

# Silicon Nitride Applications in Modern Diesel Engines

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## ABSTRACT

The need for more efficient diesel engines combined with increasingly stringent emissions standards have resulted in increased cylinder operating pressures and fuel injection pressures. These conditions result in higher contact stresses in key components, which can result in wear, galling, micro-welding and finally failure of metal components. New material options are required to solve these problems.

Silicon nitride has unique tribological and physical properties (low mass combined with high strength and contact fatigue resistance) that allow its use under high contact stresses. Selection of appropriate grade of silicon nitride can solve problems in the valve train and the fuel delivery systems for light and heavy-duty diesel engines.

Silicon nitride components produced by Ceradyne are currently in production for the following applications:

- Cam Roller for Unit Injector Fuel Pumps for Class 8 Diesel Engines
- Cam Rollers for Intake and Exhaust Valves for Class 8 Diesel Engines
- Rollers for Common Rail, High Pressure Fuel Pumps for Light Duty Diesel Engines, as well as very Large Diesel Engines.

Silicon nitride has been demonstrated to be a cost effective material solution that has eliminated wear and galling of the cam rollers and the adjoining cam lobe or pump rollers and the adjoining metal components. The use of silicon nitride components has eliminated warranty problems in these applications and has resulted in increased engine reliability.

## 1. INTRODUCTION

Emissions regulations imposed on the heavy-duty diesel industry in the 1990's have resulted in the increased fuel

injection and cylinder operating pressures<sup>1</sup> (Figure 1). This has resulted in increased cam and roller Hertzian contact stresses (1.7-2.1 GPa in some cases), increasing occurrences of failure of key metal components, especially cam rollers, cam lobes and bronze pins. At the same time, engine manufacturers have been forced, due to competitive pressures, to increase the warranties on their engines. The combination of these two events has resulted in increased warranty claims due to material contact fatigue problems of valve train system components, effectively increasing the cost of each engine.

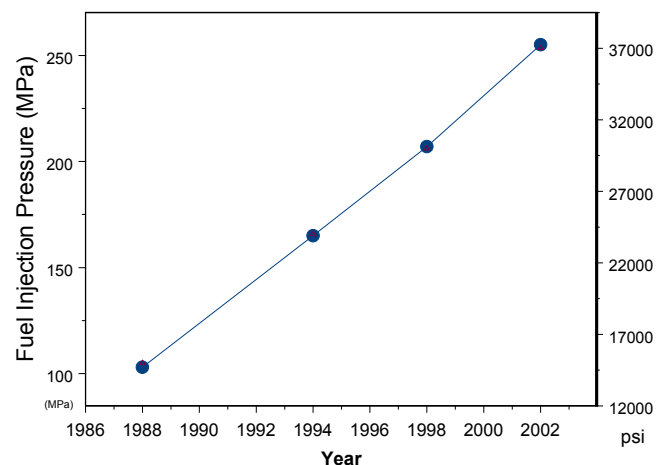


Figure 1. Unit injector fuel pressure trends due to reduced emission regulations<sup>1</sup>.

Incremental improvements in the performance of steel rollers by improvements in the design of the coolant delivery system, coolant and lubricant chemistry, surface finish of rollers and cams were made in the early 1990's; however, a performance limit was approached with the use of metal components (metal roller Hertzian stress limit is ~1.8 MPa).

Performance limits will further be challenged with the increased levels of soot expected in diesel engines using EGR (exhaust gas recirculation) devices to meet the 2002 and 2007 emissions standards<sup>2</sup>. This has prompted extensive engine testing and re-formulation of crankcase oils by Chevron<sup>2,3</sup> and other companies. Soot levels accumulated in engine oil (can be over 9%) make it more abrasive and can increase the wear of already over stressed parts by depleting the protective zinc thiophosphate film from metal mating components<sup>3</sup>, further increasing the failure rates and increasing warranty costs.

