APPLICATION OF CERAMICS TO HIGH PRESSURE FUEL SYSTEMS

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Introduction

Diesel fuel systems are facing increased demands as engines with reduced emissions are developed. Injection pressures have increased to provide finer atomization of fuel for more efficient combustion, Figure 1. This increases the mechanical loads on the system and requires tighter clearances between plungers and bores to prevent leakage. At the same time, fuel lubricity has decreased as a byproduct of reducing the sulfur levels in fuel. Contamination of fuel by water and debris is an ever-present problem. For oil-lubricated fuel system components, increased soot loading in the oil results in increased wear rates. Additionally, engine manufacturers are lengthening warranty periods for engines and systems. This combination of factors requires the development of new materials to counteract the harsher tribological environment.

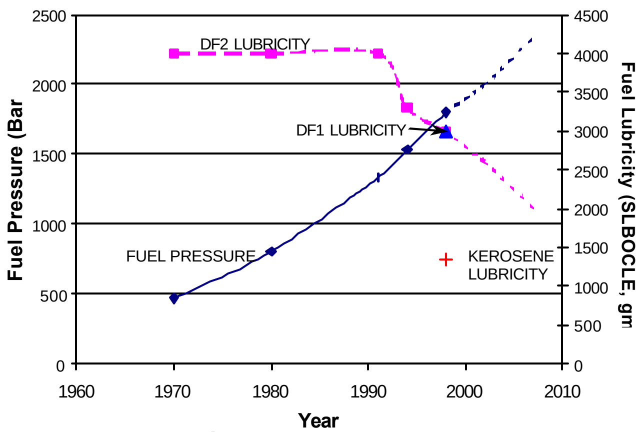

Figure 1. Fuel system pressure and fuel lubricity trends

Why Ceramics?

In highly loaded fluid-lubricated interfaces, boundary lubrication conditions often exist. In this situation the two surfaces are not completely separated by the fluid film and asperity contact occurs. Very high contact pressures exist at these points of contact. In the case of metal-on-metal contact, this can result in the micro-welding of asperities due to the similar metallic atomic bonding structure. Micro-welding results in material transfer from one surface to the other and a roughening of both surfaces, which further increases the asperity contact and frictional heat generation, eventually resulting in gross material transfer (adhesive wear), sticking, and seizing of the mating components.

Due to dissimilar atomic bonding, ceramic materials significantly reduce micro-welding of asperities and the cycle of degradation that takes place with steel-on-steel contact. Since ceramic materials are much harder than many tool steels, abrasive wear is also reduced. These characteristics increase the contact pressure/sliding velocity (PV) capability of a ceramic-steel interface.

Evidence of this benefit was observed by Cummins in the mid-1980's with FALEX 1 rig testing which compares steel-steel and silicon nitride-steel combinations in sliding contact, Figure 2. Dramatic wear reduction was observed even in used lubricating oil containing high levels of soot.

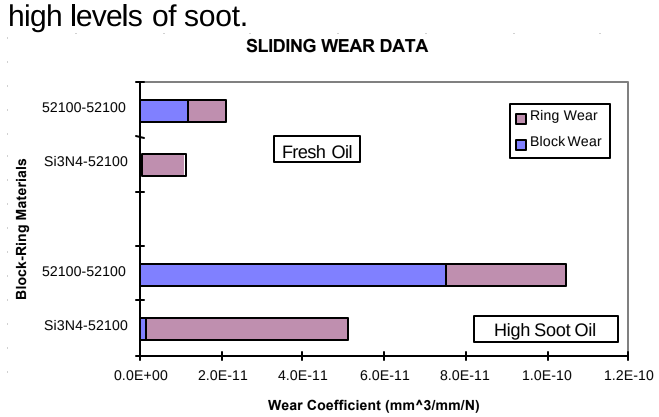

Figure 2. Silicon nitride and 52100 wear coefficients

Ceramics surfaces can be obtained as solid ceramic components or as coatings, such as titanium nitride (TiN) or amorphous carbon, on a steel substrate. Coating systems are the best choice for certain applications, but coating processes are often difficult to control and can be expensive. Coatings are also typically only a few microns thick. Once a coating is worn through to the substrate, adhesive wear again becomes a problem.

