Effect of Silicon Nitride Cam Rollers on Cam Lobe Life

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Summary

"Silicon nitride roller and steel pin have provided long cam life in many applications"[1]

"Wear of the tested cam shaft when using the ceramic roller, was less than the conventional steel roller, even though the calculated contact stress was higher" [2]

"Wear of the cam lobe always starts with problems with the cam roller. The use of silicon nitride has resulted in reduced cam lobe wear and increased cam shaft life." [3]

Nevertheless, potential new users of silicon nitride cam rollers have concerns about their use under high contact stresses due to the possibility of excessive wear (contact fatigue) of the ceramic on the metal cam.

Generally, higher contact stresses increase cam lobe wear and it is commonly assumed that the increased stresses from the higher elastic modulus of silicon nitride would result in increased wear of the adjoining cam lobe. However, there are several different wear mechanisms and operating conditions (including lubrication or lack of it) that affect wear. In steel to steel contacts, adhesive wear (scuffing and galling) is usually the dominant form of wear. This type of wear and contact fatigue is eliminated by the introduction of a silicon nitride roller. The rolling contact fatigue resistance of the cam is actually increased when silicon nitride is used because of the elimination of the various wear modes encountered with a metal cam roller.

Hardened cam lobe steel (hardened or case hardened) should be capable of withstanding stresses up to 3 GPa (440,000 psi) without plastic deformation. By eliminating the causes of wear and metal contact fatigue, the contact stress limit for silicon nitride based cam roller systems should be the same as the plastic deformation limit of the cam lobe steel.

Introduction:

Diesel engine injection pressures and cylinder operating pressures have increased and will continue to increase in order to meet current and future emission regulations. There are wear and warranty issues with current metal cam rollers and cam lobes with current operating pressures. This problem will only increase with future engine designs. At the same time, engine manufacturers are increasing warranty coverage on engine components, making reliability of the engine components more important.

Ceradyne is currently producing silicon nitride cam rollers for heavy-duty engine and high-pressure fuel pump applications[4]. Ceradyne produced over 1 million components for these applications in 2002. The silicon nitride cam rollers have reduced or eliminated warranty problems related to the use of metal components. Specifically, the use of silicon nitride has:

- Nearly eliminated the wear between the roller and the pin
- Eliminated the wear of both the ID and the OD of the roller
- Reduced the wear of the cam lobe

Nevertheless, potential new users of silicon nitride cam rollers have concerns about their use under high contact stresses, due to the possibility of excessive wear (contact fatigue) of the ceramic on the metal cam.

This paper shows the reasons for the improved performance with silicon nitride components and demonstrates that contact stresses of over 2.1 GPa (300,000 psi) are possible with the use of silicon nitride rollers and hardened steel cams.

Metal Cam Roller System:

The metal cam roller system is composed of 1) a bronze pin, 2) a metal cam roller and 3) a metal cam lobe.

The performance of this system has been extensively studied[1].

1. The wear and the high friction at the pin to metal roller interface causes the metal roller to have problems rotating 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" 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 1). This is caused by adhesive wear between the two metal surfaces.

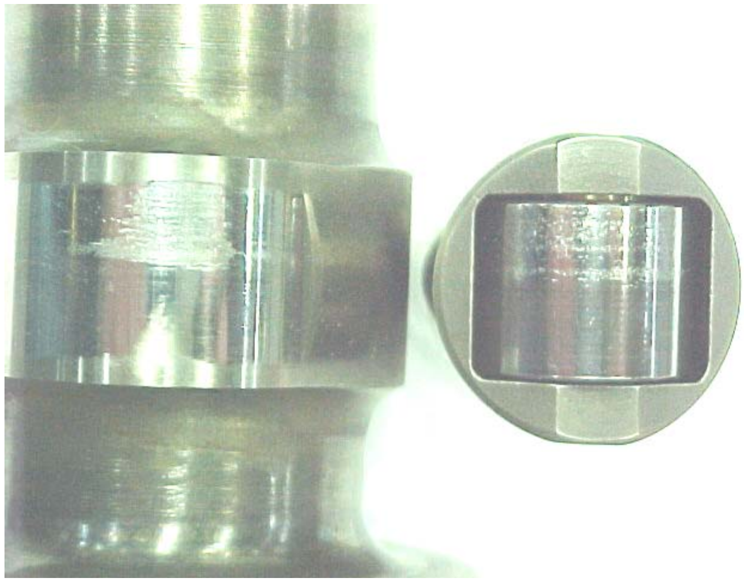

Figure 1. Pitting and glazing on a metal roller and cam.

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[1].

Typical test results of metal cam roller 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

The standard guideline for prevention of cam lobe wear is a contact stress of approximately 2.0 GPa (290,000 psi)[5], based on the above system considerations. Note this is well below the plastic deformation stress of > 2.6 GPa (380,000 psi) for non-hardened steels[6]. Case hardening of steel cams increases these numbers. In bearing applications stresses as high as 3.3 GPa (475,000 psi) can be achieved by properly hardened steel bearings without significant permanent deformation in contact geometry [5].

Silicon Nitride Cam Roller System:

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

The performance of this system has also been studied [1,2].

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 10.

