that coating theory and weighty specification discussions, we'll make it easy on you by summarizing our coating properties in a Material Property Quick Reference Guide.

Unfortunately, some of the more graphical information doesn't translate very well to a summary sheet. In cases where we were not able to condense the data in an easy-to-read reference, we added an empirical summary comment to give the reader a quick estimate of the coating property.

At SilcoTek, it's our goal to provide game changing coatings that improve the performance of your products or process. We also strive to change the game of how our customers learn about our coatings. We do our best to present unbiased data about key performance aspects of our coatings. If we have data that indicates a coating may not perform in your application, we'll tell you! If we don't know how a coating will perform, we'll tell you that as well. If additional testing in needed to better clarify how a coating will perform in your application, we'll work with you on finding ways to evaluate the coating. We'll even recommend a testing protocol if it's available and help guide you through your evaluation from preliminary testing, through beta testing, and final production approvals. Along the way, you'll collaborate with some of the best minds in the coating business to help recommend and evaluate our coatings. Our team of experts are here to assist you on your coating journey and to make your product a true game changing story.

Postscript

The information presented in this e-book is the result of a compilation of thousands of hours of testing and evaluation by our Research and Development Team. Through their efforts and extensive knowledge of physical science and chemistry, we have been able to bring all their work and effort together into this e-book.

We continue to build our knowledge and understanding of the coatings we develop. There are millions of applications, environmental conditions, and chemicals that may interact or benefit from our coatings. Because of the vast number of potential applications, our coating testing, education, and coating development is continuous. That's why one of our core values is to never stop learning, because the journey never ends!