METHODS & PROCESSES FOR CERAMICS MANUFACTURING

A VIEW TO A KILN

CoorsTek®

IN *A VIEW TO A KILN*, we explore methods and processes used to manufacture critical technical ceramic components used in many industry applications. From aerospace to automotive, semiconductor to medical, or from electronics to energy, our mission is to make the world measurably better. Our engineers take ideas from concept to firing and finishing. Or, maybe we should say, from raw material to bond. *Ionic bond.*

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01 INTRODUCTION

INTRODUCTION | OUR COMPANY

Since the early 1900s, CoorsTek founders and ceramic engineers have continually refined the processes and methods necessary for both the design and manufacturing of technical ceramics. As our company has grown and expanded to new locations around the world, so has our expertise. It's been in our DNA since the beginning.

Using the right methods and processes for manufacturing high-quality technical ceramic components is just as essential as choosing the correct ceramic material to meet the needs of the application. From advanced material processing through to forming, firing, and finishing, this requires a high-level of control and expertise that can only be provided by a manufacturer with deep knowledge and understanding of the entire production cycle.

Because these methods and processes are so critical to achieving the properties and tolerances required by the component design, CoorsTek considers and selects the ideal combinations for each project. Processes are selected because they are the best, not because we are limited by capabilities.

HOW DO WE DO THIS?

CoorsTek meets the exacting needs of its customers by having one of the largest portfolios of processes and methods in the industry. Our experts intimately understand these processes, and it's what gives us our competitive advantage. We never force component production into an unsuitable process because of limited capabilities. Quite the contrary.

> ...EXPERTISE. IT'S BEEN IN OUR DNA SINCE THE BEGINNING.

We start with a customer's specific application requirements, and select the optimal material. The best approach is selected from our wide portfolio of methods to deliver the end product, accounting for design, volume, tolerance, quality requirements, budget, and of course—end use. It's this approach that enables CoorsTek to deliver the highest quality products while keeping both efficiency and cost in mind.

It's what we like to refer to as **The CoorsTek Way.***

WHY COORSTEK?

CoorsTek has always been at the forefront of developing advanced ceramic materials. Our experts have continually refined our manufacturing processes and methods for producing leading edge, groundbreaking technical ceramic products.

Over the last century, CoorsTek has grown into a multinational company with research and development (R&D) centers and manufacturing sites strategically located around the world. With over 400 advanced ceramic formulations, unparalleled ceramics expertise, and a dedication and commitment to innovation, CoorsTek partners with our customers to make the world measurably better.

Ready to learn more? Read on to discover the many processes and methods that CoorsTek uses. Every step in the manufacturing process is critical to producing industry-leading components for the Aerospace, Automotive, Energy, Medical, Semiconductor, and many other industries.

A POWERHOUSE OF MANUFACTURING

GLOBAL REACH
Manufacturing Sites Worldwide

400+
Advanced Ceramic Formulations

61/118
Utilizing Over 1/2 of Earth's Known Elements

Custom Solutions

*The CoorsTek Way is both a compass and map equipping team members with knowledge and ability to think, feel, and act in alignment with the company's values and strategy. We see this as the key to company growth by delivering exceptional components and service to customers around the world. For more information, visit **www.CoorsTek.com/TCW.**

02

WHAT CAN BE MADE WITH TECHNICAL CERAMICS?

WHAT CAN BE MADE WITH TECHNICAL CERAMICS?

Before we go into the specifics of the ceramic manufacturing process, it's important to understand what can be made with technical ceramics. Given that CoorsTek has over 400 material formulations and a vast array of forming, firing, and finishing options, perhaps a better question than "What **can** be made with technical ceramics?" is "What **can't** be made with technical ceramics?" The possibilities are virtually limitless, which is why we use the infinity symbol in our logo (in case you were ever wondering).

SIZE

CoorsTek is capable of manufacturing "microcomponents" with a variety of potentially microscopic features, including tiny holes, channels, or inserts. We also manufacture ultra large structural components, several meters in length.

CoorsTek can manufacture microcomponents like the components shown here up to large products like a process-tube (or p-tube) used in the reaction zones of semiconductor furnaces.

GEOMETRY

While many ceramic components are standard shapes such as tubes, balls, or flat shaped discs and squares, the geometric design possibilities for technical ceramics are practically just limited to our customers' imaginations. With forming methods such as injection molding, and a wide array of finishing and machining options, the ability to produce complex custom designs is one of the core values CoorsTek offers.

VOLUME

CoorsTek employs processes suitable for prototyping all the way to high volume production (from millions to billions). Regardless of volume, we are capable of meeting our customers' needs and requirements.

TOLERANCE

CoorsTek offers our customers extraordinary design freedom with our ability to meet tolerance requirements. We can achieve exacting as-fired tolerances of near net shapes to 0.5% through forming. For more exacting tolerances and finishes, a wide array of finishing options can be used to achieve the required precision.

CoorsTek technical ceramic components often require forming methods to handle complex geometries. Pictured is a silicon nitride turbocharger rotor.

03

POWDER PROCESSING

THE PROOF IS IN THE POWDER

POWDER PROCESSING | THE PROOF IS IN THE POWDER

CoorsTek is a virtually integrated manufacturer, starting from raw materials and delivering fully finished components to customer specifications. This integration allows us to control the material properties at each step of the manufacturing process—guaranteeing consistent, unparalleled quality.

RAW MATERIALS

All technical ceramic formulations are processed in our facilities, starting with purchased and/or synthesized raw material powders. These materials have the necessary characteristics needed for achieving the desired material properties. However, these properties are not yet achieved until we process them into components, making it necessary for the advanced materials processing to be controlled and engineered to the highest degree.

POWDER PROCESSING

Powders are processed in a manner suitable for the forming method. For slip casting and tape casting, the powders are combined with water or another chemical formulation to form a liquid. For injection molding and extrusion, the powders are combined with a plastic mix, making it pliable. Pliability is necessary to effectively force the material into a die under pressure. When the component is complete, the plastic is removed during the sintering process.

For dry powder compaction, the raw materials have properties similar to talcum powder, making it unsuitable for manufacturing due to their poor flow characteristics. Like talcum powder in a container, material tends to stick to the bottom and comes out in clumps when dislodged. To overcome this, the powder is converted into a feedstock that will flow more like a liquid. This is achieved through spray drying.

Pictured: Stainless steel drying chamber used to collect the processed powder grains after the heater dries the slurry.

SPRAY DRYING

For dry powder compaction (Chapter 6), we first process the ceramic powder using the spray drying method. CoorsTek has massive spray drying capabilities across our global facilities, allowing us to produce high volumes of numerous formulations. The goal of spray drying is to create a ceramic feedstock that flows like a liquid when dry.

Before spray drying can occur, the raw powder ingredients must first be mixed together and milled. Milling homogenizes the mixed raw materials and grinds them into a targeted particle size for distribution.

There are two types of milling: wet and dry. Dry milling creates fine powders. However, wet milling can produce even smaller particle sizes, making it useful for manufacturing a wider range of products.

WET MILLING

To wet mill a ceramic powder, a liquid is added to the raw materials during the mixing stage and then milled. Because the material is in a slurry form after milling, it is sent directly to the spray dryer to complete the processing method.

DRY MILLING

In dry milling, the materials are processed directly after being mixed; nothing further is added. However, when milling is complete, a liquid carrier is added to make a slurry. At this point the milled material is ready to be spray dried.

FROM SLURRY TO AGGLOMERATE GRAINS

The purpose for spray drying is to create a uniform sand-like, grainy substance that flows easily into the dry compaction molds. Because materials at this point are in a slurry form, they can be sprayed in a drying chamber. Using either a nozzle or a slinger at the top of the spray dryer, the slurry is atomized and the droplets fall through the heated chamber. Drying occurs before the processed powder settles to the bottom of the dryer where it is then collected for dry powder compaction.

The end result is an agglomerate of hundreds of grains of ceramic stuck together in uniform sized balls. The processed powder can then be compacted to a set shape prior to locking in the intended ceramic properties during the sintering process.

