Silicon Nitride: From Supersonic to Hypersonic

Silicon nitride is solving the aerospace and defense industries' toughest engineering problems.

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We're in the age of hypersonic speed when it comes to military aerospace applications. Whether it's a state-of-the-art fighter jet soaring at Mach 3 or an advanced hypersonic missile traveling up to Mach 5, traditional materials are no longer a viable option for handling the extreme conditions experienced by vehicles travelling at these speeds.

High temperatures and aerodynamic loads degrade and destroy traditional materials quickly. In propulsion applications, demanding gas turbine engines are becoming more reliant on higher performance ball bearings for efficiency and durability. Not only are higher performing materials essential for the viability and longevity of aerospace systems, but it helps protect our military personnel, too.

When it comes to aerospace applications, reliability and safety are the most important factors. In the age of high-speed travel, we are finding that silicon nitride is becoming increasingly vital for the demanding conditions that high-speed travel puts on components in aircraft, ensuring they continue to operate at these extremes safely and reliably. Because of this, silicon nitride is fast becoming a preferred material for many aerospace components.

Silicon nitride bearings preserve jet engine longevity and reduce overall lifetime maintenance costs.

Silicon Nitride Overview

For traditional aerospace applications, metals and composites are the materials of choice for aerospace manufacturers. However, in the advent of hypersonic travel, these materials can no longer meet the extended demands of extreme conditions they experience in various applications for hypersonics. New materials for hypersonic applications require even more exceptional mechanical and thermal properties than traditional materials can provide.

Beginning in the mid-1970s, silicon nitride (Si_3N_4) emerged on the market from a concerted effort to find a low-density material with highly desired properties such as high hardness and toughness, tailored electrical properties, and resistance to corrosion and wear within a single, uniform structure. Its mechanical robustness, along with its ability to perform at increasing temperatures encountered at a high velocity, made it attractive to a variety of industries.

Silicon nitride can replace legacy materials used in ball bearings, radomes and RF windows for extreme applications. Resistance to otherwise normal mechanical wear and tear, oxidation, and thermal shock make silicon nitride a uniquely useful material that spans multiple industries.

Today, silicon nitride is used in a wide range of applications, most notably within the wind energy, automotive, semiconductor and aerospace industries. After years of research and development, silicon nitride has proven to be a highly desirable material for extreme conditions. From commercial aviation to defense applications, this advanced engineered ceramic is quickly becoming the material of choice for aerospace defense systems used by our military on a daily basis.

Moving at Mach 5

Silicon nitride is one of the few materials that can survive the thermal and mechanical conditions experienced when traveling at speeds up to Mach 5. The excessive temperatures that a vehicle endures when traveling at these speeds can degrade electrical performance, while the vibration and stress from a high-G turn can destroy a missile dome or window.

Silicon nitride can handle these demands. While other materials can be used in these conditions, silicon nitride offers many advantages due to its light weight and exceptional stiffness and strength.

Tremendous growth for ceramics is occurring in aerospace applications—not just for military and defense, but within commercial aviation as well. If technical ceramics can outperform traditional materials in some of the world's harshest conditions, they can also be used in less-strenuous environments to help extend the life and efficiency of a commercial jet.

However, advanced ceramic materials are not always the first choice for engineers designing these high-end applications. The challenge is helping component designers and engineers understand the value in employing technical ceramics. Supersonic and hypersonic travel creates extreme conditions where other materials fail. Change is difficult, but there are a very limited number of materials that can survive in these demanding environments. New advanced ceramics are continuing to be tailored to requirements and evaluated in use.

Silicon nitride combines the required strength, hardness, RF properties and thermal resistance required for an extreme application such as a radome.

Many professionals don't realize the performance aspect or availability of ceramics, especially silicon nitride. Today, a lot of education is done with engineers in the aerospace industry regarding why ceramics are a superior performing material. The focus is to show aerospace engineers, designers and purchasing agents the benefits and value of silicon nitride and how it can help them achieve their design and business goals. Three specific applications where silicon nitride excels include bearings, RF windows and radomes.

Bearing Balls

When you think of bearings, shiny silver steel balls most likely come to mind. Critical in jet turbine engines and wing flap ball screw applicators, bearing balls endure excessive temperature conditions and wear. High turbine engine revolutions and adverse flying conditions degrade traditional bearing balls.

However, silicon nitride bearings balls can outperform steel ball bearings.* From their superior strength to their extremely smooth finish that resists corrosion and wear, silicon nitride bearings preserve jet engine longevity and reduce overall lifetime maintenance costs.

This silicon nitride product is extremely lightweight. Over the years, they have been refined so they will function at high speeds with low friction, in extreme temperatures, and require less lubrication. This makes them a perfect fit for aerospace gas turbine engines, electric motors, generators, satellite control moment gyroscopes and wing flap ball screw applicators.

