Silicon Nitride—A Proven Ceramic Material for Engine Applications

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The development of silicon nitride as a structural ceramic material began in the late 1960's as a potential high temperature material for gas turbine engines. While this application was never widely adopted, Ceradyne and other manufacturers expanded the uses of silicon nitride to include a variety of industrial applications from cutting tools and other metal working products to wear components for paper and oil field solutions.

Rolling elements for hybrid ball bearings also became a widely commercialized silicon nitride application in the early development years. The success of silicon nitride as a bearing material opened the way for engine applications like cam rollers for unit fuel injectors in heavy-duty diesel engines.

Ceradyne entered the cam roller market in 1999 and expanded the use to a number of diesel engine manufacturers and also to high-pressure fuel pump manufacturers. Since 1999, Ceradyne has supplied silicon nitride components for more than 750,000 engines and fuel pumps that have operated without failure in the field.

The dramatic success rate of silicon nitride has proven without doubt that it is a high performance structural material solution for engine applications. This success is based on the unique set of physical and mechanical properties found in silicon nitride. The properties of Ceradyne's Ceralloy® 147-31N Silicon Nitride are compared to M50 Bearing Steel in *Table 1*.

Laboratory tests are substantiated in engine tests that show silicon nitride operating without failure at higher stress levels than metal cam rollers.

Silicon Nitride Bearing Properties are Superior to Bearing Steels

Rolling contact fatigue resistance is the key bearing property that limits the use of materials because it is the measure of how long the material will operate at a given stress level without failure (usually by spalling). *Figure 1* shows that Ceralloy® 147-31N Silicon Nitride demonstrated substantially superior RCF life versus M50 Bearing Steel in laboratory tests at very high stress levels.

Laboratory tests are substantiated in engine tests that show silicon nitride operating without failure at higher stress levels than metal cam rollers. The elimination of cam roller warranty problems when using silicon nitride proves this point.

Silicon Nitride Wear Resistance is Superior to Metals

The wear resistance of a brittle ceramic material is judged by its hardness and fracture toughness. The hardness of Ceralloy® Silicon Nitride is approximately 1450 kg/m^2, which is much harder than metals. Its fracture toughness is one of the best of any ceramic at 6 MPam$^{1/2}$. This combination of properties makes silicon nitride one of the finest wear resistant materials.

Theoretical properties are once again substantiated by engine durability data. *Figure 2* shows the

MATERIAL/Material Property	Bearing Steel 52100 or Similar	Bronze[1]	Ceralloy® 147-31N Si_3N_4
Density (g/cm^3)	7.8	~8.7-9.3	3.2
Elastic Modulus (GPa)	210	~72-93	310
Poisson Ratio	0.28	-	0.27
Hardness:			
HK0.5 (kg/mm^2)	~700	-	1450
HRc	60	<0.9 (off scale)	>75
Electrical Volume Resistivity (W·cm)	$60 \cdot 10^{-6}$	$10\text{-}20 \cdot 10^{-6}$	$1 \cdot 10^{16}$
Thermal Expansion Coefficient (10^{-6} °C $^{-1}$)	10.9	$6 \cdot 10^{-6}$	3.1

Table 1 **Properties of Ceralloy 147-31N Silicon Nitride versus Bearing Steel**

change in dimension of the ID of a metal cam roller in the unit fuel injection position versus a silicon nitride roller in the same location. The data shows that the silicon nitride roller exhibits less that 10 percent of wear versus the metal. The significance is that the wear of the ID of the roller is the cause of roller failure in a unit fuel injector. Using silicon nitride rollers eliminates the wear and thereby eliminates the primary cause of failure which results in increased performance.

Silicon Nitride is Tribologically Compatible with Steel and Cast Iron.

Ceralloy® Silicon Nitride has a coefficient of friction of 0.15 versus steel in a non-lubricated, dry, sliding test. The steel on steel coefficient of friction ranges from 0.5 to 0.75. The lubricated sliding friction for silicon nitride on steel is approximately 0.05.