A cylinder ball mill, like the one shown here, grinds the raw ceramic powder before adding it to a liquid for spray drying.

OUR BINDER SYSTEM

Our vertically integrated manufacturing systems are unique within the technical ceramic industry. In addition to processing and milling our own ceramic powders, CoorsTek has developed its own binder systems. Binders, or binding agents, are often necessary to hold the ceramic powder together in its "green form" (Chapter 5) prior to sintering the product.

The ability to produce and customize our ceramic feedstock by changing and modifying our proprietary binder formulations and milling processes offers a number of advantages to:

Control material properties.
We are able to control the material properties (mechanical, thermal, electrical, and chemical)* without having to manage expensive and time-consuming changes to hard tooling.

Create complex geometries with less processing.
Thick or differential cross sections can lead to cracking in fired components. By adjusting binder amounts we can create more complex geometries during the green forming process. This reduces or eliminates secondary processing or finishing operations making production more efficient.

Manufacture components with high accuracy.
For injection molded parts, modifications to the binder system allows us to adjust material viscosity (or mold flow). This ensures better mold fills, leading to higher part accuracy and efficient yields.

*To learn more about the material properties for technical ceramics, please download our free eBook The Powerhouse of Advanced Material: Ceramics at **www.CoorsTek.com/Why-Ceramics.**

04

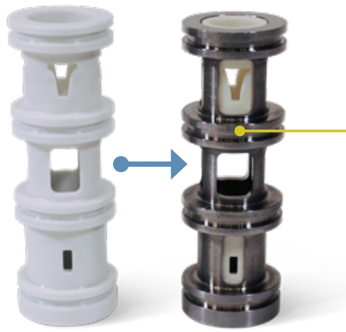
DESIGN FOR MANUFACTURABILITY

DESIGN FOR MANUFACTURABILITY

CoorsTek ceramic experts carefully consider each of our customers' projects and designs in advance of manufacturing in order to optimize cost. We actively seek opportunities to modify designs while maintaining functionality and preserving quality. Our design engineers consider a variety of options to design for manufacturability, including using alternative materials, avoiding unnecessarily tight tolerances, or employing lower cost forming methods.

Reducing grinding or other costly finishing methods can greatly reduce overall component cost. Ceramic grinding is often one of the most intensive manufacturing processes. If we can reduce or eliminate grinding operations by modifying component design, we can reduce the overall cost to manufacture.

In some cases, CoorsTek engineers may even recommend a complete design overhaul—suggesting alternative materials for a portion of the design and only using highly engineered ceramics in the areas where strength, electrical resistivity, or one of the many other advantageous ceramic properties is absolutely necessary.



Pictured here are spool valve sleeves made with zirconia for industrial gas manufacturing. The original component design was modified to reduce the amount of ceramics needed, reducing overall cost.

05

FORMING METHODS

FORM FOLLOWS FUNCTION

FORMING METHODS | FORM FOLLOWS FUNCTION

CoorsTek has a wide range of prototyping and processing capabilities using a variety of technical ceramic component forming methods. This variety creates an advantage over other manufacturers for unique and specific product development and manufacturing requirements. Our engineers can identify the best forming method for the components and production volumes needed by our customers, preventing the use of a less than optimal forming method due to lack of expertise or equipment.

Throughout the world, CoorsTek has immense forming capabilities and expertise that can be specifically geared to handle almost any geometry and production requirement. Working directly with a customer's team, our engineers identify the most efficient method for their unique requirements. No matter what your component design may be, we likely have a forming process that will fit your needs.

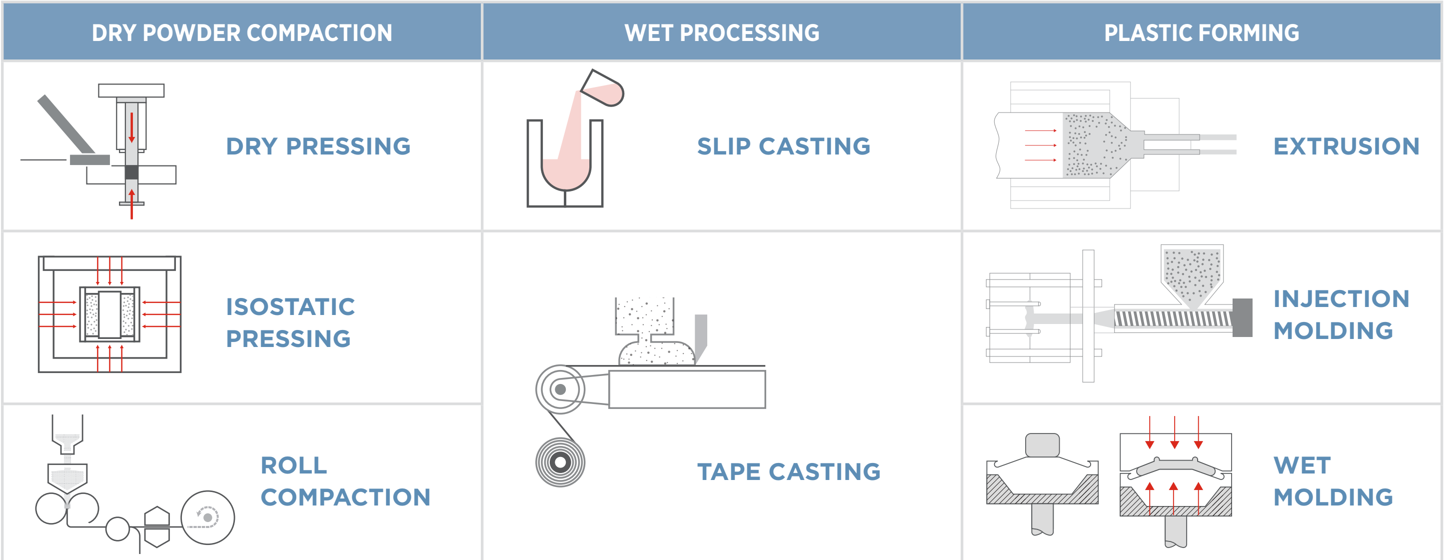
THE TRIFECTA OF FORMING METHODS

There are three primary technical ceramic forming method categories: dry powder compaction, wet processing, and plastic forming. Within each of these categories, there are unique subsets of process variations. Additionally, CoorsTek does green forming for both prototyping or highly complex component designs.

GREEN FORMING

The most common approach for prototyping components is green forming. A green part is an unfired, porous powder compact, similar to chalk. While the component is in this chalk-like state, excess material can be removed efficiently to finalize the shape before it is fired in a kiln.

For prototyping, simple geometric blanks can be created using existing or low-cost tooling.



Pictured here are the three methods, along with the variations within each of them, CoorsTek uses in its manufacturing and prototyping processes.

The final pre-fired geometry is then created with green forming. This can range from simple work using a green saw (bandsaw) to hole drilling to highly complex 5-axis CNC milling.

Though frequently used for prototyping, green forming can occasionally be the best approach for higher volume manufacturing. For example, if a part is too complex for dry pressing, a custom blank with most of the final features may be pressed. Additional features that are not amenable to dry pressing can then be added during green forming.

Over the next three chapters we will explain the three major forming categories and various sub processes.

06

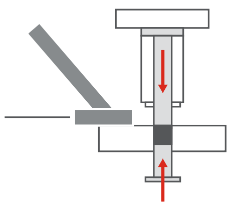
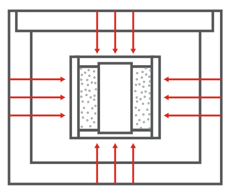
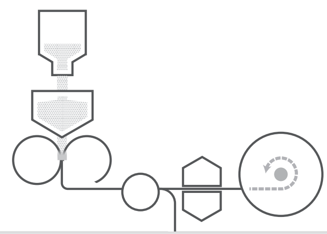
FORMING METHODS

DRY POWDER COMPACTION

FORMING METHODS | DRY POWDER COMPACTION

The first forming method is Dry Powder Compaction, which includes three different pressing sub-processes to best suit the target geometry. These sub-processes are dry pressing, isostatic pressing, and roll compaction.