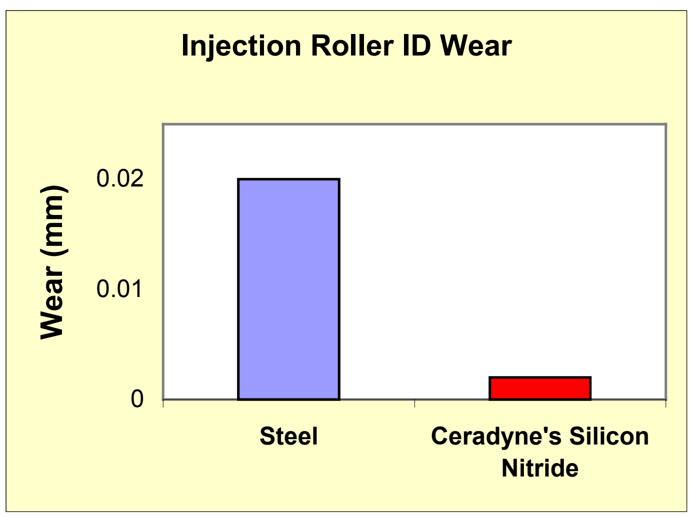

Figure 2. Comparison of the wear of the ID of metal and silicon nitride cam rollers.

4. The low wear and the low friction of the pin to ceramic roller interface and the ceramic light weight (60% lighter than metal) and subsequent low rotational moment of inertia, makes the silicon nitride roller rotate more freely. This reduces or eliminates skidding and sliding against the cam lobe, eliminating one of the major causes of contact fatigue in a metal cam roller system.

5. The contact fatigue resistance of silicon nitride is greater than bearing steels. This allows silicon nitride rollers to operate at higher contact stresses without pitting or spalling. This eliminates another source of failure in metal systems.

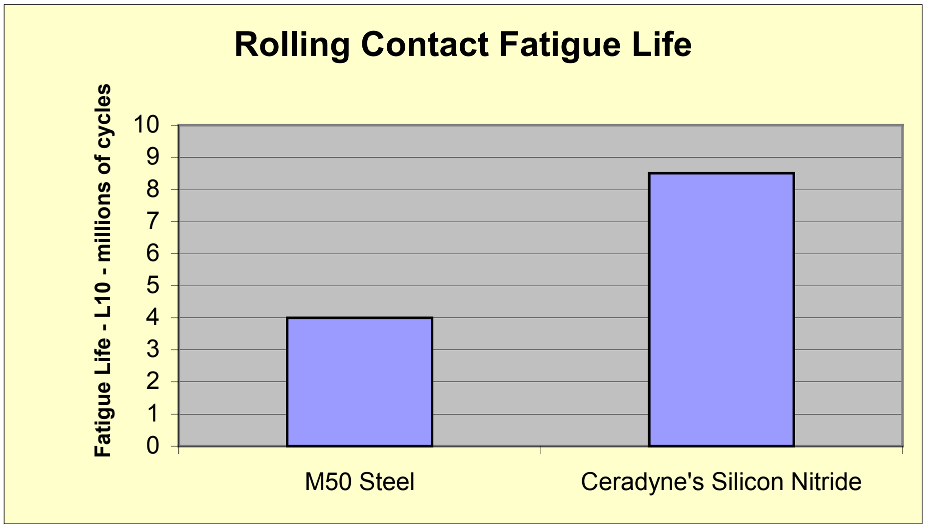

Figure 3. Comparison of the rolling contact fatigue life of Ceradyne's Ceralloy 147-31N silicon nitride vs. bearing steel.

6. With silicon nitride to 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.

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. 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 superfinished ceramic roller is used [2].

Typical test results of silicon nitride cam roller systems show the following:

- No scuffing and pitting on the OD of the silicon nitride cam roller
- No wear on the ID of the metal roller
- No scuffing and wear of the OD of the steel pins
- No wear on the adjoining cam lobe

With the major causes of failure of metal systems eliminated, the cam lobe stresses should be capable of approaching the plastic deformation limit of 3 GPa (440,000 psi) for hardened steels.

Discussion:

Bearing stresses can be ranked as follows -

- Less than 1 GPa - lightly loaded

- 1 - 2 GPa - typical or normal service conditions
- 2 - 3 GPa - heavily loaded
- Above 3 GPa - very heavily loaded

This indicates that cam rollers operating at the 2.1 GPa (300,000 psi) contact stress level is highly loaded - but not critically.

Hardened bearing steel is generally taken to deform plastically at stresses above 3.8 GPa (although according to some reports this can be as low as 3.3 GPa[5]). With a safety factor, that would put the maximum working stress at 3 GPa (440,000 psi).

Silicon nitride can easily withstand this level of stress/load.

Generally, higher contact stresses increase cam lobe wear and it is commonly assumed that the increased stresses from the higher elastic modulus of silicon nitride would result in increased wear of the adjoining cam lobe. However, there are several different mechanisms of wear and each application has different conditions (including lubrication or lack of it) that affect wear. In steel to steel contacts, adhesive wear (scuffing and galling) is usually the dominant form of wear. This type of wear and contact fatigue is eliminated by the introduction of a silicon nitride roller. The rolling contact fatigue resistance of the cam is actually increased when silicon nitride is used because of the elimination of the various wear modes encountered with a metal cam roller. This is one of the selling points of silicon nitride hybrid bearings operating in poor lubrication conditions[7].

Conclusions:

Hardened cam lobe steel (hardened or case hardened) should be capable of withstanding stresses up to 3 GPa (440,000 psi) without plastic deformation. By eliminating the causes of wear and metal contact fatigue, the contact stress limit for silicon nitride based cam roller systems should be the same as the plastic deformation limit of the cam lobe steel.

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