## 2. SILICON NITRIDE MATERIAL PROPERTIES

Component testing of silicon nitride roller cams in engine rigs<sup>4</sup> started in the late 1980's based on extensive experience in Si<sub>3</sub>N<sub>4</sub> hybrid ball bearings<sup>5,6</sup>, which have been used successfully for a number of years in applications where bearings with steel balls exhibit similar failure modes as cam rollers. From a range of available technical ceramics, silicon nitride was chosen based on its high strength and hardness, low porosity, high fracture toughness and its ability to withstand high Hertzian stresses under rolling contact fatigue with spall failures similar to steel.

Comparison of some material properties of a metal cam roller assembly (bearing steel and bronze) relative to Si<sub>3</sub>N<sub>4</sub> ceramics (Table 1), show that due to its density, Si<sub>3</sub>N<sub>4</sub> can offer faster accelerations. Si<sub>3</sub>N<sub>4</sub> is significantly harder, has a significantly lower thermal expansion coefficient than steel and is an electrical insulator. Additionally, Si<sub>3</sub>N<sub>4</sub> has a low friction coefficient in sliding with steel compared to steel/steel<sup>7</sup> or steel/bronze, and exhibits no micro-welding in contact with steel (a common cause of galling and scuffing in metal component lubricated wear<sup>8</sup>). Si<sub>3</sub>N<sub>4</sub> is also significantly less sensitive to operation in un-lubricated conditions; its friction coefficient shows no change under dry/flooded conditions (ball on flat tribometer contact)<sup>1</sup>.

Table 1. Material Property Comparison of Si<sub>3</sub>N<sub>4</sub> to 52100 steel and Bronze

MATERIAL/ Material Property	Roller Steel (52100 or similar)	Bronze <sup>9</sup>	Si <sub>3</sub> N <sub>4</sub>
Density (g/cm <sup>3</sup> )	7.8	~8.7-9.3	3.2-3.35
Elastic Modulus (GPa)	210	~72-93	290-320
Poisson Ratio	0.28	-	0.25
Hardness: HK0.5 (kg/mm <sup>2</sup> ) HRC	~700 60	- <0.9 (off scale)	>1500 >75
Electrical Volume Resistivity (Ω·cm)	60·10 <sup>-6</sup>	10-20·10 <sup>-6</sup>	>1·10 <sup>13</sup>
Thermal Expansion Coefficient (10 <sup>-6</sup> °C <sup>-1</sup> )	10.9	6·10 <sup>-6</sup>	3.2

## 3. SILICON NITRIDE SOLUTIONS

As the contact stresses on the metal rollers increased in the early 1990's (Figure 1), field failure of metal rollers increased, increasing the system cost, which eventually made certain grades of Si<sub>3</sub>N<sub>4</sub> rollers affordable. In 1993, Detroit Diesel Corporation was the first US diesel engine manufacturer to introduce Si<sub>3</sub>N<sub>4</sub> cam roller followers into their Series 60 engines (Figure 2).



Figure 2. DDC Series 60 rocker arm assembly with a Si<sub>3</sub>N<sub>4</sub> cam roller follower (dark gray) in the fuel injector position, allowing fuel injection pressures of over 210 MPa (30 ksi)<sup>10</sup>.

Since then, additional successful applications for Si<sub>3</sub>N<sub>4</sub> rollers have developed (Table 2). In some cases (Detroit Diesel Corporation and Stanadyne), low levels of ceramic spalling were found with the grades of Si<sub>3</sub>N<sub>4</sub> initially used in the applications. Both companies, after evaluation of other material grades, chose a gas-pressure sintered reaction bonded silicon nitride (SRBSN) material, **Ceralloy**<sup>®</sup> 147-31N produced by Ceradyne to eliminate the spalling problem.