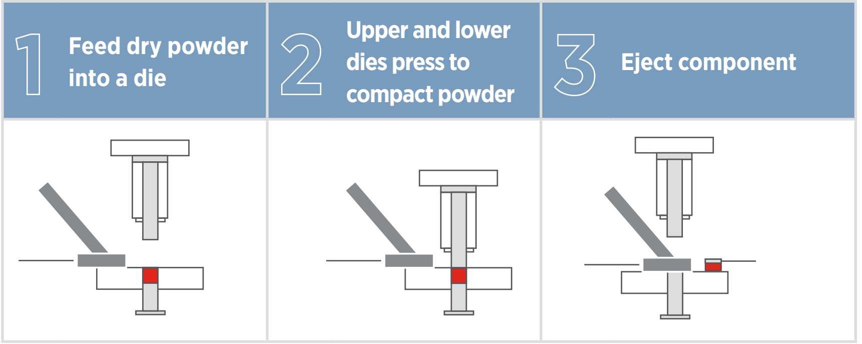
Because the raw materials for dry powder compaction have properties similar to talcum powder, they are unsuitable for manufacturing due to poor flow characteristics. To overcome this, the powder is converted into a feedstock that will flow more like a liquid when still dry (Chapter 3). After the powder is processed, it is ready for use in the dry powder compaction process.

DRY PRESSING	ISOSTATIC PRESSING	ROLL COMPACTION
		

Pictured are the three dry powder compaction methods: dry pressing, isostatic pressing, and roll compaction.

DRY PRESSING

When high volume, custom components are required, dry pressing is an excellent method to use. CoorsTek is able to manufacture millions of components at locations around the world with pressing compaction operations ranging from two to 1,500 tons.



Pictured here is the three-step process used in dry powder compaction manufacturing.

Dry press tooling contains a die, ejector, punch, and fill shoe. The pressing operation starts when the fill shoe deposits ceramic powder into the die cavity and then retracts to level off the material with the top of the die. The ejector below the die cavity lowers, dropping the powder beneath the die surface. The punch moves into the die cavity.

The punch and ejector then close the distance between them to compact the powder. After full compaction, the punch retracts and the ejector pushes the pressed part from the die.

Finally, the fill shoe moves over the die, pushing the part away from the tooling and deposits ceramic powder into the die to repeat the cycle.

After pressing, oxide components typically do not require a separate de-binding operation. The amount of binder used is small and the pressed part still has open porosity to facilitate binder burnout during the front end of the sintering profile. For non-oxides, the sintering kiln environment may not be appropriate for binder removal. A separate binder burnout step may be required.

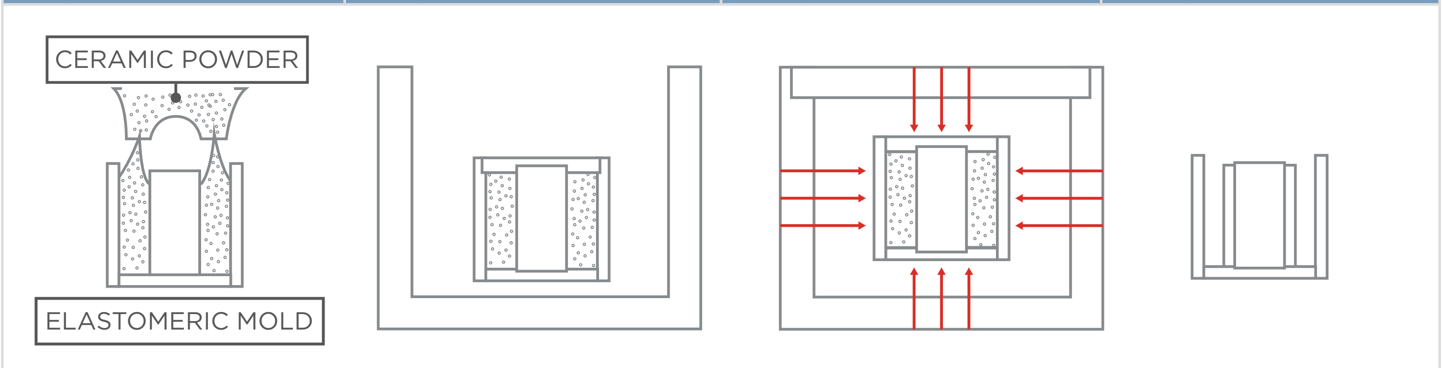
Dry pressing can be readily automated for high volume manufacturing and is able to produce anything from simple shapes to highly complex geometries where core rods and die inserts are moving independently of the punch and injector.

ISOSTATIC PRESSING

Isostatic pressing is a method that applies equal pressure in all directions while compacting the ceramic powder. It is an excellent method for low and medium volume production. High volume production can be accommodated with special press and tooling considerations.

This method is also advantageous for some larger geometries. Compaction is amortized over three directions in this process, as opposed to dry pressing where all of the compaction is one direction.

1 Feed powder into mold	2 Seal and apply hydraulic pressure	3 Powder compacts to form solid component	4 Release pressure & remove component



Shown here is a tube being manufactured using the four-step wet bag isostatic pressing method. This method is ideal when uniform density and component structure is required..

The same type of spray dried ceramic powder used in dry pressing is used in isostatic pressing.. However, the powder is sometimes engineered with minimal material characteristic differences to add efficiency to the process.

In isostatic pressing, the tooling or mold is an elastomeric sack. The mold is filled with ceramic powder, sealed off, and placed inside a pressure chamber with liquid (typically water) surrounding it. The liquid medium is then pressurized, which acts on the mold to compact the powder.

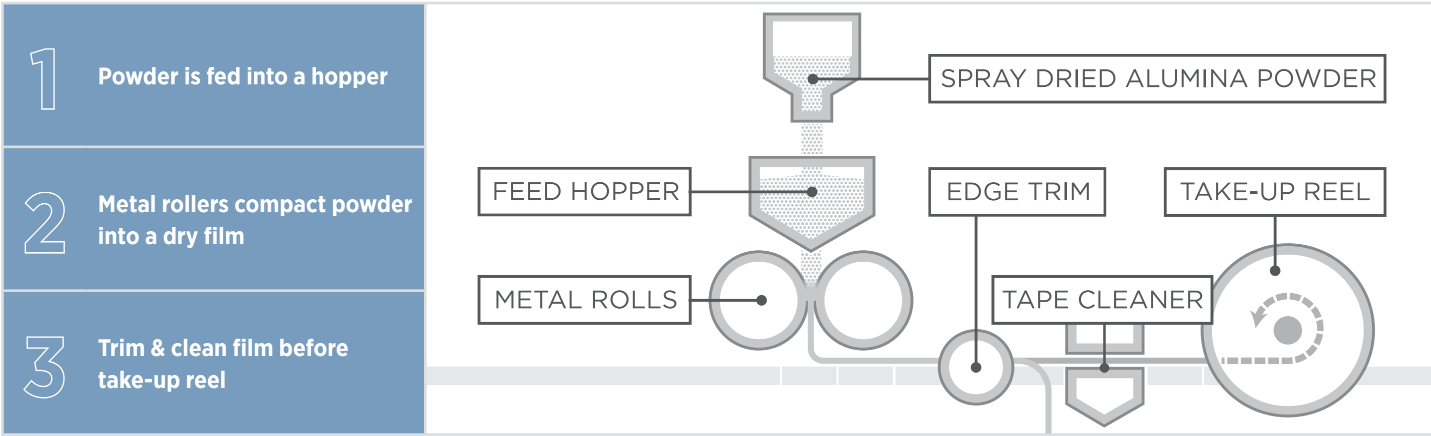
To press a technical ceramic tube, a steel arbor can be located inside the rubber sack to create the inside surface of the component. Because the hydraulic pressure is equal in all directions, parts with highly uniform green densities can be achieved. This is advantageous for shrinkage control and uniformity during sintering. Depending on production volumes required, and compaction pressure needed, CoorsTek engineers will either use wet bag pressing or dry bag pressing in this method.

