



44<sup>TH</sup> TURBOMACHINERY & 31<sup>ST</sup> PUMP SYMPOSIA  
HOUSTON, TEXAS | SEPTEMBER 14 – 17 2015  
GEORGE R. BROWN CONVENTION CENTER

## THE EVOLUTION AND APPLICATION OF MECHANICAL SEAL FACE MATERIALS

### William Dietzel

Engineering Supervisor  
Flowserve Corporation  
Kalamazoo, MI, USA



*William Dietzel is a supervisor in the Flowserve mechanical seal Applied Technical Solutions Group. During his 12 years at Flowserve he has provided technical support to several regions of the United States. He has experience in application, troubleshooting and design of mechanical seals. He is currently an Engineering Supervisor at Flowserve's Kalamazoo, Michigan location. William received his bachelor's degree in Mechanical Engineering from Western Michigan University.*



*Jack Vasko is the Product Manager for Flowserve's engineered mechanical seals applied in the oil & gas, petrochemical, and power markets. Jack joined Flowserve in 2005 and took on the role of Product Manager in 2011. Prior to this role, Jack worked in various pump and seal sales positions in Philadelphia, PA and Houston, TX. Jack holds a bachelor's degree in Mechanical Engineering from the Georgia Institute of Technology.*

### ABSTRACT

The advancement of seal face material technology since the first known mechanical seal design in 1903 can be closely tied to standardization, regulation, and social concerns in industry. The authors will show how these different factors interacted and resulted in the advancement of mechanical seal faces and ultimately the advancement of mechanical seal applications. The

### Jack Vasko

Product Manager – Engineered Seals  
Flowserve Corporation  
Bridgeport, NJ, USA

historical discussion frames the discussion on contemporary seal face material selection philosophy.

### EARLY ERA OF MECHANICAL SEALS: PRE 1940

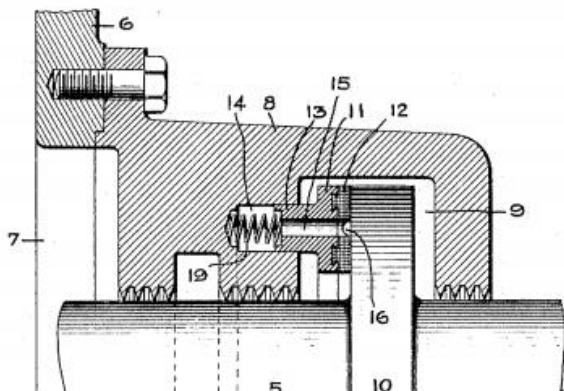
The history and development of mechanical seals is closely linked to the popularity and growth of the centrifugal pump and compressor. Centrifugal pumps and compressors have commonly been found in operation since the 19<sup>th</sup> century, but their use was limited by the lack of an economical and reliable power source to generate rotation. This changed dramatically around 1895 as electricity spread and the reliable electric motor brought a stable power source to the centrifugal pump. This led to industry applying them in simple applications as industry determined the use of these new centrifugal fluid handling devices. The applications began to grow as the benefits were quickly realized and industry started to apply them in more challenging services.

The popularity of the new electrically powered pumps created a condition where the existing pump suppliers could not keep up with the demand. This stimulated several new companies to enter the market with new designs while older companies reconfigured their products to remain competitive. This growth in the industry sparked an initiative to standardize the markets which led to the creation of several institutes such as the Hydraulic Institute (HI) in 1917 and the American Petroleum Institute (API) in 1919. These institutes remain active and strong leaders in the industry today.

During this early era there was very little development in the area of the primary “seal” between the pump and compressor's rotating and stationary elements. Most early

sealing devices were an adaptation of the existing steam packing or lantern rings that were most commonly used by steam engines at that time. The application of these sealing technologies in non-hazardous steam was relatively straight forward; however, in centrifugal pumps and compressors the application ranges were broader, which quickly revealed the limitations of packing and the need for a different sealing concept. A new sealing concept, the end-face mechanical seal, was first introduced in 1903 by George Cook. While the original “Cook seal” was intended for a centrifugal compressor refrigeration application, the technology was soon applied in centrifugal pumps. From here on, this tutorial will focus on mechanical seals used in centrifugal pumps.

Early seals, modeled after the ‘Cook seal,’ had some of the basic design concepts of the modern mechanical seal, but were still heavily influenced by traditional packing. The biggest change incorporated by early seal designs was the change of the sealing interface from along the shaft to a radial surface perpendicular to the shaft. Figure 1 shows an example of an early mechanical seal.



**Figure 1. Early mechanical seal, US Patent #1,315,822 Published September 9<sup>th</sup>, 1919**

There were several benefits to changing orientation of the seals but the biggest was it reduced and changed the loads acting on the seal and allowed the exploration of more compliant materials designed for use as seal faces.

Early mechanical seal designs reflect a desire to pair dissimilar materials running opposite each other. The classic combination included a conforming face made of a soft or flexible material and a hard or stiff face made of

metal or plastic. Typical hard faces used during this period included materials pump companies were familiar with such as cast iron and hardened steel. These early ‘hard’ seal faces were simple and did not incorporate many considerations such as flatness, smoothness and perpendicularity that are taken into account today. As a result, the opposing face material needed to have the flexibility to match the surface profile of the ‘hard’ metal seal face. Pump and seal manufacturers experimented with different compliant seal face materials to run against the ‘hard’ seal face. During this period a large number of materials were tried including materials traditionally used for braided packing (graphite based), neoprene rubber, leaded bronze, Bakelite, Micarta, and a wide range of metal impregnated graphites. Copper, tin, lead, antimony, bronze and zinc were all common Babbitt materials used in early mechanical seals.

Although advancements in mechanical seals were taking place during this period, they were still considered a product for a niche market and only considered if packing would not work in the application. This period still had the vast majority of centrifugal pumps supplied and operated with packing as it was considered simple and reliable.

However, as this period was ending the needs and expectations of industry were changing and with it was the opportunity for end-face mechanical seals. Industry was beginning to explore more mechanical seals for a broader range of services. The marketing campaigns of several major packing companies in the 1930’s also highlighted mechanical seals and helped increase the installed population.

### THE MECHANICAL SEAL EVOLUTION: 1940-1980

The period between 1940 and 1980 was a period of rapid growth for mechanical seals and seal face materials. In fact, nearly all the common seal face materials used today were developed during this period.

The general attitude towards sealing device technology during this period was influenced by several factors. Advancements in rotating equipment design and operation were encouraged by new regulations which required industry to consider environment and personnel safety. The emergence of widespread global trade and competition pressured plant operators to reduce operational costs and improve plant efficiency. All of

these factors forced industry to start looking for a better performing, more reliable, and more economical sealing solution for their rotating equipment applications.

At the heart of the advancements was the experimentation and development of the rubbing surfaces or the mechanical seal faces. Early development of face materials concentrated on achieving low wear by pairing readily available compliant seal face materials with corresponding ‘hard’ metal bodies. As mechanical sealing evolved, the focus shifted to developing materials that would broaden the mechanical seal application range, while incrementally reducing their leakage rates. To achieve these new goals, while maintaining wear resistance, new developments in seal face design and materials were required.