The wear of Ceralloy® Silicon Nitride versus either steel is negligible for either material. Conversely, the wear of steel on steel at high stress levels results in galling and micro welding of steel components. This is a common failure mode for metal cam rollers and cam lobes.

These laboratory observations are consistent with engine results. Neither Ceralloy® Silicon Nitride cam rollers nor the companion steel cam lobes exhibit any galling or excessive wear. In fact, the life of cam lobes has been shown to increase with the use of Ceralloy® Silicon Nitride cam rollers.

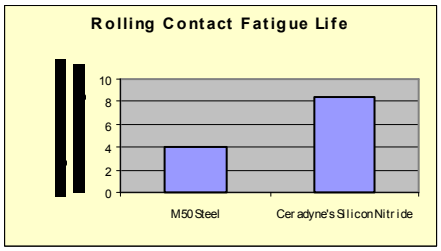

Figure 1: Rolling Contact Fatigue Properties of Ceralloy® 147-31N Silicon Nitride versus M50 Bearing Steel at 6.4 GPa Contact Stress

Silicon Nitride is Lighter than Steel by 60 Percent

The specific gravity of Ceralloy® 147 Silicon Nitride is 3.2 g/cm^3 where bearing steels have a specific gravity of 7.8 g/cm^3. This lighter weight results in a reduced rotational moment of inertia of the silicon nitride cam roller compared to steel.

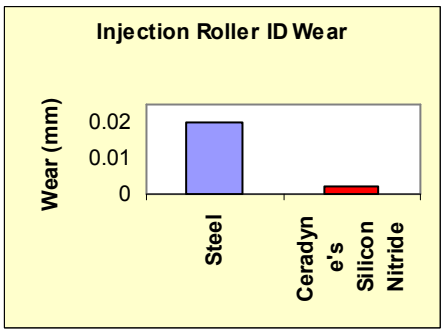

Figure 2: Wear of the ID of Metal versus Ceralloy® 147-31N Silicon Nitride Cam Rollers after Engine Operation

Ceralloy® Silicon Nitride's low moment of inertia combined with its lower coefficient of friction, results in the elimination of cam roller "skidding" which is another common cause of failure in metal systems.

Figure 3: Ceradyne's Ceralloy® 147-31N Silicon Nitride Roller and Cam Roller Products

Silicon Nitride is a Proven Material that Solves Warranty Problems

Three engine manufacturers of heavy-duty diesel engines have incorporated silicon nitride into their engines as cam rollers for unit fuel injectors, and cam rollers for intake and exhaust valve operation. These have gone into both rocker arm and roller lifter configurations. Silicon nitride was selected because it solved the warranty problems associated with the use of metal cam rollers in those applications.

Two fuel pump manufacturers have also incorporated silicon nitride rollers into a rotary distribution pump and a high-pressure common rail pump. Again, in both of these applications, silicon nitride solved significant warranty problems. Examples of Ceradyne's Ceralloy® Silicon Nitride roller and cam roller products are shown in Figure 3.

Silicon nitride was cost justified because of its quantified life cycle cost advantage over metal. Although not quantifiable, the use of silicon nitride eliminated severe performance and warranty problems allowing OEM manufacturers to claim a higher quality product. This resulted in an undocumented improvement in the "branding" of their product.

Silicon Nitride is an Enabling Material that Allows Engineers to Improve Engine Performance

One diesel engine manufacturer incorporated silicon nitride cam rollers into their engine in order to radically change the cam profile so that the engine could meet more stringent 2004 emission standards. Another manufacturer used silicon nitride rollers in a rotary distribution pump that allowed increased pump performance and helped the company gain a new product niche that resulted in increase sales.

These examples demonstrate that silicon nitride is a material that provides the design engineer with a new method to improve engine performance. Ceradyne is positioned to assist engine designers and manufacturers with the incorporation of silicon nitride into their designs.

Further information about Ceradyne, Inc. and its Ceralloy® 147-31N Silicon Nitride can be found at www.ceradyne.com.

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