DRY BAG VS. WET BAG PRESSING

For low to medium level production rates, wet bag pressing is generally preferred. Higher production rates can be achieved for this process by using cluster sacks. This enables more components to be pressed simultaneously during the same cycle. Because the liquid fills around the elastomeric mold, no matter what the sack looks like, it can use any press large enough to accommodate the mold.

Conversely, dry bag pressing is generally used in higher volume isostatic pressing and can only use tooling specifically designed for the press used. This method uses a rubber sack inside of the press holding back the liquid. The outside of the press tooling must be specifically designed to fit the inside sack within the press. When pressure is applied, the outer sack (in the press) pushes the inner sack (the mold) to compact the powder.

Because the tooling remains dry, faster pressing cycles are possible and can be more readily automated. For high volume production, multi cavity, fully automatic dry bag presses can be employed.



The roll compaction process uses three steps to produce ceramic tape and thick-film substrates used in electronic components.

ROLL COMPACTION

The third method of dry powder compaction is roll compaction. This process is most often used for manufacturing ceramic substrates.

Spray dried ceramic powder, using an additional binder to make the composition highly plastic, runs continuously between two rollers. The plasticized ceramic material is squeezed between the rollers to press it into the desired thickness. Typically, the edge of the tape is unusable due to the material's plasticity. This excess is cutoff and recycled.

The compacted material is then rolled onto a take-up reel. Afterwards, the pressed material is unrolled and sent through a kiln for binder removal and sintering.

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FORMING METHODS

WET PROCESSING

FORMING METHODS | WET PROCESSING

The next category of forming methods is wet processing. This process is used to manufacture components ranging from igniters to body armor to substrates for electronic devices. There are two categories in wet processing: slip casting and tape casting.

SLIP CASTING

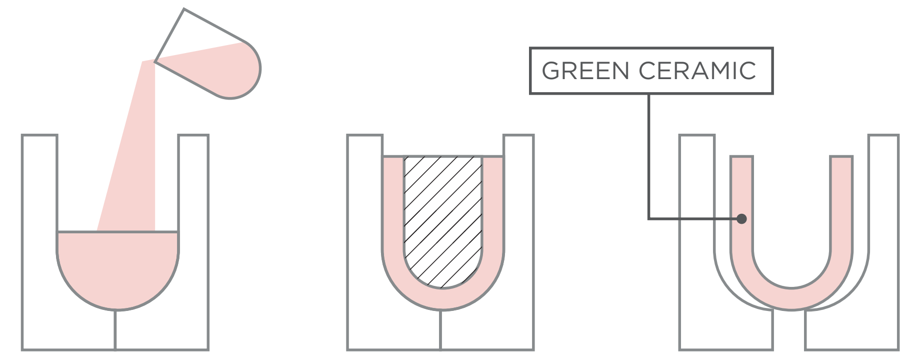
Slip casting, a technique used for making conventional pottery, is also used for forming technical ceramic components like body armor. Though CoorsTek no longer makes pottery, this method is seen throughout our company's history and still used today.

The slip casting method is used for the production of body armor that protects our service men and women, along with first responders. Pictured here are torso body armor plates.

1 **Pour slip (suspended ceramic powder) into a porous mold**

2 **Mold extracts liquid, solid forms on mold walls**

3 **Drain excess slip & remove the dried green part**



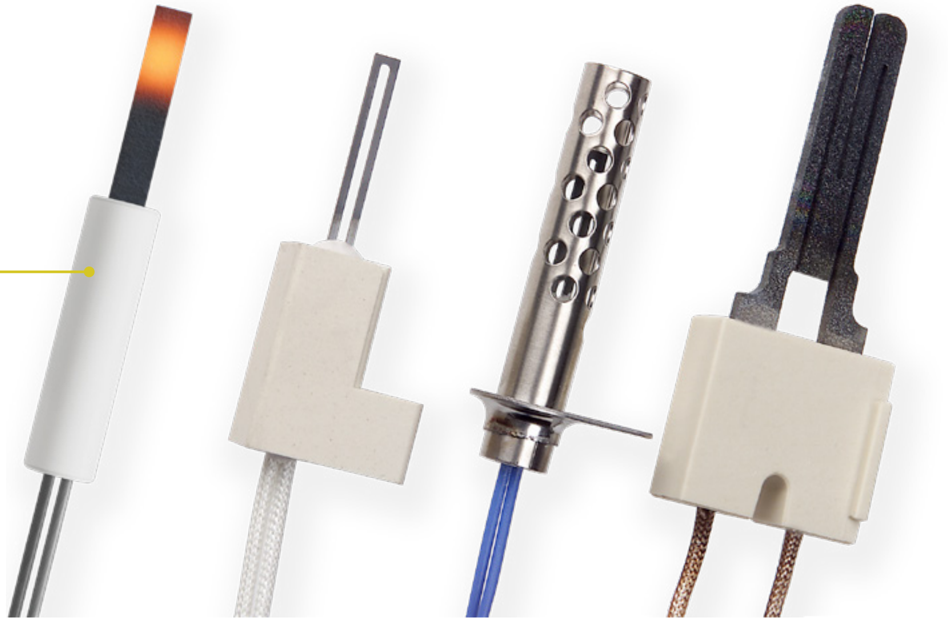
Pictured here is the three-step process for slip casting.

The process begins by dispersing a ceramic powder inside a liquid carrier to make a slurry, or slip, which is then cast into a porous mold. The capillary forces of the mold pull liquid into the porosity, and the ceramic particles, which are larger than the pores, cast against the mold wall and build up in thickness. When the target thickness is reached, the excess slip is drained, leaving a green component ready for firing in a kiln.

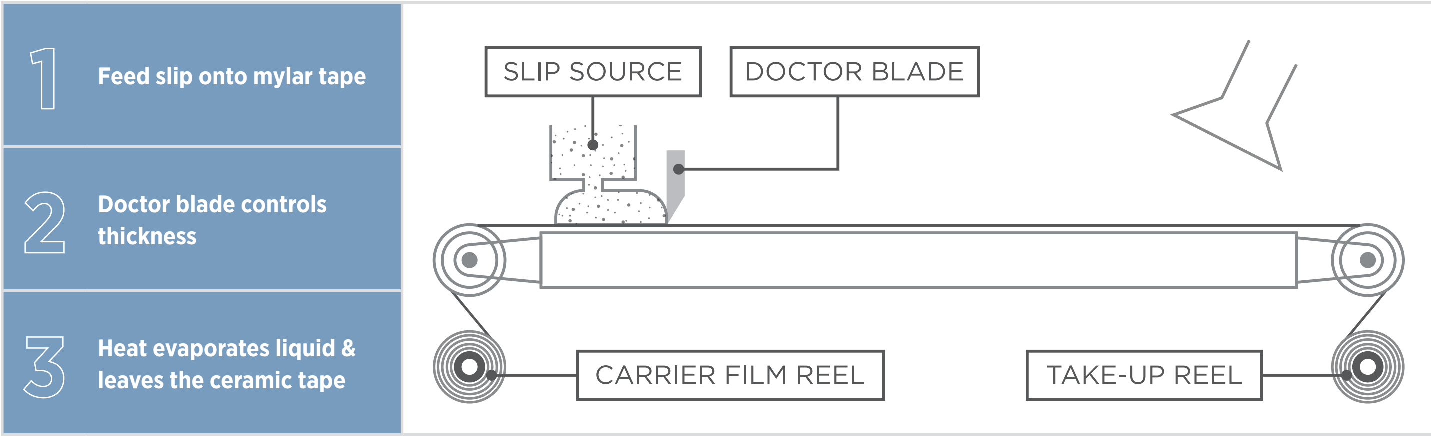
For higher volume production, the rate of casting can be accelerated through the application of external pressure. This is called pressure casting. A porous plastic mold is often used to provide the strength needed for higher casting pressures.

TAPE CASTING

For high-end, thin-film ceramic substrates, tape casting is the preferred method. Unlike roll compaction used for thick-film tape, this process is more suitable for lithography-based electronic circuits. This method is also used to manufacture components like those needed for igniters.