In the past 10 years, solid ceramic components have become a viable, cost-effective alternative to coatings and provide superior performance to steel.

Applications/Benefits

The benefits that solid ceramic components can provide to fuel systems are illustrated through several successful production applications.

Fuel Injector Link

The first known application of a ceramic component in a heavy-duty diesel fuel system was the silicon nitride link used in the Cummins STC™ unit injector, Figure 3. This component

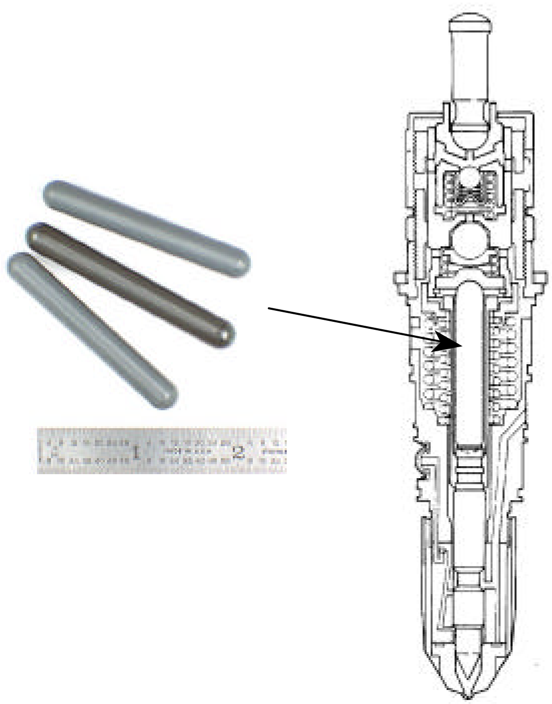

Figure 3. Silicon nitride injector links and Cummins STCÔ unit injector

was introduced to improve the tolerance of the injector to higher levels of soot in the lubricating oil, as a result of changes required to meet the 1988 U.S. emission reductions. From previous wear testing, it was known that silicon nitride would provide improved wear resistance. Engine testing proved the performance increase, Figure 4.

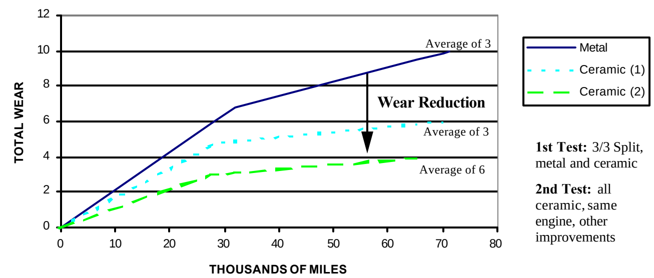

Figure 4. Engine test data on silicon nitride link

By replacing this one part, the total wear rate of the injector train was reduced significantly, more than doubling the mileage until adjustment was required. Additional changes to the injector increased this adjustment interval further. In the 11 years since introduction, 2 million links have been put into service without a single reported incident. The links are often re-used when the injectors are rebuilt, further evidence of the wear resistance of the ceramic link.

Fuel Pump Roller

Stanadyne's DS 50 electronically controlled fuel pump is used on the General Motors 6.5L diesel engine, which is installed in full-size pickups and vans, Figure 5. Stanadyne began seeing higher rates of pump distress after the federally mandated reduction in diesel fuel sulfur levels in October 1993. The steel rollers, which are fuel lubricated, were scuffing and seizing at an increased rate. The rollers experience both sliding and rolling contact in this application. Several years previously, Stanadyne had tested silicon nitride rollers for operation with kerosene and were familiar with this potential solution.

Stanadyne had worked on improving the form and surface finish of the steel rollers in an attempt to increase the lubricating film thickness and thereby reduce the boundary

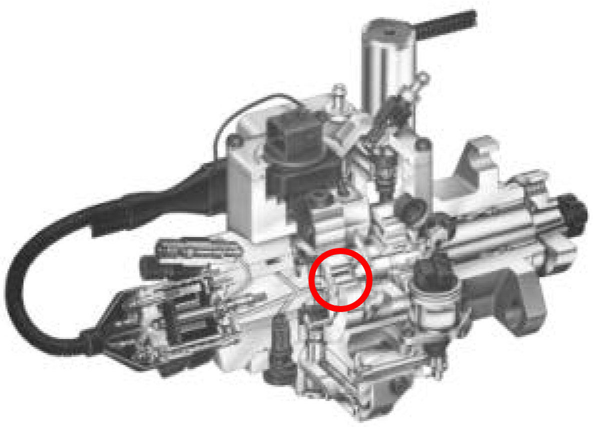

Figure 5. Stanadyne DS 50 fuel pump

lubrication conditions. With the silicon nitride roller, form and surface finish tolerances could be relaxed, as the silicon nitride-on-steel combination was more tolerant to asperity contact.