As mechanical seal manufacturers grew their knowledge through experimentation, they started to understand and develop the set of material properties that are used today. They understood that a suitable compliant face is a balance between having enough material strength to resist excessive deflection from pressure loading and still be soft enough to allow the face to wear evenly when paired with a harder face. They knew that materials are subjected to the process fluid and must resist mechanical attack from abrasives and chemical attack from corrosive fluids. They learned other material characteristics such as thermal conductivity, thermal expansion, and having a certain range of mechanical properties heavily influence the performance of the seal face materials.

Mechanical seal manufacturers started to evaluate face materials by their identified material properties and lower cost and availability.

At this point several early face materials were found unsuitable for the long term performance mechanical seal manufacturers were trying to achieve. However, seal manufacturers started to experiment with new materials, and they organized these materials into two categories: compliant soft materials and hard materials.

## **COMPLIANT SOFT FACES**

### *Mechanical Carbon*

Carbon-graphite or “carbon” was identified by mechanical seal manufacturers during the 1940-1950s as a viable mechanical seal face material due to its excellent

self-lubricating properties. The initial use and incorporation of this material proved to be challenging because low quantity usage only made it economical to purchase and manufacture from raw tube stock. This was a problem because carbon is not a homogeneous material like metal but is a material full of interconnecting voids sealed with an impregnation material. This was quickly discovered as the carbons were machined to their final shape; the thin impregnation layer was removed leaving only porous carbon remaining. This translated into the carbon requiring extra manufacturing steps and giving carbon the reputation of being difficult to work with. However, once the manufacturing process was understood, the benefits of this self-lubricating material were demonstrated in early trial applications. The next step for applying this material was determining the grade(s) of carbon that could be used in mechanical seals.

Carbon manufacturers during the 1950s were a constrained group and most of their time was spent developing materials for the chemical and metallurgical industries. These industries did not have an abundance of funding available for new materials, which resulted in the slow introduction of new materials to industry. During the 1960s, the arrival of the nuclear and aerospace industries increased the funding available for improving the quality and reliability of the existing carbon grades and development of several new grades of carbon (Paxton 1979). This rapid expansion of mechanical carbon grades, combined with the quality requirements of the nuclear and aerospace industries, helped drive the mechanical carbon industry and ASTM to release new testing guidelines from the late 60s until the early 80s to help improve quality and reliability with the new and existing carbon materials.

The initial development and use of carbon by mechanical seal manufacturers was complicated by the number of carbon manufacturers and their substantial inventories of unique grades. The combination of companies and grades created several hundred choices of carbon grades available for use in mechanical seals. From these grades, mechanical seal manufacturers found numerous grades of carbon that performed well in poor lubricating fluids.

The abundance of choice has since decreased by several orders of magnitude due to the consolidation of several mechanical carbon companies and their subsequent efforts to rationalize the grades they offer. Working with the mechanical seal industry, the mechanical carbon industry

standardized approximately a dozen grades for use in mechanical seal applications.

### *Carbon Manufacturing*

The benefits of carbon start with choosing the right combination of base ingredients and then having the right methods of manufacture to create the desired properties. Carbon manufacturing begins with choosing the right blends and types of filler (Natural graphite, synthetic graphite, Petroleum graphite, lampblack, charcoal), binder (synthetic resins, coal tar pitch, petroleum pitch, metals), and any additives (Abrasives, film formers, antioxidant, graphitizing aids) required to achieve the desired properties of the finished carbon parts. Once the ingredient mixture is complete, it is formed into a near-final shape using die molding, isostatic molding, or an extruding process. The carbon is then ready for high temperature heat treatment. During the heat treatment the binding agent is converted to carbon while a small amount volatizes and leaves the carbon. At the end of this stage the resulting carbon is soft and contains porosity throughout the part.

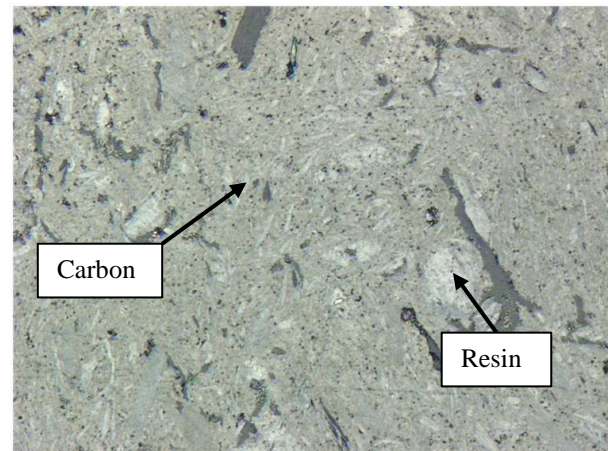
To eliminate the porosity, an impregnation material capable of flowing into the voids to seal the leakage paths is required. This amount of impregnation material in the final carbon ring is pretty significant and has a large influence on the final material properties of the carbon ring.

Typical fillers used as impregnation material include resins, thermoplastics, metals, inorganic salts and other materials. The characteristics of each impregnant will determine what types of enhancements or limitations it can provide to the base carbon.

### *Resin Impregnated Carbon*

General purpose resin carbon is one of the most common materials used for carbon seal faces. The thermosetting impregnate (phenolics, epoxides, polyesters, furan) is applied with a vacuum-pressure process to impregnate the material as deep as possible. A high penetration depth is desirable to fill the porosity, improve lubricating qualities, and maximize mechanical strength. A heating process is typically used to cure the material and will not soften once it has been cured. Resin bound carbon has a moderate high temperature capability, moderate hardness and strength, and excellent chemical compatibility. These

excellent properties allow its use in a wide range of applications. An example of resin carbon under magnification is shown in Figure 2.

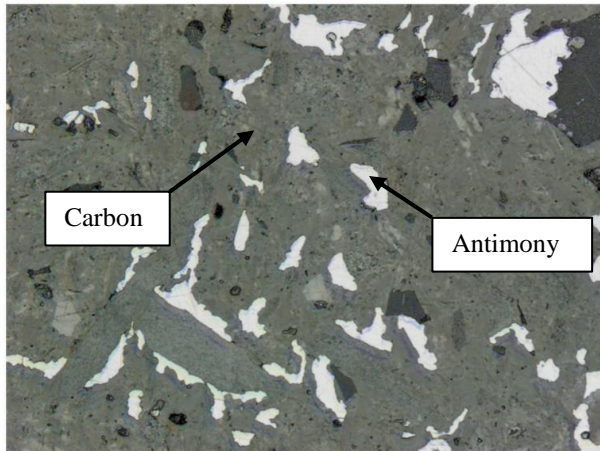


**Figure 2. Resin Impregnated Carbon at 100x magnification**

### *Metallized Carbons*

As the name implies, metallized carbons are impregnated with a molten metal to increase the strength, thermal conductivity and modulus of the base carbon material. These types of carbons are actually categorized with the thermoplastic impregnant materials because the metals have the potential to melt and run back out of the carbon at high temperatures. The metals used to impregnate seal faces must have good tribological properties and a moderate melting point. Soft babbiting materials such as bronze, copper, nickel, antimony, and tin meet these requirements and have been used as impregnation materials of carbon rings. Of these materials the addition of antimony has proven to be the most success for use as a seal face material due to its higher melting point relative to other babbiting materials.

Antimony carbon is considered a high quality material that provides good operation in higher pressure and speed applications and it is also considered to have an increased blister resistance when compared to standard resin carbon-graphite materials. Though this material provides advantages in higher duty service, the antimony impregnate limits the temperature capabilities and reduces the corrosion resistance of the seal face. Antimony impregnated carbon is generally not recommended for use in strong acids or bases. An example of antimony impregnated carbon is shown in Figure 3.