Tape casting is used in the manufacturing process for igniters. Pictured is a family of igniters used in applications such as gas heating systems, ovens and ranges, and dryers.



Pictured here is the three-step process for tape casting.

Tape casting is similar to slip casting. To make the tape, a ceramic slurry is cast onto a moving sheet of mylar. The mylar moves the slurry under a doctor blade to set the thickness of the tape. The tape is then added to a reel, similar to roll compaction, and sent for firing.

08

FORMING METHODS

PLASTIC FORMING

FORMING METHODS | PLASTIC FORMING

The third category of technical ceramic forming methods is plastic forming.

In plastic forming, the feedstock material is ceramic powder dispersed within a plastic medium. This mixture is then forced into a die under pressure to shape the component.

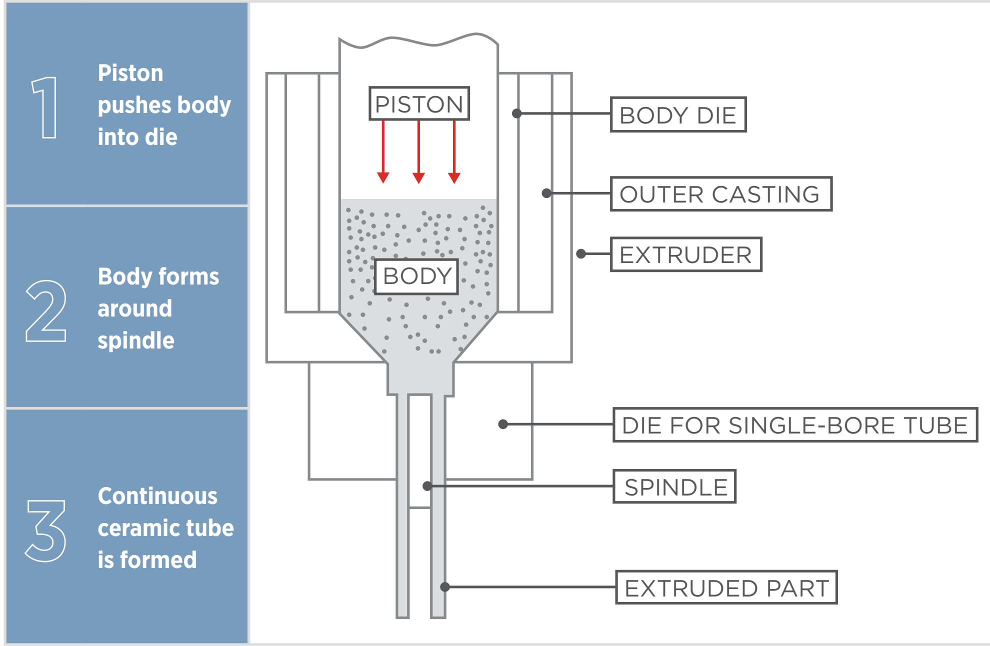
There are three different processing methods for plastic forming: extrusion, injection molding, and wet processing.

Extrusion is used to manufacture high-performance technical ceramic tubes and rods for a variety of industrial applications. Shown here are various shapes and sizes of extruded tubes and rods.

EXTRUSION

Do you remember playdough as a child? Pushing it through plastic cutouts making long unique shapes? This is extrusion. Extrusion is ideal for components with high aspect ratios, such as tubes, rods, and bars that are skinny and long.

CoorsTek has a long history of making technical ceramic tubes and rods for a variety of applications. We extrude hundreds of standard shapes and sizes and stock for catalog sales. But we also create many custom extrusions for our customers.



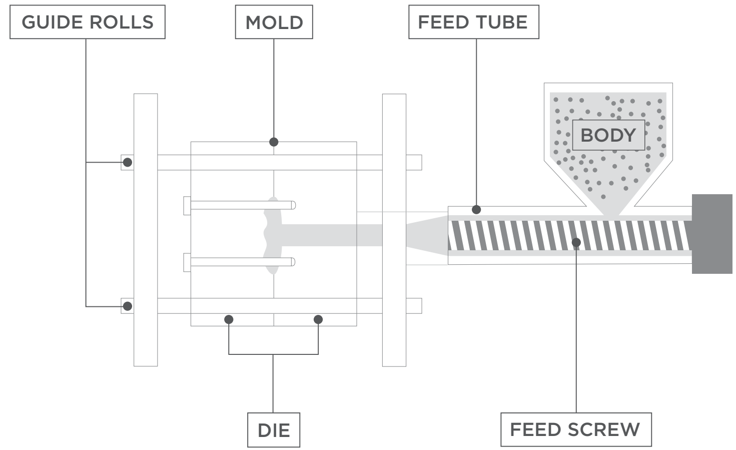
Pictured here is the three steps used for extruding technical ceramic components.

Extrusion is a continuous process making it ideal for long, straight components with constant cross-sections. The process begins with the plastic-ceramic material mixture. This plastic mix is forced through an extrusion die, then solidifies for handling prior to firing. Although extrusion is a continuous process, the extrusion is typically cut to the target length prior to firing.

INJECTION MOLDING

Ceramic injection molding is preferred for complex, three-dimensional shapes with high volume production needs. In some instances, injection molding is used for lower volume production scenarios where injection molding is best for some geometries, and where no other commercially available forming can produce the required geometry in a production environment.

1. Piston pushes body into die
2. Body forms around spindle
3. Continuous ceramic tube is formed



Shown here are the steps for injection molding, along with the different areas of the machine used in this process.

Ceramic injection molding is mostly the same as plastic injection molding. We are essentially molding a plastic that is highly filled with ceramic powder, then removing the plastic carrier after molding.

The same types of molding machines used for plastics are also used for technical ceramics. But because the ceramic powder is highly abrasive, injection molding machines are modified to replace wear components with extremely hard materials to resist abrasion and improve wear life.

The molding process starts with the plastic-ceramic mixture entering the feed screw chamber. The feed screw forces the material through the feed tube into the mold cavity. Once the shape is molded, the die separates to release the component.

In plastic molding, the part would be done at this point and the molding process complete. However, for ceramic injection molding, a de-binding operation is required before sintering to get the injected component back to its green state without plastic. Removing the plastic opens the component's porosity for applications that require this property, such as filtration.

WET MOLDING

Lastly, there is another plastic forming process called wet molding. Here the ceramic material is mixed with water, giving it characteristics similar to clay. The material is then placed between to mold platens, typically plaster, then pressed to shape. The plaster absorbs excess water forced from the component during pressing.

CoorsTek manufactures injection molded components in a wide variety of shapes and sizes as seen here.

09 SPECIALIZED FORMING

SPECIALIZED FORMING
CHEMICAL VAPOR DEPOSITION & PRESSURE ASSISTED

Chemical vapor deposition, or CVD, is the process of reacting a gas within a chamber to form a structural part. It can also be used to apply a coating on a component. These ultra-high purity ceramics are formed by layering another composition – atom-by-atom or molecule-by-molecule – onto a ceramic surface or substrate.

The CVD process takes place in a gas-tight reactor. Pre-cursor gases flow into the reactor. At a controlled temperature the gases react to deposit silicon and carbon atoms, which form into silicon carbide (SiC) on the structure. Byproduct gases are exhausted from the reactor when finished.

To create a freestanding CVD component, the SiC molecules are added layer-by-layer onto a graphite substrate until the thickness is structurally sound. The graphite tooling is then removed. When added as a coating, CVD SiC is applied onto a pre-sintered part.

Because the CVD reaction takes place at temperatures nearing 1000°C, it is necessary for the substrate material (such as graphite) to have the same thermal expansion rate as the coating. Otherwise, cracks form when cooling.

This unique process creates an ultra-high purity ceramic generally used for semiconductor fabrication.