Figure 6. Silicon nitride rollers

The improved performance of the silicon nitride rollers was proven through rigorous abuse and durability testing. Abuse testing included high fuel temperature and pressure, overspeed condition, water in fuel, debris in fuel, and testing with low lubricity fuels. The improved performance has been demonstrated conclusively in the field. In the four years that the silicon nitride roller has been used in production, there has not been a single reported pump failure due to roller sticking or seizing.

High Pressure Check Balls

Check balls are another vulnerable fuel system component that seal pulsating, high fuel pressures. The combination of high frequency, high-load impact of the ball against the seat combined with the poor lubrication environment leads to deformation and wear of the ball and seat. The resulting fuel leakage can result in poor idle control, inability to turn the engine off, and other fuel system performance problems.

Silicon nitride has been proven to be a superior material for this application. With less than half the weight of steel, impact forces are reduced. The high hardness of the balls minimizes the deformation and causes the seat to conform to the ball for an improved seal. Reduced adhesive wear prevents transfer of material. Resistance to corrosion and being non-magnetic are additional useful properties. Because the silicon nitride balls are widely used in the bearing industry, they are readily available in a variety of sizes at reasonable cost.

Incorporation of silicon nitride check balls in Cummins CELECT™ injectors in 1992 improved the injector performance. Other major fuel system manufacturers are also using silicon nitride check balls in both diesel and gasoline systems.

High Pressure Pumping Plungers

The use of advanced ceramic materials for high-pressure pumping plungers has dramatically increased the reliability of Cummins' fuel systems in recent years. Cummins had experienced a certain level of plunger scuffing and seizing since the introduction of the CELECT™ fuel system in 1990. The rate of incidents was observed to increase in winter months in northern climates when the use of DF1 was increased. Water in the fuel was also found to initiate scuffing and seizing. The problem became more widespread with sulfur reduction in diesel fuel in late 1993. Various attempts to improve the situation, such as improvements in bore and plunger geometry, surface treatments, different steel materials, etc. met with limited success.

Due to the low thermal expansion coefficient of silicon nitride, this material could not be used in this application. A tight clearance between the plunger and bore had to be maintained over the operating temperature range to prevent fuel leakage. Zirconia was determined to be a more suitable material. Cummins was familiar with zirconia technology as a result of work that was sponsored by the DoD in the early 1980s. Cummins was the project manager of a program to work with U.S. suppliers to develop advanced zirconia materials capability in this country. Figure 7 shows a sectioned schematic of the Cummins CELECT™ injector with the pumping plungers visible.

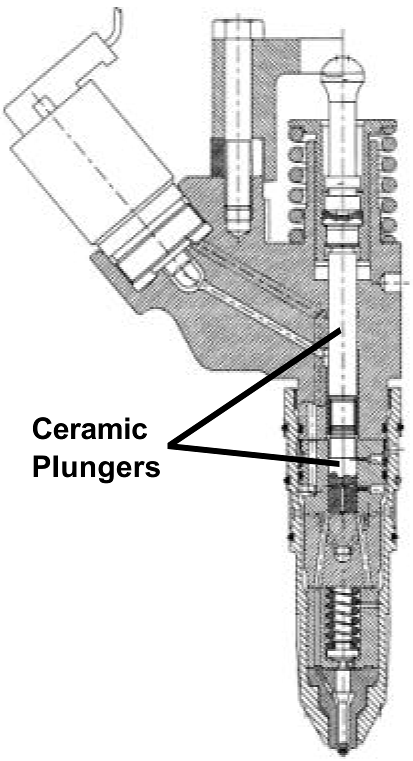

Figure 7. Cummins CELECTÔ injector

Testing of injectors with ceramic plungers provided dramatic evidence of improvement. With 1% water in fuel, steel plungers would seize in 10 hours or less. Zirconia plungers operated more than 300 hours with 2% water in fuel without failure. Plungers were also tested with an angled top surface to purposely increase the side loading forces. There was no affect on performance. Other tests included overspeed and overpressure conditions and alternative fuel (low lubricity) testing. In all cases, the zirconia plungers far exceeded the performance of the steel plungers. A comparison test to determine injector bore wear when using plungers of different materials found zirconia to be far superior to uncoated steel and titanium nitride coated steel, Figure 8.