**Figure 3. Antimony Impregnated Carbon at 100x magnification**

#### *Dry-Running Carbons*

Dry running grades of carbon are used in sealing applications where there is not a liquid fluid film present to lubricate the faces. These grades are applied when the seal face material itself is required to create the lubricating film. These grades of carbon are typically softer than other grades due to the higher amount of graphite used to promote the formation of the fluid film. Other carbons in this category use a special impregnation material such as a salt (i.e. barium fluoride, lithium fluoride) to improve the performance of the carbon by aiding in film formation between the faces (Huebner 2005).

#### *Acid Grade Carbon*

Acid grade carbons are materials with minimal amounts of components and impurities that are subjected to the effects of aggressive chemicals and can be used in these highly corrosive applications. Carbon manufacturers create these grades of carbon by removing as many ingredients as possible. This includes items such as beneficial additives and key fillers like graphite. They further reduce the potential for corrosion by using an extremely pure source for the base carbon material which has had chemically incompatible impurities removed. These steps to remove impurities are important, because the aggressive process fluid will leach out some common additives and impurities in the carbon. The absence of these additives leaves a very weak carbon structure (Huebner 2005). These special grades of carbon have increased chemical resistance but compromise on other properties, including strength and

lubrication. Acid grade carbons are most appropriate for low duty applications which operate at low speeds and pressures.

#### *Additional Compliant Soft Faces*

There are a few additional softer face materials used in mechanical seals for very specific applications. Softer metals such as tin bronze can be applied in applications that exceed the limits of carbon material but require some degree of forgiveness when paired with a harder face material. The benefits of this material are typically an increase in strength, hardness, thermal conductivity and thermal expansion, when compared to typical carbon materials. Although these materials do have significant benefits in certain applications, they are not self-lubricating and tend to experience increased thermal distortion due to the higher thermal expansion rates of the material. For these reasons the window to apply these materials tends to be limited as the benefits do not outweigh the concerns in the majority of applications.

Plastics like nylon, rubber, or solid filled PTFE can also be used as seal faces but these tend to have very low melting points, low thermal conductivity, and a low modulus of elasticity. Having these weak properties only make the use of these materials viable for very low duty applications.

#### **HARD FACES**

During the same period of advancement in compliant materials, mechanical seal suppliers began to look towards improving the properties of the mating faces. Until now, the most commonly used materials were already found in industry, such as hardened alloy steels and tool steels. While these materials were certainly harder than the compliant materials they were being paired with, they lacked sufficient wear resistance for long life. Early metallic hard faces also lacked sufficient stiffness to maintain flatness, which made it hard to achieve low leakage levels over a wide range of application conditions.

In order to broaden the application range of mechanical seals, manufacturers developed a number of hard overlays and ceramics to be used as seal face materials. These materials had better tribological properties when paired with the aforementioned mechanical carbons, and therefore tended to generate more consistent wear and lower leakage.

## Coatings and Overlays

Just after World War II, industries with wear-resistant needs began to widely apply hard overlays on stainless steel substrate materials. One of the most popular overlays used on mechanical seal face surfaces was cobalt-chromium (CoCr). Applications of cobalt-chromium in mechanical seals began to appear as early as 1949. The combined properties of good availability, low cost, and a high hardness (40-50 Rockwell C (HRC)) made CoCr a dominant face material choice for over 20 years. For some applications, CoCr remains in use on seal faces, although it is more frequently applied in other areas of the seal where relative motion between parts exists. Two examples of other uses for CoCr coatings are on the surface opposing a close-clearance bushing or on a surface where an elastomer is intended to slide during operation.

In 1978 an overlay harder than cobalt-chromium was introduced for mechanical seal faces. Chromium oxide coating has an outstanding hardness of 54 HRC. Both cobalt-chromium and chromium oxide coating technologies can be applied in several ways with the most common being Plasma Transferred Arc Welding (PTAW). A typical coating thickness is 0.2 to 0.3 mm (0.008 to 0.012 inches).

Although these hard overlays greatly advanced seal face capabilities at the time, several weaknesses led to their eventual replacement.

Weaknesses of PTAW coatings include:

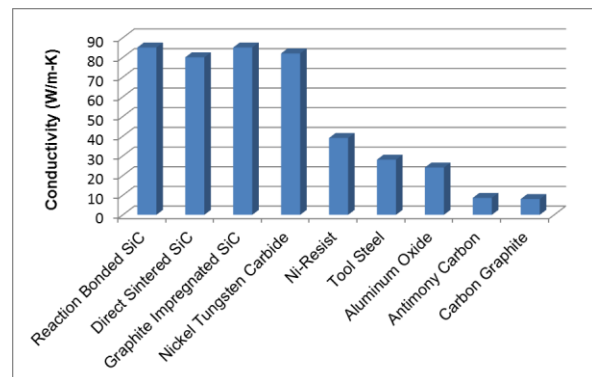
- Heat checking / thermal cracking
- Delamination / film failure
- Limited corrosion resistance
- Flatness retention

Early in the 1970's cast cobalt-chromium was offered to eliminate some of the coating-related issues with CoCr; however it was not widely adopted. By this time, several ceramic options were available that offered improved hardness and stiffness. Another new technology introduced at the same time was a ceramic layer on a carbon substrate. This new ceramic coating, Silicon Carbide (SiC), would signal the birth of a new family of seal face materials, which today is the basis of over 70% of hard seal face materials.

## Ceramics

Seal face surfaces can be made extremely flat and smooth using a machining process known as lapping. Lapping is a process where the seal face is rubbed against a flat surface with an abrasive media between them. In the early days of mechanical seal innovation, leaded bronze emerged as a preferred metal face material because of its ability to be easily and quickly lapped. Bronze also had desirable properties including good thermal conductivity and non-sparking. However, early metallic materials, including bronze, were not able to "hold a lap" well. This means that shortly after being lapped, thermal and mechanical stresses could cause the face to go "out of flat" and become wavy. To fully realize the benefits of lapping, a much stiffer material was required, and ceramics proved to be capable of filling that role.

Ceramics as seal face materials could categorically be described as one of the most significant leaps forward in mechanical seal capabilities. Specific ceramics were selected for high hardness, high thermal conductivity, and high chemical resistances. Ceramics such as aluminum oxide were first introduced in the late 1950s and 1960s. Aluminum oxide has outstanding hardness and chemical resistance compared to metallic-based seal faces. However, its thermal conductivity is similar to metallic-based seal faces and its tribological properties are poor. Figure 4 compares the thermal conductivity of aluminum oxide to other seal face materials.



**Figure 4. Thermal conductivity of seal face materials**

Unfortunately, a low thermal conductivity exacerbates the problems of a high friction material, such as aluminum oxide. This results in seal generated heat effectively being insulated at the seal face running surface. In demanding applications, this can cause a localized "hot spot" where product fluid lubricity drops and seal generated heat rises.

Furthermore, aluminum oxide will fracture if exposed to a rapid change in temperature, which is known as a thermal shock. This occurs most frequently when cool fluid is introduced to a seal face that has been running exceptionally hot due to low lubricity fluid or dry running. While aluminum oxide remains cost effective to form into a seal face, it continues to be used in low pressure applications, low surface speeds, and mild temperatures.