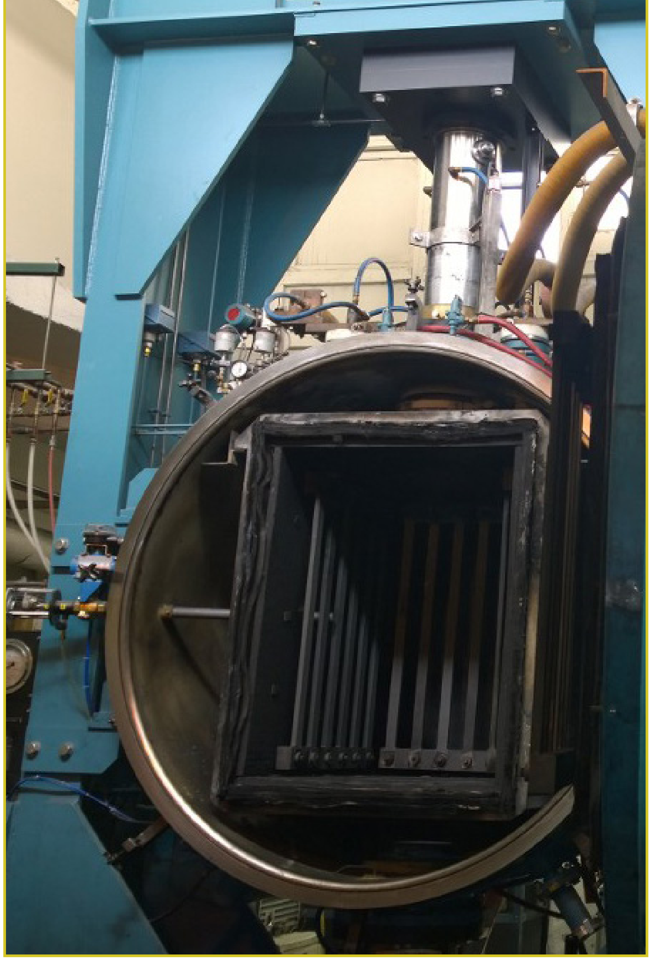
PRESSURE ASSISTED FORMING: HOT PRESSING AND HOT ISOSTATIC PRESSING

Certain materials need to be formed and fired using pressure assisted options, where both temperature and pressure are applied at the same time. These methods ensure refractory materials maintain the intended shape and material density during the firing process.

CoorsTek offers two pressure assisted forming and firing methods:

- Hot pressing applies pressure uniaxially (in one direction) during the forming and firing process, similar to the dry pressing forming method.
- Hot isostatic pressing (HIP) is similar to the isostatic forming method—employing force in every direction through a pressurized gas medium at temperature.

As this process is both a forming and a firing method, we explore it further in the next chapter on firing.



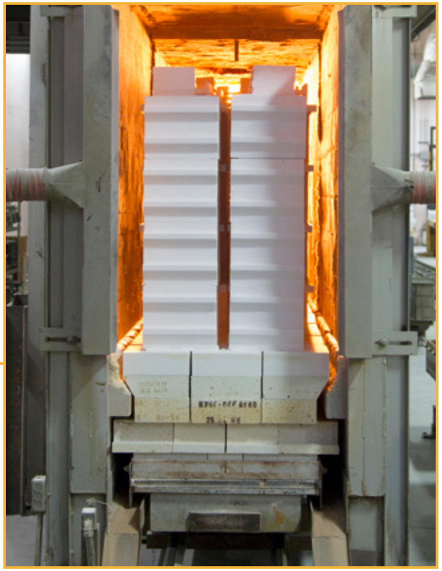
10

FIRING
A VIEW TO A KILN

FIRING | A VIEW TO A KILN

CoorsTek has literally hundreds of production kilns throughout its facilities worldwide that are suited to particular projects, expanding our manufacturing options and capabilities well beyond what is available from smaller producers. Combined with the availability of over 400 material formulations, numerous forming and finishing methods, firing is yet another way that ceramics can be customized to fit the exacting requirements for your design.

There are several different types of kilns suitable for different material formulations and requirements such as production volume, density, and cost, allowing our engineers to select the most advantageous techniques for optimal end results.



CONTINUOUS KILNS

Continuous kilns, also called tunnel kilns, provide the most economical firing method for large volume production runs. These kilns run train-like cars on a track through a continuous chamber (or tunnel), sintering the product for long periods of time as they move through. This method is generally used for high volume oxide ceramics, but it is possible to have controlled atmosphere firing in a tunnel kiln for non-oxides.

PERIODIC KILNS

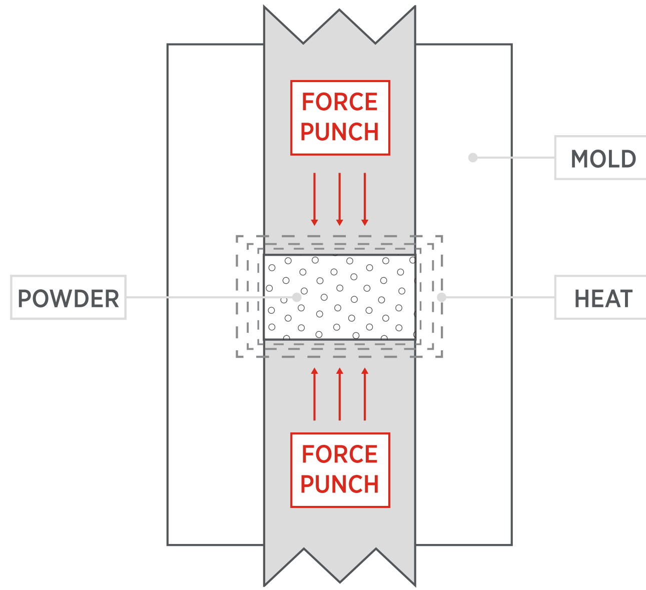
Periodic kilns are better suited to smaller volume productions. Products fired in these kilns remain stationary throughout the process, and the kiln is fired and heated with each production batch. These kilns are advantageous for firing several different products, as it is possible to change the kiln temperature and firing time with each cycle. There are several different types of periodic kilns, including, hot presses, hot isostatic presses, and atmospheric or vacuum furnaces.

PRESSURE ASSISTED FORMING AND FIRING: HOT PRESSING AND HOT ISOSTATIC PRESSING

Certain material compositions are too refractory (resistant to heat) for firing with only high temperatures. These materials can be fired using pressure assisted options, where both temperature and pressure are applied at the same time. These methods ensure refractory materials maintain the intended shape and material density during the firing process. CoorsTek offers two pressure assisted firing options: hot pressing and hot isostatic pressing.

HOT PRESS KILNS

Hot press kilns apply pressure uniaxially (in one direction) during the firing process, similar to the dry pressing forming method (Chapter 6). Hot pressing is used for any material composition that requires pressure assistance for densification and is amenable to the geometric requirements such as simplified shapes with minimal curvature, like plates and rings.

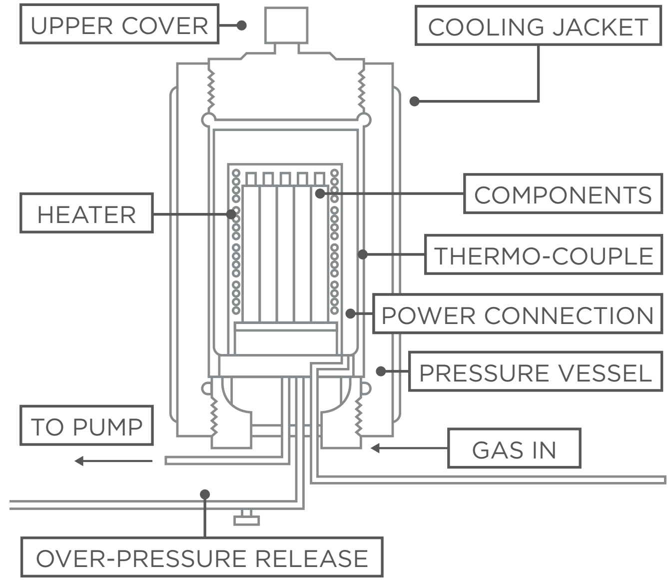


The process starts with feeding the dry powder into a graphite mold. Graphite tooling is necessary, as it is one of the few materials that can survive the high heat environment. Heat is then applied while the punch applies the axial pressure. The densified, fired part is then removed from the kiln.