Table 2. Silicon Nitride Applications in the Heavy Duty Diesel Engine Industry

Company	Application	Component
Detroit Diesel Corporation	Fuel Injector, Intake and Exhaust Valve	Cam Roller
Cummins Inc.	Fuel Injector	Link Pin
Mack Trucks	Roller Lifter (Intake and Exhaust Valve)	Cam Roller
Stanadyne Inc.	Electronic Fuel Pump	Roller
L'Orange GmbH	Common Rail Fuel Pump	Roller

For fuel pump applications (Figure 3), the roller sees both rolling contact against the internal cam ring and

sliding contact against the roller shoe under boundary lubrication conditions in a hot diesel fuel environment. The roller must be capable of operating under extreme conditions and continue to operate for many thousands of miles.



Figure 3. Silicon nitride rollers in the Stanadyne model DS and DE Rotary Distribution Fuel Pumps – Peak Injection Pressures to 1000 bar (14,000 psi)<sup>11</sup>.

New emissions regulations are scheduled for introduction in the first decade of the 21<sup>st</sup> century. These are expected to require even higher fuel injection and cylinder operating pressures under increased soot levels in engine oils. This will further stress metallic components leading to more applications requiring the use of silicon nitride components. Additional interest in evaluating the use of silicon nitride components in various other applications has started.

#### 4. CAM ROLLER APPLICATIONS

To understand the benefits of using silicon nitride for cam roller applications, one must understand the application and more importantly understand why metal components fail.

##### 4.1 METAL CAM ROLLER SYSTEM

The metal cam roller system is composed of, 1) a steel cam roller, 2) a steel cam lobe and 3) a bronze pin (Figure 4A). The performance of this system has been extensively studied<sup>1</sup>.

1. The wear and the high friction at the pin to metal roller interface prevents free rotation of the metal roller which in turn causes wear at both the ID and the OD of the metal rollers and at the cam lobe.
2. Cam roller sliding caused by high contact stresses and frictional “stick-slip” conditions causes the area of maximum stress to move

from below the surface toward the surface and may initiate contact fatigue failures on both the roller and the cam lobe (Figure 5). This is caused by adhesive wear between the two metal surfaces.