### Tungsten Carbides

Tungsten carbide (WC) was introduced to mechanical seals in the late 1950s. The technology was brought to seals from the machine tools industry where it had been used as a cutting tool since the 1930s. Initially, WC was cemented with either cobalt or nickel. Cobalt-bound WC is slightly harder and stiffer than nickel-bound versions; however, it is susceptible to chemical attack when exposed to some strong acids and bases, particularly hydrogen sulfide (H<sub>2</sub>S). Cobalt-bound WC is more common in general industry applications. Due to the prevalence of H<sub>2</sub>S in sour crudes, the oil & gas industry prefers the nickel-bound version of WC. With otherwise similar material properties and a lower cost, nickel-bound WC became the standard tungsten carbide offering for seal face applications by the 1970s.

Tungsten carbide can be applied as a solid seal face or as a coating on a stainless substrate. In fact, both application techniques have been in use since the 1960s. As a coating over a stainless substrate material, the high hardness of WC provides abrasion resistance; however, the other material properties provide little benefit. A strong reason to use WC as a seal face coating is to achieve a lower production cost. Conversely, as a solid face, tungsten carbide's many additional benefits can be taken advantage of. For example, the modulus of elasticity is unmatched by any other seal face material. When WC is applied as a solid piece, the high modulus of elasticity makes it extremely resistant to pressure deflections and other environmental influences that can cause the seal face to lose its flatness. Figure 5 compares the modulus of elasticity of Nickel bound WC to other seal face materials.

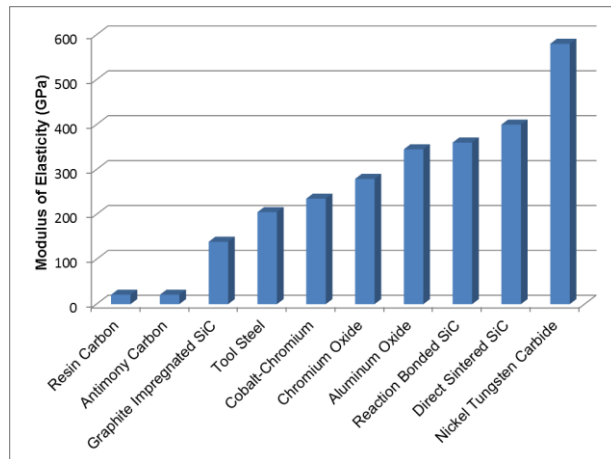


Figure 5. Modulus of Elasticity of seal face materials

Good thermal conductivity aids in dissipating seal generated heat, which can improve lubrication conditions at the running surface and prevent fluid flashing. Among ceramics in general and specifically carbides, tungsten carbide's superior fracture toughness is much appreciated by users. For comparison, WC's fracture toughness is 3 to 5 times higher than silicon carbide and aluminum oxide. While still not as fracture resistant as metals, light impacts will generally not fracture WC. An additional benefit of high fracture toughness is resistance to thermal shock. Figure 6 compares instantaneous temperature changes that can cause fractures in common ceramic seal face materials.

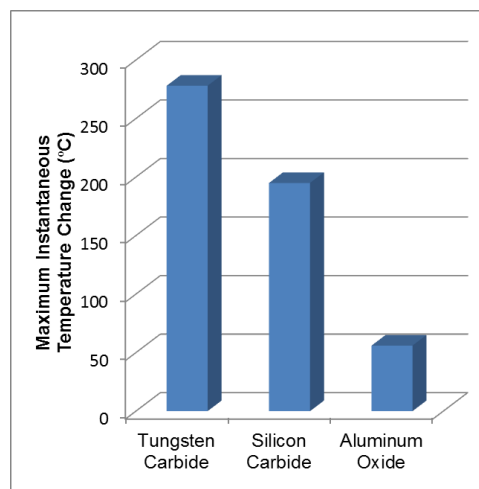


Figure 6. Susceptibility to thermal shock fracture of common ceramic seal faces

Although there are many beneficial properties of WC, there are also weaknesses. A high difference in thermal expansion rates, over 2 to 1, between the nickel or cobalt

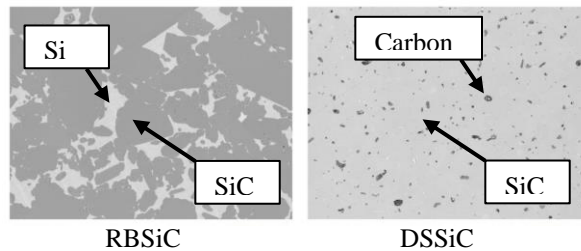
binder and tungsten carbide makes it very susceptible to surface thermal cracking, known as heat checking. In cases where lubricity is questionable or dry running is possible, combinations of WC with higher friction materials such as aluminum oxide, SiC, or WC itself should be avoided. Heat checking is far less of a concern when pairing WC with low friction opposing surfaces of carbon or diamond. Finally, both cobalt and nickel bound tungsten carbide grades are limited by the chemical compatibility of the cobalt and nickel binders. For strong acids and bases, another carbide material offers a broader range of application compatibility with one version offering near universal chemical compatibility.

### Silicon Carbides

The first creation of synthetic silicon carbide (SiC) occurred well over 100 years ago during the industrial revolution of the 1890s. It took over 80 more years for SiC to be ready for the challenging duty required by mechanical seals. The first mechanical seal use of SiC was the application of the carbide as a layer on a carbon substrate. This first step took place in the early 1970s. By the mid-1970s a solid form of SiC became available through the reaction bonding process. The reaction bonding process is detailed in the referenced paper, "Material Selection for Mechanical Seals." While the process is very repeatable, it relies on a reaction between molten silicon metal and carbon where 8 to 12 percent of the final composition is free silicon. This free silicon provides both a benefit and a limitation to reaction bonded silicon carbide (RBSiC). In one respect, the free silicon lowers the coefficient of friction versus pure SiC by roughly 10 percent when running against many common opposing seal face materials. This translates into lower seal generated heat and wear. In another respect, the free silicon provides a chemical compatibility weakness where the silicon may react with strong acids and bases. This creates a similar binder failure as metallic cemented tungsten carbide.

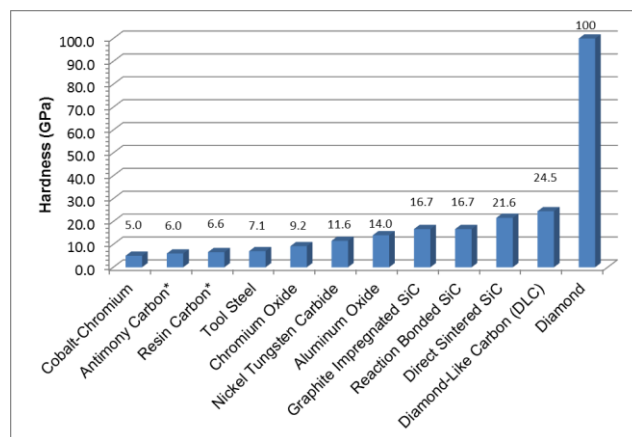
To improve the chemical resistance of SiC, a new process of direct sintering silicon carbide (DSSiC) was patented in 1979. Initial use of DSSiC in seal faces began in the early 1980s. The direct sintering process results in a 100 percent SiC material with no free silicon. The direct or self-sintering process is also described in the referenced paper, "Material Section for Mechanical Seals." The

visual difference between RBSiC and DSSiC is apparent under 100x magnification as shown in Figure 7.