To scale up production using the hot press firing method, multiple parts can be pressed simultaneously by spacing them within the die and using multiple hot press tools within the same press. Doing this enables CoorsTek to offer some of the most optimized hot pressing capabilities within the industry for higher volume production.

HOT ISOSTATIC PRESSING (HIP)

Hot isostatic pressing is similar to the isostatic forming method—employing force in every direction through a pressurized gas medium at temperature. Ceramic powder or a pre-sintered ceramic body are inserted into a steel vessel. The vessel is then filled with an inert gas such as argon, or in certain cases, nitrogen. A combination of heat and pressure are applied within the chamber to press the part from all directions. The densified, sintered part is then removed from the chamber.



ATMOSPHERIC AND VACUUM KILNS

Non-oxide ceramics such as nitrides and carbides require specialized firing environments. For these materials, CoorsTek operates atmospheric or vacuum furnaces which provide a stable environment for sintering.

Oxide materials, as implied by the name, are already oxidized so they do not react catastrophically when fired in air. Non oxides, however, must be fired in a vacuum or inert environments. Otherwise, they will react to form another composition.

Vacuum and atmospheric furnaces prevent the atmosphere from interacting with and changing the properties of the materials during the firing process. If fired in air, silicon nitrides (Si_3N_4) would form into glass (SiO_2). Aluminum Nitrides (AlN) would form into Aluminum Oxides.

Atmospheric kilns are used for sintering materials in a controlled environment to prevent changes to the ceramic material properties.

11

FINISHING

FINISHING

To meet tight tolerances and achieve requirements for precision applications, ceramic finishing is often necessary. CoorsTek offers a multitude of finishing options including several methods of shaping, coating, assembly, and other specialized methods. Each component CoorsTek manufactures is customized to customer specifications.

MACHINING

Some geometric features maybe be logistically difficult to create during the forming process, often requiring additional shaping after firing is completed. This can be accomplished through a variety of methods, including grinding, laser cutting, lapping, tumbling, and polishing.

Grinding is the most common shaping method and is especially effective at achieving precision tolerances. CoorsTek employs several different types of grinding machines, including 5-axis CNC routers, 5-axis vertical machining, and 5-axis high speed machines, as well as milling machines and lathes.

Free abrasive machining processes, such as lapping and polishing, are essential for creating exacting flatness on components such as ceramic substrates used for electronic circuitry. CoorsTek provides secondary diamond head lapping and polishing down to surface flatnesses of <2-3 helium light bands. (1 He light band = 0.3 microns)

Laser and waterjet machining are used to create complex cut-outs and precise edges for substrates and other applications. Tumbling is a common method used to break down sharp edges of components.

CoorsTek has over 1,000 shaping centers available throughout the world to serve its customers.

ASSEMBLY: BRAZING, BONDING, AND OTHERS

Numerous options are available for assembling ceramic components with other ceramics, metal, or other materials. A common method for assembly is brazing and bonding.

Brazing bonds ceramic to metal by creating a thin, uniform joint between the two components. Assembly can also be achieved with specialized adhesives and epoxies, as well as chemical bonding, soldering, and mechanical assemblies such as screws and bolts.

Interference fitting is often employed for ceramic-metal assemblies where the ceramic is housed by a larger metallic component. In most instances, this is done by shrink-fitting. The thermal expansion mismatch between the metal and ceramic materials creates a clearance for assembly at an elevated temperature. When cooled, this creates the appropriate interference between the two materials.

Some technical ceramic geometries are too complex for conventional forming methods but can be created by co-sintering two or more ceramic components together. With this method, it is possible to create a monolithic piece with a hermetic seal between the ceramics. When viewing the chemical properties under a scanning electron microscope, it is virtually impossible to distinguish between the separate ceramic parts and the area where the bond has been created.

In addition to machining and assembly, coatings can be applied as part of the finishing process. In the next chapter, we explore the various coating methods CoorsTek can apply for a variety of applications.

Hermetically sealed ceramic-ceramic joint.

12

COATINGS

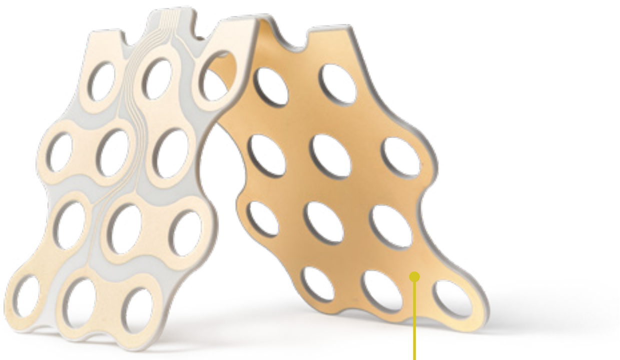
COATINGS

Ceramic coatings are useful for numerous applications, generally providing enhanced or specialized material properties such as increased electrical insulation, corrosion resistance, or increased purity.

METALLIZING

Metallizing is a secondary process used with mainly oxide ceramics, and is accomplished by applying a thin layer of refractory metal paste to the ceramic surface which is then fired to create a strong bond with the ceramic. Subsequently, the refractory layer is plated with metallic compositions suitable for brazing.

CoorsTek provides reliable and cost-effective metallization solutions for common applications including electronic circuit pathways on high-purity substrates. It is also useful for other applications including antennas, x-ray tubes, and feedthrough insulators.



Metallized aluminum nitride component for energy recovery in automotive applications.

GLAZING

Glazing is used to put a glass overlay onto a ceramic component. This is often used to achieve a high polish finish resistive to dust and dirt—helpful in outdoor industrialized applications such as electrical insulator components.

PLASMA SPRAYING

Plasma spray coatings are used mainly for semiconductor applications to provide high corrosion resistance. These coatings are applied using a dry powder gun. A ceramic powder, such as yttria, is sprayed through an ionized gas environment at very high temperatures. The powder melts and hits the surface of the components as a molten particle, instantly solidifying.

CHEMICAL VAPOR DEPOSITION

Chemical vapor deposition, or CVD is both a specialized forming and coating process, where a gas is reacted within a chamber to build the ceramic material atom by atom, layer-by-layer. More information on this unique and innovative process can be found in Chapter 9: Specialized Forming (page 34).

RESISTIVE COATINGS

Resistive coatings can be used for manipulating the electrical properties of a component without compromising bulk properties such as strength and other mechanical properties. These coatings can be tailored to control the dissipative or conductive properties required by the application and are particularly useful in X-ray/XRF/XRD applications where electrostatic discharge can threaten the integrity of the component.

Resistive coating applied to a ceramic cylinder.

13 SPECIALIZED CAPABILITIES

SPECIALIZED CAPABILITIES

As a vertically integrated manufacturer, CoorsTek is able to control the entire process from powder production through shaping and/or coating. Many projects require additional processes prior to shipment. These specialized capabilities are also available in-house to ensure the highest quality possible.

PRECISION CLEANING

Precision cleaning is a necessary process for the manufacture of certain components, particularly those used in semiconductor fabrication applications, where a single speck of dust can destroy an entire yield. To prevent contamination and impurities, components are processed and cleaned in specialized areas known as cleanrooms. CoorsTek has in-house cleanrooms certified to ISO Class 6.

Cleanrooms are critical to the manufacture of high-end components like those used in semiconductor production.

INSPECTION & TESTING

CoorsTek has full inspection metrology capabilities at each of our facilities to inspect everything we produce. Our components are inspected to the levels required by our customers. Additionally, we can do functional testing upon request.

All CoorsTek facilities are certified to a minimum of ISO 9001:2015 and/or ISO 14001:2015 standards. Many facilities also have specialized certifications required by different industries, including IATF 16949:2016 for automotive and ISO 13485 for the production of implantable medical components.*

*CoorsTek Bioceramics only.

ANALYTICAL LABORATORIES

CoorsTek conducts a wide array of testing at our analytical laboratories. Housed within our renowned research and development centers, CoorsTek analytical labs conduct application development for our customers, including failure analysis of products produced by other manufacturers.