Produced with high-purity raw silicon nitride materials in a highly controlled process, these ceramic balls are manufactured with both consistent chemistry and microstructure. When it comes to value over the lifetime of an aircraft, silicon nitride bearing balls can easily outperform steel balls due to their low density, high hardness and thermal expansion properties (see Table 1).

Silicon nitride is a difficult material to produce. Following process improvements over the years, capabilities have been expanded to provide this material on a much broader basis. Through continuous development and refinement, engineers have further refined the thermal and mechanical properties of silicon nitride formulations. Because of these innovations, the semiconductor industry began adopting silicon nitride for use in its precision motion applications. From there, it expanded into other applications.

RF Windows

The original promise of silicon nitride was for RF applications and microelectronics, not bearing balls. The RF properties of silicon nitride (a moderate dielectric constant and low RF loss), combined with its exceptional strength and thermal resistance, made this material ideal for RF applications such as windows. The use of silicon nitride in semiconductor applications also proved the material could be used in electronics, albeit in thin film applications. Nonetheless, its electrical and mechanical properties began to show promise in other mechanical applications.

Because of its thermal properties, silicon nitride's RF properties don't degrade as much at higher speeds, compared to traditional RF materials. Silicon nitride exhibits a small change in dielectric properties at the temperatures experienced in supersonic and hypersonic applications. This makes

Cerbec® Balls from CoorsTek

Table 1 | Properties of silicon nitride-based ceramic balls.

Property	Silicon Nitride	Traditional Steel	Si_3N_4 Difference
Density (g/cc)	3.2	7.6	58% lighter
Hardness (Vickers hardness test)	1,550	700	121% harder
Elastic modulus (GPa)	320	190	68% stiffer
Thermal expansion coefficient, 1×10^{-6}/°C (RT to 1,000°C)	3.7	12.3	70% less expansion
Maximum use temperature (°C)	1,000	320	680°C higher
Surface finish, grade 5 (microns)	0.005	0.02	75% smoother

it an ideal material for use at high speeds and temperatures because the RF properties are relatively constant when compared to the large changes in properties in materials like slip-cast fused silica or alumina. Growth across this industry remains strong, especially when coupled with the increasing amount of information and data processing required by civilian and military platforms.

Radomes

Silicon nitride combines the required strength, hardness, RF properties and thermal resistance required for an extreme application such as a radome. Radomes (or nose cones) are a critical and complex component when it comes to material requirements needed for missile and hypersonic systems. These domes need to provide an aerodynamic envelope and environmental protection while acting as a sensor window for the complex electronics that allow missiles to track and detect targets.

For missiles in high-speed flight, radomes experience the most extreme range of thermal loading compared to other components in the structures. During acceleration, radomes will quickly heat and experience significant thermal stress with temperatures that can easily approach 500°C at Mach 3, and 1,000°C at Mach 5. The radome has to survive these sudden changes in temperature and effectively transmit radio signals during the rest of the flight regime. Silicon nitride's high thermal conductivity and low thermal expansion properties provide excellent heat-resistant barriers for the RF components behind them.

It's not just the heat with which the radome must contend and survive—these domes also endure dynamic pressure changes. High-G maneuvers create vibrations that disintegrate weaker materials. Engineers and manufacturers have long understood that the ideal materials needed for designing and producing radomes feature:

- Low dielectric constant and loss tangent
- High thermal resistance
- Strength to withstand structural, aerodynamic and aerothermal loads
- Resistance to impacts from environmental agents
- Impermeability to water
- Support for pressure differentials between the interior and exterior
- Light weight

Silicon nitride checks all the boxes. These radomes are transparent to microwave radiation and can withstand the tremendous heat and stress associated with traveling at high speeds. As high-speed applications evolve, ceramics will continue to be a critical material for this industry.

Key Properties of Silicon Nitride

- Low density
- High-temperature strength
- High wear resistance
- High thermal shock resistance
- Oxidation resistance
- Low mechanical fatigue
- Low dielectric loss

Tailored Solutions

Significant growth is happening within the aerospace and defense industries, with tremendous investments being made in high-speed air travel, missile defense, and hypersonic systems. As requirements increase, they drive the ongoing need for new cutting-edge materials that can perform in some of the world's toughest conditions. Technical ceramics, especially silicon nitride, continue to enable this industry to address the many challenges that aerospace, hypersonics and missiles continue to face with a desire for ever-faster speeds and higher performance.

By working directly with aerospace engineers, silicon nitride producers are showing how the material can be used to design and produce a wide range of advanced component assemblies for tailored applications. Ceramics are not always their first choice. However, through customer collaboration, silicon nitride is able to maximize their product's efficiency, functionality and durability, providing significant customer value such as increased reliability, lower lifetime costs, or increased operational performance. Ci

For more information, visit www.coorstek.com/aerospace.

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