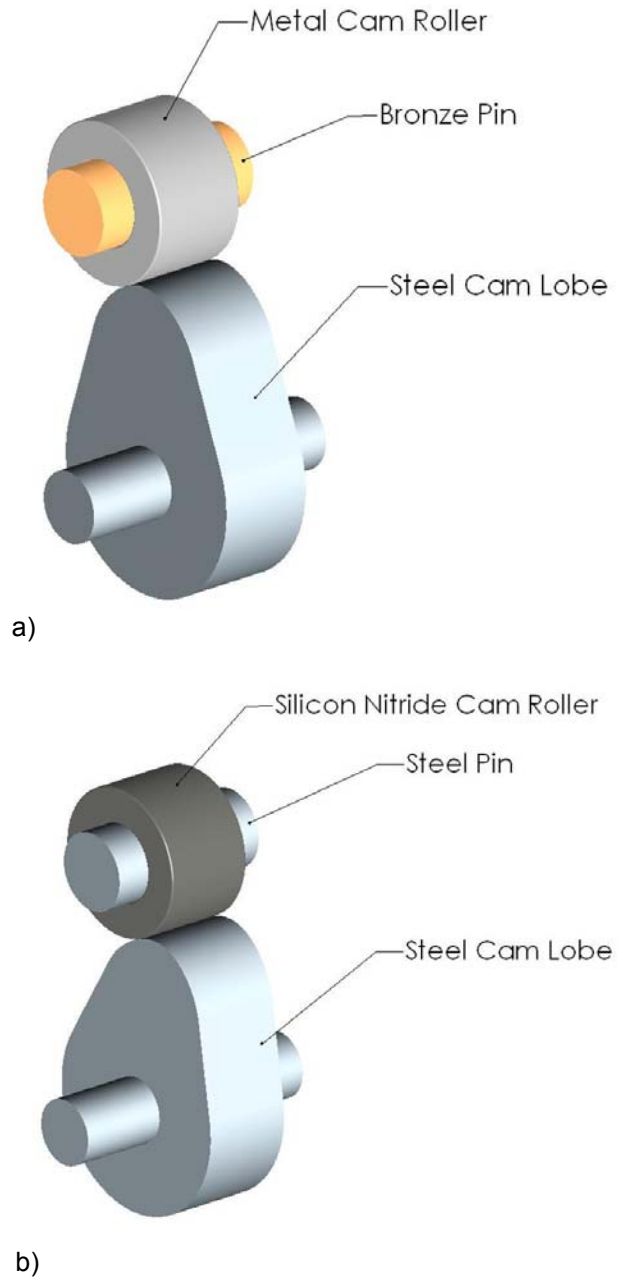


Figure 4. a) Schematic of a Metal Cam Roller System  
b) Schematic of a Ceramic Cam Roller System

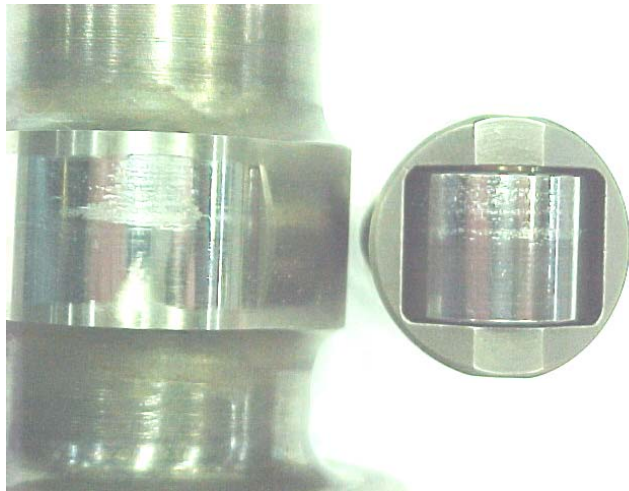


Figure 5. Pitting and glazing on a metal roller and cam.

3. High contact stresses can cause fatigue failure in the metal roller. The pitting in the metal roller will translate to wear of the adjoining cam lobe.
4. Adhesive wear (scuffing and galling) is the dominant form of wear in highly stressed steel-to-steel contacts. Metal to metal contacts at high stresses also result in contact fatigue micro-pitting or micro-welding.
5. The bronze pin is the weak link in this system. Bronze is a relatively soft material and is susceptible to wear and corrosion due to a variety of reasons including:
  - High contact stresses
  - Low levels of lubrication
  - Dirty lubrication
  - Debris
6. The bronze pin and the metal cam roller exhibit high friction with “stick-slip” under high levels of lubrication, and very high friction and severe “stick-slip” under starved lubrication conditions<sup>1</sup>.

Due to this, typical metal cam rollers in high-pressure systems show the following:

- Scuffing and pitting on the OD of the metal cam roller
- Wear on the ID of the metal roller
- Scuffing and wear of the OD of the pins

#### 4.2 SILICON NITRIDE CAM ROLLER SYSTEM

The silicon nitride cam roller system is composed of, 1) silicon nitride cam roller and 2) steel cam lobe 3) steel pin (Figure 4B).

The performance of this system has also been studied<sup>1,12</sup>.

1. The steel pin is much harder than the corresponding bronze pin of the metal system,

making it more wear resistant to dirty lubrication and other debris.

2. Silicon nitride and steel make an excellent tribological couple. Silicon nitride and steel exhibit low and constant friction at both flooded and starved lubrication conditions.
3. The wear of the ID of the silicon nitride rollers is lower than the corresponding metal rollers by approximately a factor of 3-10 (Figure 6)<sup>13,14</sup>.