Testing can be conducted on virtually any material property, including chemical, thermal capacity, compositional, mechanical, and electrical analysis. Our state-of-the-art instrumentation is calibrated on a regularly scheduled basis and data is traceable to standards set by the National Institute of Standards and Technology (NIST).

At our in-house, state-of-the-art analytical laboratories, CoorsTek performs a wide array of material property tests. In this photo, our ceramic material is being tested for corrosion resistance.

COMPUTER SIMULATION

CoorsTek offers expert computer simulation services to help address difficult part, material, and process challenges. Simulated analysis is often quicker and more economical than running a series of physical experiments. It allows us to help our customers by improving process efficiencies and yields, speeding product development, and reducing time to market and implementation.

CoorsTek Research & Development engineers use strong collective experience to create accurate data models, perform predictive analysis, and make expert recommendations. Using computer models to simulate various conditions helps our customers understand how systems behave and why — leading to better decisions and optimized product performance. Computer modeling can be used to analyze a wide range of performance, including structural, vibrational, heat transfer, gas and liquid flow, and other linear and non-linear effects.

RESEARCH AND DEVELOPMENT

With regional research and development hubs in Japan, the United States, and Europe, CoorsTek is consistently spearheading efforts to create new ceramic and advanced material frontiers. Our customers often help us push these boundaries by presenting us with new and interesting material challenges. When our current material and process portfolios do not meet the needs of a particular project, CoorsTek engineers are uniquely qualified to develop an innovative solution.

14

SUMMARY

MANUFACTURING PROCESSES & MATERIAL PROPERTIES

SUMMARY | MANUFACTURING PROCESSES & MATERIAL PROPERTIES

Selecting the right partner for your specific application needs is critical for success. At CoorsTek, we take immense pride in our experts and their ability to pair the right technical ceramic material with our industry-leading design and manufacturing capabilities.

As a vertically integrated manufacturer with immense global capacity, unsurpassed expertise and extensive forming, firing, and finishing options, CoorsTek partners with customers to turn innovative concepts into reality. With over 400 advanced ceramic compositions, and one of the broadest manufacturing portfolios in the industry, our engineers can start with your most demanding requirements and work back to find the right material and process.

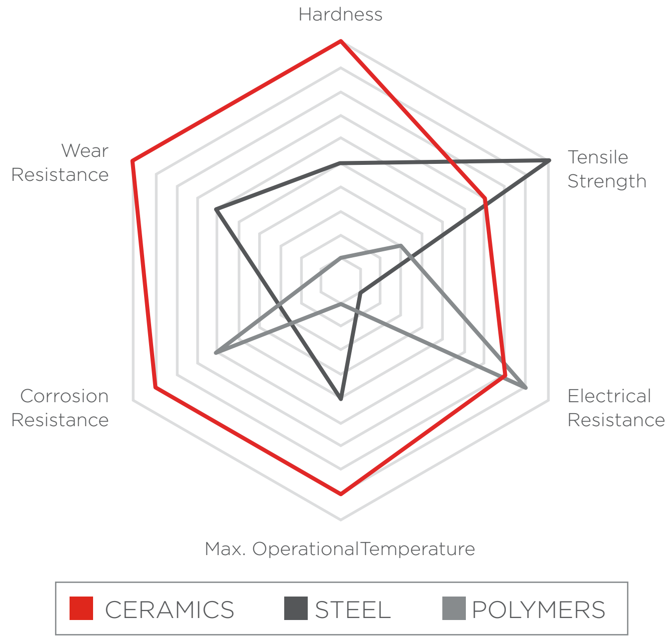
Bring us your latest design challenge. We'll bring in our experts to solve it.

WHY CERAMICS?

Unsure why you should choose technical ceramics over metals or polymers? We can help you with that.

The properties of technical ceramics are impressive when viewed singularly, but it's the combination of properties that makes them stand apart. Ceramics are remarkable precisely because they are not a one-size-fits-all solution.

We have an entire booklet that explores the mechanical, thermal, electrical, and chemical properties and benefits. Download it at **www.coorstek.com/why-ceramics.**



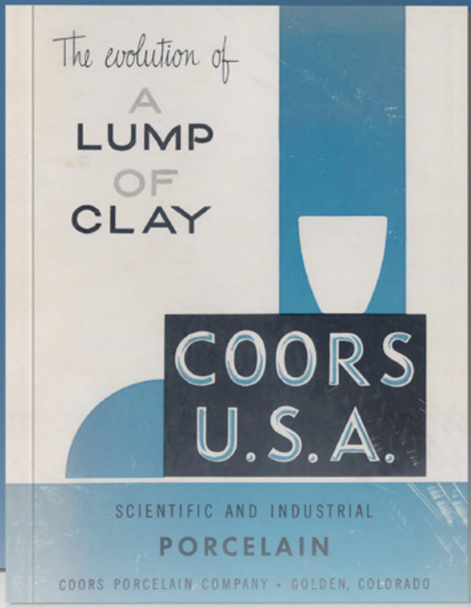
OUR HERITAGE

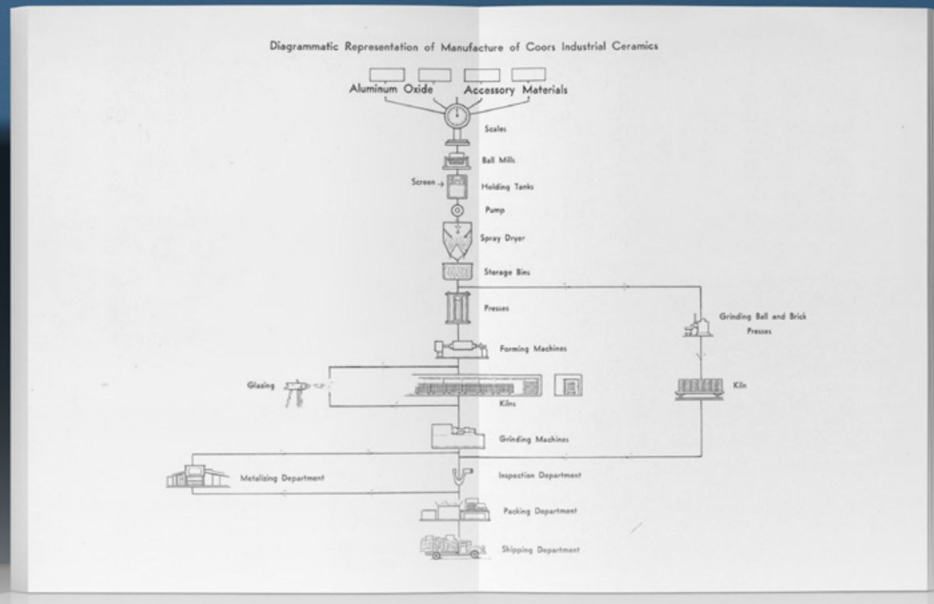
Founded in 1910 as an art pottery, CoorsTek has been at the forefront of technical ceramic process innovations since the start of the technical ceramic revolution in the early 1940s. Our engineers helped develop the technical ceramics industry from porcelain labware to leading solutions for virtually every industry sector. We did this by developing and manufacturing the highest quality technical ceramics.

Not only have we been making ceramics for over 110 years, but we've been writing about them, too. One of our earliest booklets, *The Evolution of a Lump of Clay*, was first produced and published in 1957 by the Coors Porcelain Company (now CoorsTek). The information and processes are as applicable today as they were then. We've just refined our materials and processes over the years.

You might say we're continuing this tradition.
For more history, visit **www.coorstek.com/history.**

Prior to entering into the manufacturing of technical ceramics, Coors Porcelain manufactured dinnerware. This photo from the 1930's shows a Coors Porcelain employee removing a Rosebud water pitcher from a mold after firing. Rosebud was one of the company's most popular dinnerware lines.





This illustration is taken from the 1957 booklet *The Evolution of a Lump of Clay* produced by the Coors Porcelain Company (now CoorsTek).

The schematic shown here depicts the manufacturing process to make ceramics for industrial use. Today the process is similar, with a few modifications made to continually improve our capabilities over the years.

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