**Figure 7. Comparison of SiC grades at 100x magnification**

Both SiC grades offered outstanding hardness, and even today they are the hardest solid composition seal face materials available. The extreme hardness makes SiC grades resistant to both wear and three-body abrasion damage. Often times, for the harshest slurries, SiC seal faces are chosen for both seal faces to resist abrasive wear. Figure 8 compares the hardness of silicon carbide grades and several other seal face materials.



**Figure 8. Hardness of seal face materials**

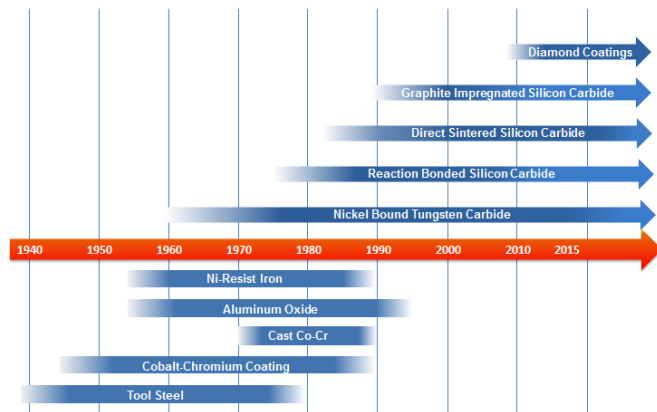
*\*Due to the low modulus of elasticity, carbon grades are tested using a scratch test rather than an indentation test. The carbon results are therefore not directly comparable.*

In the 1980s it was thought that SiC offered almost every important material property seal vendors were looking for except low friction. By the late 1980s and early 1990s several grades of graphite impregnated SiC were developed to solve this challenge. Graphite impregnated SiC is a heterogeneous mixture of free graphite and either RBSiC or DSSiC. Early testing showed weakness in cohesive bonding of the carbon and RBSiC mixture and subsequently inter-material failure. Graphite impregnated DSSiC has a more tightly bonded microstructure, which



lead to its dominance between the SiC/graphite composites. Graphite impregnated SiC achieves the promise of high harness with low friction. Due to its lower modulus of elasticity compared to RBSiC or DSSiC, concerns over inter-material bond strength, and its random distribution of graphite particles, graphite impregnated SiC has not been able to reach the usage levels of the other SiC grades.

Within the hard seal face materials, refineries and petrochemical plants have largely standardized on RBSiC as their standard hard face material. DSSiC is applied sparingly for strong acids and bases and WC is generally reserved for heavy oils and applications requiring fracture-resistance. In more chemically demanding industries, DSSiC has been established as the standard hard face material grade. To date, graphite impregnated SiC has not found its place in the chemical, petrochemical, and refinery markets, although it is widely applied in general industry applications.



**Figure 9. Timeline of the introduction and extent of popular use for a number of hard seal face materials.**

While this application philosophy has been in place for several decades, the history of hard seal face materials shows a constant evolution. The number of seal face materials in common use today is easily equaled by the number of materials that have been abandoned. Figure 9 shows periods of popular use for several historic and modern seal face materials.

Numerous recently developed materials promise higher performance than traditional materials. These new, advanced materials create many interesting directions for the industry to take. One promising material already taking hold is diamond coating. Diamond coating is

applied to the running surface of a DSSiC face. By using diamond in this way, the benefits of diamond can be realized at the running surface, while the benefits of DSSiC including: inertness, stiffness, availability, cost, and thermal conductivity can be realized in the bulk material.

**MECHANICAL SEAL ENHANCEMENTS:  
1980 - PRESENT**

The current era of mechanical seals from 1980 to the present represents a rapid expansion in seal face technology, development tools, and materials. This era coincides with advancements in computer aided design (CAD), Finite Element Analysis (FEA), and Computer Numerical Control (CNC) machining. These capabilities aided seal manufacturers in developing new seal technology with greater capabilities than ever before. Notably, the 1<sup>st</sup> Texas A&M Pump Symposia in 1984 included a lecture on mechanical seal face design using mathematical modeling.

These new computing capabilities enabled seals to be designed for better reliability on poor lubricating fluids at high temperatures and high pressures. The new tools introduced the capability of supporting seal faces with gases in addition to liquids. This revolutionized the compressor and agitator industries and had applications in pumps for dry running containment seals and zero emissions dual seals that could be pressurized by an external gas such as nitrogen.

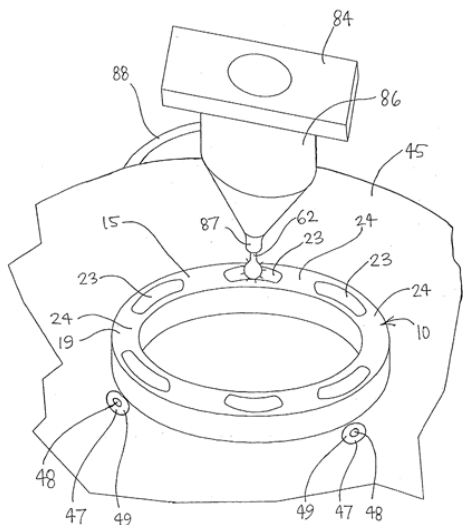
*Face Materials Create Seal Advancements*

Manufacturing improvements from seal face material manufacturers over the decades have created highly consistent materials that produce repeatable performance in mechanical seals. This repeatability has enabled mechanical seal manufacturers to utilize FEA to analyze and predict the performance of a mechanical seal in critical applications. This tool, and other specialized seal analysis software, has become important as today's industrial plants strive to maximize plant uptime while minimizing the cost of maintenance. It is well known that industrial pumps are most often pulled from service for maintenance when a seal leak is detected; therefore pump reliability depends on seal reliability. For many applications with high pump reliability, it is becoming common for new plants to forego installing spare pumps and instead rely on one pump to achieve a lower plant

construction cost. This makes the performance of that single pump extremely critical, and more specifically that pump's mechanical seal. Simply put, the quality and consistency of modern seal face materials is the foundation for establishing dependable seal performance, raising pump reliability, and enabling users to eliminate unnecessary pump redundancies.

Consistent material performance allows mechanical seal manufacturers to offer new solutions to existing problems through upgrading existing products or developing new ones. The best example of this is the development and operation of the gas lift-off seal. During operation the faces need to remain flat to each other in a non-contacting state. The added topography feature must be consistent to separate the seal faces reliably. If the material was inconsistent, then the topographical feature may not perform as designed. Material inconsistency may also cause unplanned distortions or material corrosion that could lead to erratic seal performance.

Consistent materials allow for repeatable performance between seals of the same type and size, as well as the development of new sealing solutions. This allows mechanical seals to be applied in higher duty applications. Figure 10 shows an example of one method to apply seal face topography using a laser. Other methods such as milling and micro-abrasive blasting are also used.



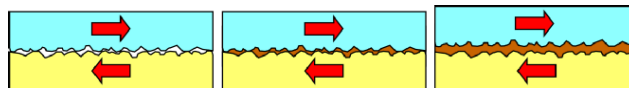
**Figure 10. Method for creating seal face surface topography. US Patent # 20,030,209,859**

## CONSIDERATIONS FOR SELECTING TYPICAL FACE MATERIALS

The wide range of different materials available for mechanical seal faces makes choosing the right face combination seem difficult. It is even more intimidating knowing that the wrong combination of materials may lead to premature seal failure, which in turn leads to significant costs due to replacement of the seal, downtime of the pump, and potential damage caused to the equipment.