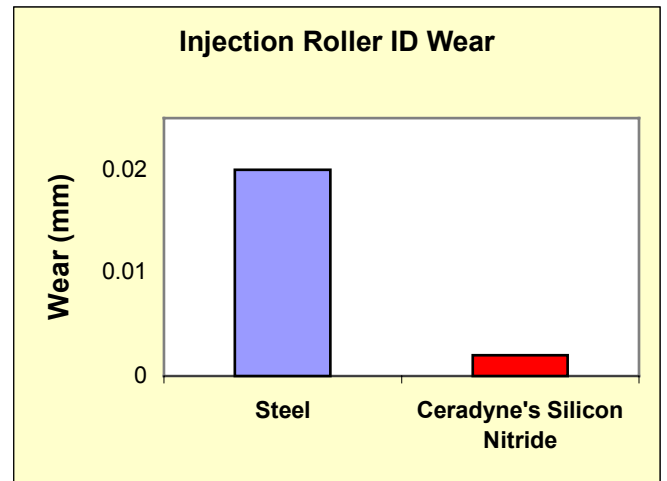


Figure 6. Comparison of the wear of the ID of metal and silicon nitride cam rollers.

4. The low wear and the low friction of the pin to ceramic silicon nitride roller interface and the light weight of silicon nitride (60% lighter than metal) and subsequent low rotational moment of inertia, makes the silicon nitride roller rotate freely. This reduces or eliminates skidding and sliding against the cam lobe, eliminating one of the major causes of contact fatigue and wear in a metal cam roller system.
5. The contact fatigue resistance of silicon nitride is greater than bearing steels (Figure 7). This allows silicon nitride rollers to operate at higher contact stresses without pitting or spalling. This eliminates another source of failure in metal systems.

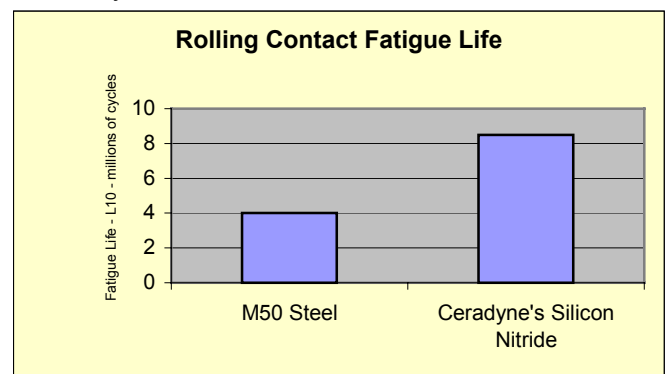


Figure 7. Comparison of the rolling contact fatigue life of Ceradyne's Cerallloy<sup>®</sup> 147-31N silicon nitride vs. bearing steel at 6.4 GPa Contact Stress.

6. With silicon nitride-steel contacts, adhesive wear should not take place or should be insignificant, eliminating another source of wear and contact fatigue in the metal cam roller system. Due to a change in contact to dissimilar materials, tests show that despite an increase in contact stress, the wear of the metal cam is reduced when a super finished ceramic roller is used<sup>13</sup>.
7. The crown profile of a silicon nitride roller needs to be large enough to keep the line contact away from the edges of the ceramic roller. The contact stresses will generally be higher in a silicon nitride system due to a higher elastic modulus of the silicon nitride versus steel, for the same steel-to-steel profile, but an optimized profile for the ceramic can reduce this.

## 5. ENGINE PERFORMANCE USING SILICON NITRIDE COMPONENTS

The engine performance results provided by Ceradyne's customers is qualitative in nature and can be summarized as follows:

- The wear of the ID of a silicon nitride roller is reduced by a factor of 10 relative to the ID of a metal roller (Figure 4).
- The life of a cam lobe running against silicon nitride is longer than one running against a metal cam roller, even at higher contact stresses. This is supported by independent laboratory study<sup>13</sup>.
- The reliability of the engines using silicon nitride components has increased. Warranty claims against the silicon nitride component systems have been significantly reduced or eliminated with the use of silicon nitride components.
- The reliability of fuel pumps using silicon nitride has also increased and warranty claims have been eliminated.
- Over 2.5 million silicon nitride components manufactured by Ceradyne have been placed into engines and fuel pumps (1999 through 2003). Since that time there have been no reported material related failure of silicon nitride components by Ceradyne customers.