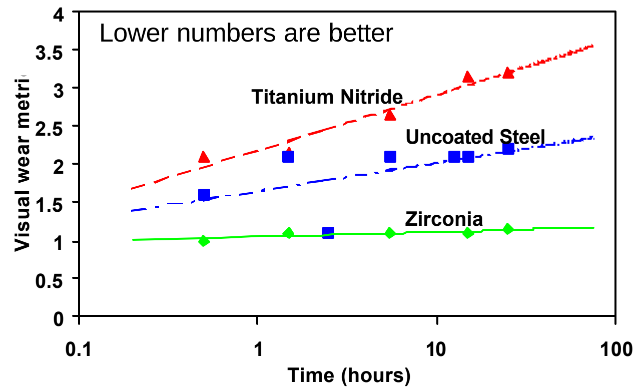

Figure 8. Injector bore wear as a function of plunger material and time

The improvement provided by the zirconia plungers was immediate and dramatic in production. Occurrences of plunger sticking were essentially eliminated with the introduction of the first zirconia plunger, Figure 9. A dramatic improvement in injector reliability resulted as the use of zirconia plunger-equipped injectors became widespread.

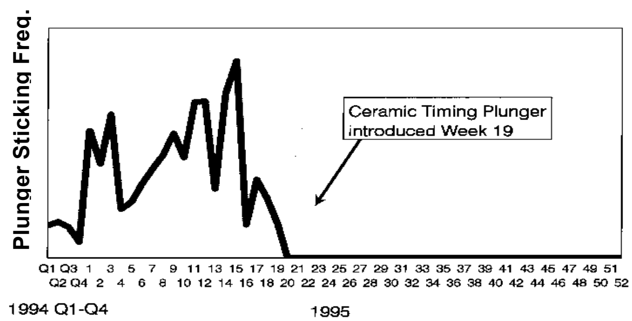

Figure 9. Plunger sticking frequency

The excellent experience with the CELECT™ injector led Cummins to incorporate zirconia plungers into the new CAPS™ common rail fuel system early in the development program, Figure 10. This marked a milestone, as it was the first time that a diesel engine company had introduced a ceramic component before a system was in commercial production. All prior ceramic applications had been retrofits of an existing steel component to resolve some wear or scuffing issue in a production system.

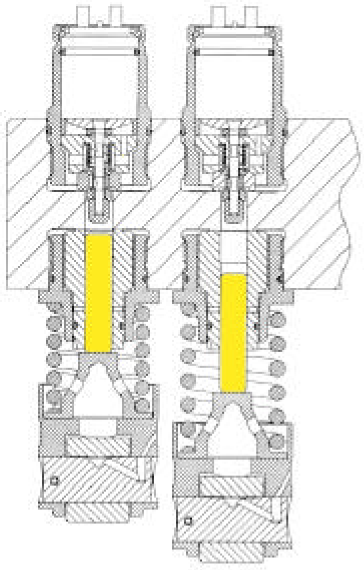

Figure 10. CAPSÔ high pressure pump section showing ceramic plungers

Summary

Ceramic materials have proven to be a valuable technology for improving the reliability and durability of high-pressure diesel fuel systems in the more challenging environment brought on by the drive to produce engines with lower emission levels. The reduction in adhesive wear between ceramic and steel components in boundary lubrication conditions has resulted in dramatic reductions in seizing, sticking and wear of diesel fuel system components that operate with reduced lubricity and/or contaminated fuels and oils. The increased capability of these materials allow fuel system developers to design more capable systems that can operate as-designed for longer periods of time. Continuing efforts to develop improved materials and machining processes and the confidence gained with these successful applications will allow ceramics to be applied in new ways and at lower cost.

Acknowledgements

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