Each mechanical seal requires at least two opposing seal faces. They are typically categorized as either a soft vs. hard or a hard vs. hard combination. The first question to ask when trying to choose the combination is: Do the faces need to have self-lubricating properties?

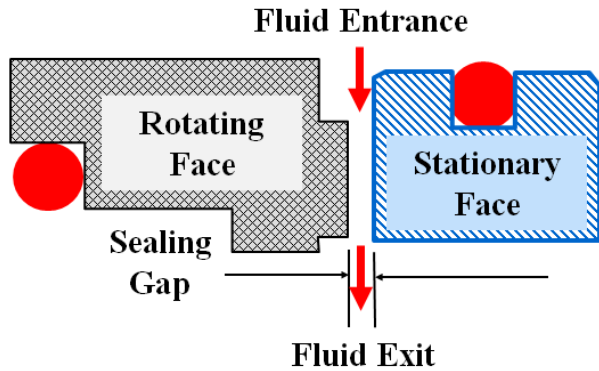
Soft vs. hard seal face combinations are traditionally used in boundary lubricated and mixed lubrication modes that require self-lubricating properties. The face materials will contact each other and good tribological pairings prevent the seal faces from causing significant damage to each other. Hard vs. hard faces are typically applied in full fluid film applications that do not necessarily need good tribological properties since the face materials should not come into contact. Examples of the three lubrication regimes are illustrated in Figure 11.



**Figure 11. Left to right: Boundary lubricated, mixed boundary lubricated, and full fluid film lubrication modes**

### *Effects of Fluid Phase*

The first area of consideration when choosing seal face materials is the product phase (liquid or gas) as it enters and exits the mechanical seal sealing gap. A cross section of a typical seal face pair is shown in Figure 13 and highlights how fluid typically enters and exits the sealing gap.



**Figure 13. Typical fluid flow through the sealing gap separating two opposing seal faces**

The three basic classifications are:

- The sealed product enters and exits the sealing gap as a liquid
- The sealed product enters and exits the sealing gap as a gas
- The sealed product enters the sealing gap as a liquid and vaporizes to a gas before it exits

In the two classifications where the product exits as a gas, the lubrication mode is going to be boundary lubricated or mixed lubricated. This means the face materials selected must have good tribological pairings and are typically a soft vs. hard face combination.

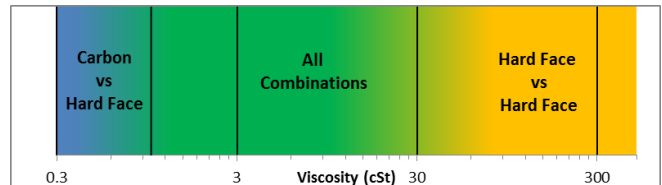
The majority of mechanical seals are applied in applications where the product enters and exits the mechanical seal faces as a liquid. The properties of the liquid are important as they have a large impact on determining the lubrication mode of operation. In particular, these types of applications depend on the fluid viscosity to choose the right materials.

#### *Fluid Viscosity*

The most common consideration for face selection is the viscosity of the fluid at the working temperature. In general, low viscosity services are more likely to operate in boundary or mixed lubrication environments and thus are most appropriately sealed with a soft vs hard face combination.

In higher viscosity fluids, the fluid creates a full fluid film lubrication mode and allows either soft vs hard or hard vs hard material combination. However, certain soft

materials, like carbon, are not recommended in higher viscous fluids due to high viscous shearing forces between seal faces which can cause a localized binder failure known as blistering. To avoid this, it is generally practical to apply a hard vs hard face combination in higher viscosity fluids. Figure 12 shows general guidance on the range of each face combination without considering other application factors or seal face topography features.



**Figure 12. Typical Selection Range Considering Only Viscosity**

Once the properties of the fluid acting between the faces is understood, the lubrication profile can be evaluated using tools such as FEA or by looking at physical evidence from a previously run set of seal faces in the exact application or in similar services.

Once the initial seal combination has been chosen using the viscosity, a few other considerations have to be evaluated to ensure the face materials will perform as expected.

#### *Abrasive Particles and Crystallization*

In dirty or contaminated applications, the properties and concentrations of suspended solids or crystallization particles becomes critical. Particles that are harder than the face material have a high potential to damage the face. When hard particles are present, face materials with a higher hardness must be selected for both seal faces.

Fluids that crystallize or salt as they migrate across the faces or salt on the atmospheric side may also cause significant damage to a soft face. If soft vs. hard faces are required in these applications, then special considerations should be employed such as selecting seal designs with the process fluid at the outer diameter (OD) of the seal face and applying API Plan 62 external quench at the ID to flush away the particles on the atmospheric side of the seal. If an external quench is not available, then the application should be evaluated with a hard vs. hard face combination, potentially using special features on the faces.

### Material Chemical Compatibility

Seal faces are exposed to a wide variety of process fluids. Some of these process fluids are aggressive and will chemically react with individual components of the material such as the base material, the binder, or filler material. Table 1 shows an overview of general chemical compatibilities of common face materials.

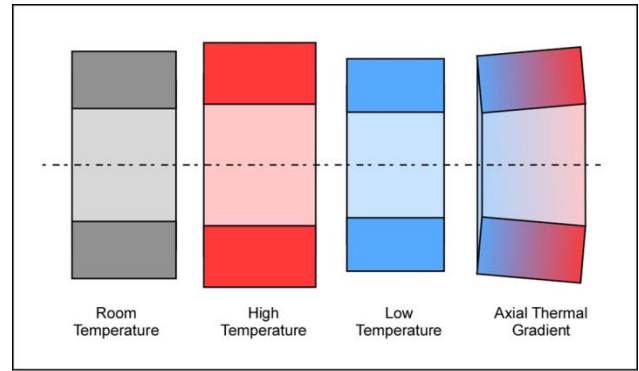
	Carbon - Resin Impregnated	Carbon - Antimony Impregnated	Carbon - Dry Running	Carbon - Acid Grade	Silicon Carbide - Reaction Bonded	Silicon Carbide - Self Sintered	Tungsten Carbide	Aluminum Oxide
Light Hydrocarbons	C	A	A	A	A	A	A	A
Heavy Hydrocarbons/Oil	B	B	A	A	A	A	A	A
Acids	B	D	B	A	C	A	B	A
Bases	B	D	B	A	D	A	B	A
Overall Chemical Resistance	B	C	B	A	B	A	B	A
<b>Note 1: Ratings should be interpreted as A = Excellent, B = Good, C = Fair, D = Poor</b>								
<b>Note 2: Ratings indicate properties when run against common seal face materials</b>								

**Table 1. Chemical Compatibility of Common Face Materials (Huebner, 2005).**

### Thermal Considerations

Mechanical seal face materials react differently to the various external and internal temperatures acting on the seal faces. External temperatures from sources such as the pumped fluid, a heating/cooling jacket, or seal cooling piping plans, all influence the overall average face temperature. Internal heat sources such as friction and turbulence can cause locally higher temperatures acting on a portion of the seal faces. These sources can lead to unwanted thermal growth or retraction and potential destruction of the impregnation or binding material.