## 6. SELECTION OF A SILICON NITRIDE GRADE FOR AUTOMOTIVE APPLICATIONS

Performance of silicon nitride in diesel engine/fuel delivery applications depends on the selection of the specific silicon nitride grade and manufacturing route. Cost of the product and the lifetime benefit are major factors for successful automotive applications even after the technical benefit has been demonstrated. Silicon nitride component costs are generally dependent on the raw materials costs, material processing route and the

product finishing costs, the latter often contributing ~50% to the costs.

Table 3 shows different silicon nitride manufacturing processes currently used in the manufacture of near net shape silicon nitride blank components. Because the GP SRBSN (gas pressure sintered reaction bonded silicon nitride) process starts from the least expensive raw materials (silicon metal powder rather than silicon nitride powder), the direct material costs of the blank using this route can be 50-70% lower than other routes. Additionally, even though this process uses gas pressure sintering, lower shrinkages experienced by GP SRBSN parts during densification enable more parts to be processed in the same furnace volume, decreasing the furnacing costs.

Figure 8 gives a comparison of rolling contact fatigue lives for three grades of Si<sub>3</sub>N<sub>4</sub> based on densification gas pressure, showing considerably longer lives when the densification occurs at 10 GPa (GP) or 100 GPa (HIP). Based on this, GP SRBSN has the potential of offering the most economical products of the required quality.

Of course, for automotive applications considerable cost of the components are in the final finishing, especially for rollers which often need crowning and super-finishing operations on the OD surfaces. In this area, the advantage is usually with a company that has already invested in the grinding and finishing equipment, and has gained the experience in making the components in production quantities.

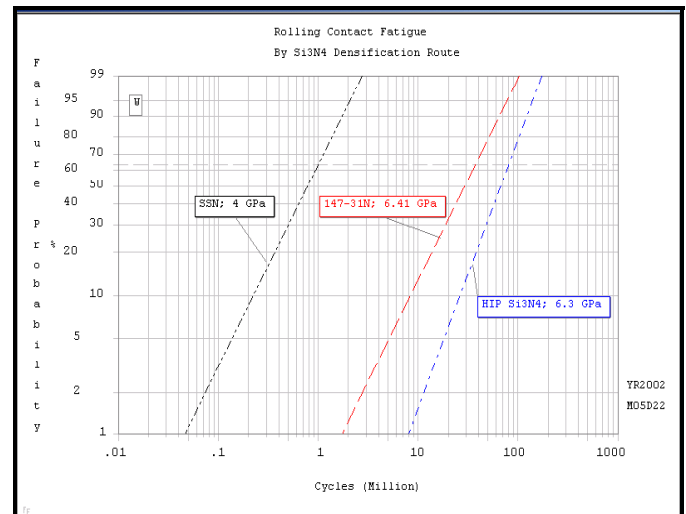


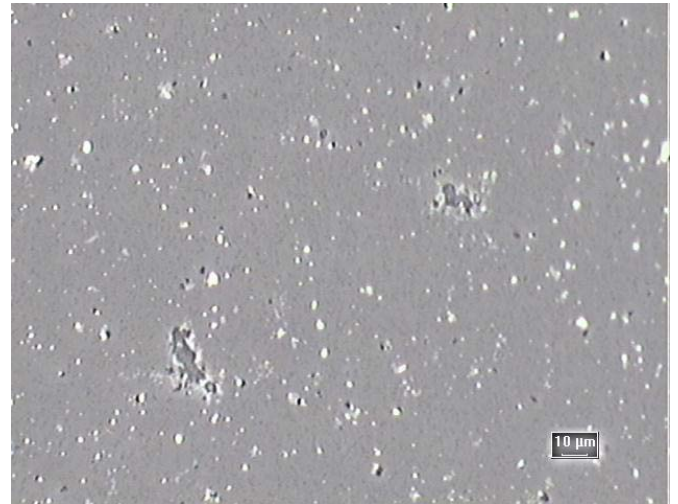
Figure 8. Comparison of rolling contact fatigue life for an SSN, GP SRBSN (Ceralloy® 147-31N) and HIP-ed<sup>15</sup> silicon nitrides (Federal Mogul ball on rod test data). Note the contact stresses used for the tests are different.

Table 3. Comparison of the SRBSN and SSN Processes

GP SRBSN Gas Pressure Sintered Silicon Nitride (Ceradyne, Inc. Process)	SSN Sintered Silicon Nitride	GPSN Gas Pressure Sintered Silicon Nitride	HIP SN Hiped Silicon Nitride
Raw Materials (Silicon + Additives)	Raw Materials (Silicon Nitride + Additives)	Raw Materials (Silicon Nitride + Additives)	Raw Materials (Silicon Nitride + Additives)
<\$10/kg	\$30-80/kg	\$30-80/kg	\$30-80/kg
Spray Drying	Spray Drying	Spray Drying	Spray Drying
<b>Fabrication</b>	<b>Fabrication</b>	<b>Fabrication</b>	<b>Fabrication</b>
Nitriding ( $3Si + 2N_2 \rightarrow$ $Si_3N_4$ ) ~1.5-1.62 weight gain	Not applicable	Not applicable	Not applicable
Gas Pressure Sintering 10.3 MPa (1500 psi) $N_2$ pressure Better furnace utilization	Sintering, atmospheric pressure in $N_2$ gas	Gas Pressure Sintering 10.3 MPa (1500 psi) $N_2$ pressure	Hot Isostatic Pressing (HIP) at 100-200 MPa (15-30 Ksi) in $N_2$ gas
<b>Relative Cost</b>			
Low/Moderate	Low	Moderate	High

Comparing the different processes for manufacturing silicon nitride in Table 3, it is important to understand that they produce different qualities of silicon nitride in general, although within each process a number of different grades from different manufacturers have a range of properties. The densification process for silicon nitride generally requires an elevated gas pressure to close off the internal pores in the material, which is used in GP (Figure 9a) and HIP processes. Due to significantly higher gas pressures, the HIP-ing process can produce stronger materials than GP sintering, however with a significantly higher furnacing costs. In the case of pressureless sintering, small amounts of porosity remains in the material (Figure 9b), which can affect the performance of the material in high stress rolling contact applications.

a)



b)

Figure 9. a) GP SRBSN (Ceralloy® 147-31N grade) and b) SSN silicon nitride grade.

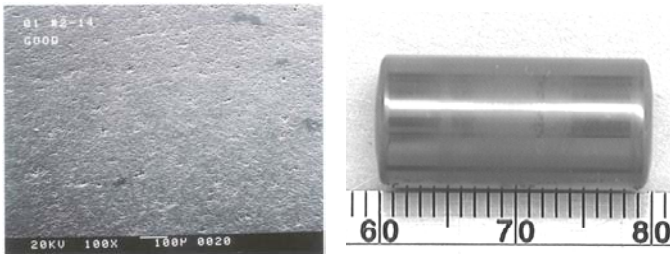
The importance of the material porosity levels on the component's performance is illustrated in Figure 10 where a component with no surface porosity, such as GP SRBSN, shows no wear in the application, whereas the same component with surface porosity fails due to spalling of the ceramic surface.

Selected properties of **Ceralloy®** 147-31N grade of material (GP SRBSN), which has been proven successful in several high volume roller applications, are presented in Table 4. This material has been found to perform without failures in the field, and has the advantage of being very cost competitive when compared to other  $Si_3N_4$  grades.