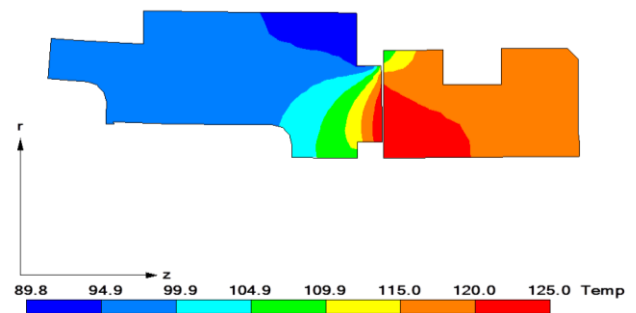
Axial thermal gradients across a seal faces can create uneven thermal expansion in the face leading to detrimental thermal coning as illustrated in Figure 14.



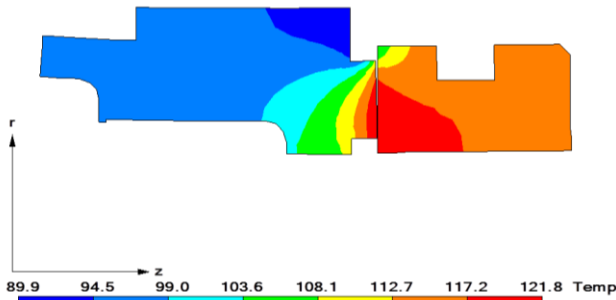
**Figure 14. Different Temperature Effects**

Thermal conductivity of the face material is an indication of how the face will effectively dissipate heat generated from the sealing gap to the rest of the face. A lower conductivity material will have a higher temperature gradient and distort the seal face in undesirable ways. Figures 15, 16, and 17 offer comparisons of net pressure and temperature distortions for three common seal face material combinations under the same conditions. The seals in these figures were run under the same operating conditions but only the left hand face material was changed. These show the resin carbon, with the lowest thermal conductivity, kept the heat trapped at the faces causing a higher temperature than the other two faces. The silicon carbide, with the highest conductivity, transferred the heat from the sealing interface, keeping the wear nose temperature the lowest.

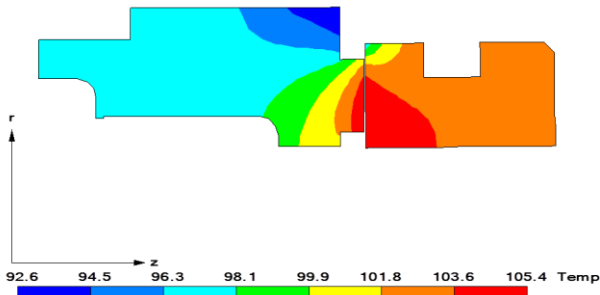
Even small temperature increases can have a large, indirect influence on the face material by changing the aggressiveness of corrosive fluids, affecting the phase change of the fluid, or decreasing the fluid viscosity.



**Figure 15. Resin Impregnated vs. Reaction Bonded SiC**



**Figure 16. Antimony Impregnated Carbon vs. Reaction Bonded SiC**



**Figure 17. Reaction Bonded SiC vs. Reaction Bonded SiC**

### *Rotational Velocity*

The rotational velocity of the seal face also impacts the choice of seal face materials. Seal face materials in the boundary lubricated or mixed lubricated mode may experience high wear rates if surface velocities are high. Reducing the wear rate may require changing the seal geometry and using material with self-lubricating properties. Higher rotational velocities also increase friction-generated heat between the seal faces and create a larger thermal gradient that causes uneven wear or higher leakage (See Thermal Considerations).

Low velocities (less than 350 RPM), when combined with lower pressures, may allow self-lubricating seal face materials to operate in a fully boundary lubricated mode of operation for a significant period of time.

### *Pressure Limits*

High operating pressures can push the limits of the face material's mechanical properties. For this reason, the materials should be evaluated against their interaction with the location and magnitude of pressure acting on the faces. This evaluation should examine if the strength of the

material is sufficient enough to prevent face fractures, especially if the higher pressure is on the inside of the face. The high pressure may require face geometry changes to the face wear nose to reduce the potential for high contact loads. The inherent self-lubricating properties of certain materials often come paired with a lower modulus of elasticity and the potential for significant pressure deformations. These high deformations should be minimized to avoid accelerated or heavy wear and higher than normal leakage.

### *Trends in Applying Face Material*

In recent history, whenever carbon is compatible with the product fluid it has been the general practice to select a hard face material such as silicon carbide or tungsten carbide versus a compliant soft material usually a grade of blister-resistant carbon. Low cost, ability to conform to the opposing face, self-lubrication properties, and low coefficient of friction are just a few of the reasons for carbon's popularity as a seal face material. However, even with these desirable characteristics, there are limits for this material such as a relatively low modulus of elasticity, poor thermal conductivity and low material hardness of the face. Table 2 compares the application advantages of carbon grades versus hard face options. The search to advance these limitations without sacrificing the excellent tribological properties has been a major driving force in the evaluation and advancement in carbon materials.

### *Face Features*

Even the best material combinations can still experience unwanted performance such as accelerated wear or high leakage. In these cases seal vendors have continued to use these combinations, but apply special considerations to meet the seal's performance expectations. Special considerations are features added to seal faces intended to change the lubrication mode toward something that achieves the desired performance of the seals. Typical features applied to mechanical seal faces include hydro pads, lube grooves, hydrodynamic grooves, waves, or in some cases creating specialized flat-face seal face geometry. The use of these features can also allow application of materials that may not traditionally be used in some services; like a hard vs. hard combination in a flashing hydrocarbon application.

	Carbon - Resin Impregnated	Carbon - Antimony Impregnated	Carbon - Dry Running	Carbon - Acid Grade	Silicon Carbide - Reaction Bonded	Silicon Carbide - Self Sintered	Tungsten Carbide	Aluminum Oxide
General Duty Service	A	C	D	D	A	A	B	C
Dry Running - see Note 2	B	D	A	C	C	C	D	B
Abrasive Services	D	D	D	D	A	A	A	C
Blister Resistant - see Note 2	C	A	D	C	A	A	C	C
Impact Resistance	B	A	B	B	C	C	A	C
Thermal Shock Resistance	A	A	A	A	A	A	A	D
<b>Note 1: Ratings should be interpreted as A = Excellent, B = Good, C = Fair, D = Poor</b>								
<b>Note 2: Ratings indicate properties when run against common seal face materials</b>								

**Table 2. Strengths and Weaknesses of Common Seal Face Materials (Huebner, 2005).**

## INDUSTRY STANDARDS

From 1954 to 1994, mechanical seal requirements for refinery services were included in the American Petroleum Institute (API) Standard 610 (Gabriel 2011). As a secondary topic in API 610, the application and design guidance for mechanical seals was very basic. One lasting contribution from API 610 was a standardized mechanical seal code indicating common seal face material pairings amongst other seal features. It wasn't until 2014 that another industry standard mechanical seal code was developed that included designations for seal face materials. Incidental, the new code contains most of the same designations as the 20 year old API 610 code.