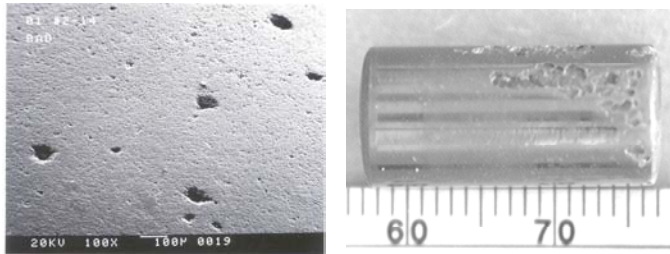
Table 4. Typical Properties of Ceradyne's Needlelok® SRBSN

Grade	<b>Ceralloy® 147-31N</b>
Density	3.21 g/cm <sup>3</sup>
Characteristic Strength	700-800 MPa
Weibull Modulus	15-50
Hardness (HV5)	1500 kg/mm <sup>2</sup>
Fracture Toughness	5.5 – 6.5 MPa m <sup>1/2</sup>
Thermal Conductivity	25 W/m K
Surface roughness (Ra)	<0.1 µm on polished





a)



b)

Figure 10. Effects of porosity of the  $\text{Si}_3\text{N}_4$  material on the performance in RCF applications: a) pore free surface results in no wear; b) surface porosity leads to spalling of the roller.

## 7. RELIABILITY OF SILICON NITRIDE COMPONENT SYSTEMS

The high reliability of the silicon nitride components supplied by Ceradyne is due to a number of factors.

- The High Pressure, Gas Pressure Sintering technique of Ceradyne's Ceralloy 147-31N grade of silicon nitride results in improved microstructure and contact fatigue life as well as a consistently high Weibull modulus and B(1) strength. These factors give this grade of silicon nitride excellent mechanical reliability.
- The use of silicon nitride eliminates many of the wear mechanisms related to metal on metal parts increasing the reliability of the entire valve train or fuel system.
- The design of the silicon nitride components is key to their mechanical reliability. In all cases the components were specifically designed to take into account the mechanical properties of the silicon nitride. The components were designed to minimize contact stresses in the silicon nitride component.
- The selection of these particular components, rollers and cam rollers (Figure 11) are ideal for the use of ceramic materials. Ceramics are purely elastic materials and have their highest strength in compression.



Figure 11. Ceralloy<sup>®</sup> 147-31N silicon nitride cam roller followers for unit fuel injector and roller for diesel fuel pump.

## 8. COST COMPETITIVENESS OF SILICON NITRIDE COMPONENTS

Ceramics components will always cost more than metal parts. However ceramic parts can be cost competitive when the life cycle costs of the components are taken into account.

Ceradyne's **Ceralloy<sup>®</sup>** 147-31N grade of silicon nitride is cost competitive because of a number of factors.

- The use of low cost starting raw materials (silicon vs. silicon nitride)
- The use of semi-continuous and continuous machining techniques
- The use of automated material handling in the ceramic and machining processes

## 9. CONCLUSIONS

Silicon nitride has a unique set of tribological and physical properties (low mass combined with high strength and contact fatigue resistance) that allow its use under high contact stresses. The selection of the appropriate grade of silicon nitride has been shown to solve problems in the valve train and the fuel delivery systems for light and heavy-duty diesel engines.

Ceralloy<sup>®</sup> 147-31N silicon nitride has performed reliably in several commercial diesel engine applications (roller cam follower and fuel pump applications) and has solved major warranty related problems associated with the metal components. This grade of silicon nitride has been proven to be a cost effective alternative to metal components when the life cycle cost of the system is taken into account. Ceradyne has supplied over 2.5

million rollers (from 1999 to 2003) to four major engine and fuel system OEM's with no reported material related field failures.

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