DIN standard 24960 (now adopted as ISO standard 3069) defined standard installation envelope dimensions for mechanical seals starting in the 1970s. However, DIN 24960 offers no application or material use guidance. In 1994, API released the all new Standard 682 (API 682), the first industry standard providing broad application and design guidance particularly in the area of mechanical seals. API 682 is an end-user driven standard designed to reflect the best practices of the industry. The 1994 First Edition specified the default seal face combination as

carbon versus Reaction Bonded SiC. API 682 has broad adoption in the refining and petrochemical industries, and some adoption in the chemical, power, and pipeline industries. An unintended consequence of defining a default seal face combination in the widely applied standard was that it effectively disallows most other seal face combinations, including newly developed materials. This issue was largely addressed in 2014, with API 682 Fourth Edition, which now includes specific language to allow the use of RBSiC, DSSiC, or performance enhancing coating. Tungsten carbide and graphite impregnated SiC are also specifically allowed in API 682 with customer approval.

## SEAL FACE MATERIAL INFLUENCE ON SEAL DESIGN

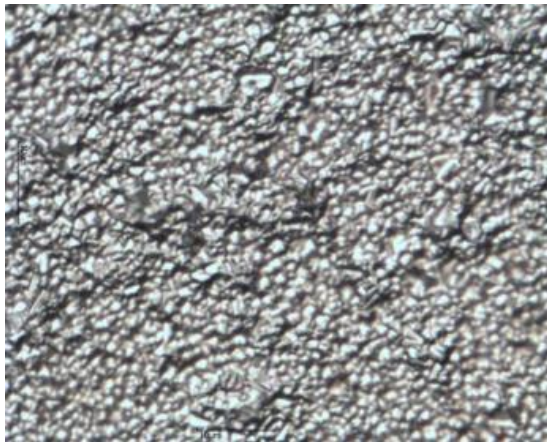
The dominant use of carbon has greatly influenced seal design. Carbon's compliance (low modulus) and self-lubricating characteristics are a benefit at the running surface where carbon can conform to exactly match a hard mating face. This compliance can mask imperfections in the seal face and enable seals to provide low leakage in many common services. Carbon's compliance becomes a major hindrance when designing seal faces for larger sizes and higher pressures. Carbon deflections due to pressure are around 10 times greater than the deflections of silicon carbide in the same shape. This means, when using carbon, seal designers are required to use larger cross-section seal faces to control flatness (at the seal face running surface) that would not be required with a stiff material such as silicon carbide. In other words, to make seals suitable for the continual increase in pump size and pressure, seal designers may need to replace carbon with a stiffer seal face material.

An additional benefit of using only stiff seal face materials is the capability to make an axially short and radially narrow seal. Most seal and pump users recognize the benefits of a pump's low shaft length versus shaft diameter (L/D). Reducing L/D has been one of the primary focuses of pump vendors for the past two decades. Unfortunately, during this same period the industry has pushed towards feature-laden dual seals that actually *increase* the required shaft length. Currently for the most common sizes, API 610 specifies an L/D for the seal chamber of 1.8 to 4.0. To shorten this further, and still provide full-featured dual seals, seal vendors will need to develop materials for seal faces that offer many of the

advantages carbon does, but with a much higher resistance to pressure distortions.

### **FUTURE OF SEAL FACE MATERIALS**

The history of seal face materials helps us predict the future of these materials. It tells us that every few decades new materials emerge and replace what was previously the best available technology. Since the early 1990s, seal vendors have been pursuing a hard face material to offer increased hardness and lower friction than traditional carbides. The latest undertaking has been in diamond coatings. Diamond is an attractive coating material because diamond has five times the hardness of silicon carbide with one fifth the coefficient of friction. These properties combine to provide the capability to resist wear from the hardest natural materials, while also generating the lowest heat of any conventional contacting face material combination. With a very large installed base of diamond coated faces already applied in industry, it is arguable that diamond coatings are already in the present discussion. Currently however, diamond coating are generally applied as a niche solution, which is well short of their potential application range. An example of an unlapped diamond coating is shown in Figure 18.



**Figure 18. Diamond coating at 500x magnification (West)**

When we think of the ideal properties for a seal face material, the properties of diamond address almost every requirement. Speculation has been made that synthetic diamond coating could replace all seal face materials within a few decades. It should be noted that man-made materials classified as “superhard” exceed the hardness of diamond, and may become a future generation of seal face

materials. At this time, no “superhard” materials are known to have been commercialized as a seal face material.

In parallel to the development in hard face materials, carbon materials are being pursued that offer increased temperature and chemical compatibility.

In order to take advantage of all the benefits of next generation seal face materials, the standard material selection practices, seal design philosophy, and seal support system requirements will likely have to be reconsidered.

In particular, the idea that inherent self-lubricating properties of certain materials must come paired with a low modulus of elasticity may be eliminated. By solving this challenge with new materials, we may be able to apply hard versus hard seal faces in the boundary and mixed phase lubrication regimes, use much smaller but stiffer seal faces, and operate seals directly on poor lubricating product fluids without cooling or external sources of lubrication. All of these goals may be achievable with a small number of advanced materials that greatly simplify the seal face material selection process.

### **CONCLUSION**

The progression in seal face technology has ranged from solid metals, plastics, Babbitt, and overlays to mechanical carbons, ceramics, advanced coatings, and surface topography. Advancement has been driven by end users’ desires to reduce leakage, extend runtimes, and improve reliability. Each step forward in seal face materials has resulted in an increase in the ability of mechanical seals to operate over a broader range of applications and operating conditions. This has also been paralleled by more advanced analytical techniques to take advantage of the properties of these new materials. Seal face material selection in the present time remains a balance between the positive and negative material properties for each application.

### **DISCLAIMER**

Throughout this paper, data on physical properties and chemical compatibility are given. This data was obtained from a number of sources listed in the references and bibliography. In some cases data may not be directly comparable and may only be representative of a family of

materials which have similar, but not identical properties. The ratings and application recommendations are the authors' opinions. Although all of the data in this paper is believed to be correct, neither the authors, nor any other entity associated with this paper, makes any claim to its use or accuracy. Users of materials of any nature are urged to obtain specific information from the OEM about its applicability in a specific application (Huebner 2005).

## REFERENCES

- API Standard 610, 1989, "Centrifugal Pumps for General Refinery Service," Seventh Edition, American Petroleum Institute, Washington, D.C.
- API Standard 682, 2014, "Pumps-Shaft Sealing Systems for Centrifugal and Rotary Pumps," Fourth Edition, American Petroleum Institute, Washington, D.C.
- Doran, J.H., 1919, "Packing for Steam Turbines," US Patent 1,315,822
- Gabriel, R. 2011, "The History of Pumps: How Seals Have Changed the Pump industry," *Pumps & Systems Magazine*, Birmingham, Alabama, USA
- Huebner, M. 2005, "Material Selection for Mechanical Seals," Proceedings from the Twenty-Second International Pump Users Symposium, Turbomachinery Laboratory, Texas A&M University, College Station, TX, pp 127-135
- ISO 3069, 2000, "End-suction centrifugal pumps – Dimensions of cavities for mechanical seals and for soft packing," Second Edition, ISO Geneva, Switzerland
- Mayer, E, 1969, "Mechanical Seals," Iliffe Books, London, England
- Miller, A.H., 1992, "People, Products and Progress: The Durametalllic Story," The Pricilla Press, Allegan, Michigan
- Paxton, R.R., 1979, "Manufactured Carbon: A Self Lubricating Material for Mechanical Devices," CRC Press, Boca Raton, Florida
- West, Charlie, Diamond Coating, Digital image, *Thindiamond.com*, Advanced Diamond Technology, n.d. Web

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions from Joseph Boylan, Mike Huebner, and Ian Lincoln in the production of this paper. A special thanks goes to Flowserve Corporation for their support in this tutorial.