Success Story

Ceramic Fuel Injectors Help Reduce Diesel Emissions

Background

The electronically actuated fuel injectors on today's heavy-duty diesel engines operate at temperatures as high as 815˚C and pressures approaching 20,000 pounds per square inch (psi). Research has shown that improving engine efficiency and lowering emissions always depends on the engine's fuel injection system achieving very high performance. To meet these exacting requirements, fuel injectors must be machined to extremely close tolerances that are sometimes less than one micrometer. The harsh environment in which they operate, however, often causes the injection plungers to display signs of wear, erosion, and scuffing, depending on the construction material.

The introduction of low-sulfur diesel fuel in 1993 for on-highway vehicles was milestone in the continuous improvement of diesel technology. The new fuel has five to seven times less sulfur than the fuel in use prior to 1993, however this has resulted in lower lubricity and a subsequent increase in scuffing and wear for metal plungers in fuel system injectors.

With the assistance of Oak Ridge National Laboratory (ORNL), Cummins, Inc. (Columbus, Indiana), began researching the possibility of using ceramic fuel injection plungers to replace the metal ones. At first glance, most ceramics would seem to be ideal construction materials for fuel injector plungers because they generally have very hard surfaces, can be polished to smooth finishes, are resistant to corrosion and erosion, and often perform very well in wear and friction applications. But typical ceramics are also very brittle, meaning that they could eventually fracture or chip.

Zirconia fuel injector components are replacing metal ones, eliminating some of the problems associated with the use of low-sulfur diesel fuel.

One ceramic material that doesn't fracture in such a demanding application is transformation-toughened zirconia (TTZ). This very resilient ceramic resists fracturing and chipping because of a unique property whereby stress induces changes in its crystal type rather than causing fractures. This material was selected for further research under Cummins' fuel injector plunger development program.

A critical feature in the operation of injector plungers is maintenance of a minimum clearance to prevent fuel leakage. Silicon nitride, a ceramic originally considered a candidate material for the new injectors, has a coefficient of thermal expansion (CTE) much lower than steel (2.6 ppm/˚C vs. 12 ppm/˚C). Silicon nitride would therefore be unable to maintain the tight clearances required over the entire range of operating temperatures.

Yttria-stabilized zirconia had a CTE closer to that of steel (10.5 ppm/˚C) but exhibited a phase transformation and loss of strength when exposed to water and organic acids in the operating temperature range.

Magnesia-stabilized zirconia had an adequate CTE (9 ppm/°C) and showed no loss of strength from environmental or temperature factors.

Cummins conducted extensive bench and rig testing of the new timing plunger, and additional engine testing proved its ability to withstand scuffing and seizing even with water introduced into the fuel.

A significant barrier to timing plunger implementation was the lack of high-volume centerless grinding capability to grind the outer diameter of the plungers to sub-micron tolerance levels. Cummins has since developed this capability and performs the final outer diameter grinding operations in-house.

Commercialization

A zirconia timing plunger was introduced in 1995 under the CELECTtm trademark. Following the success of the timing plunger, a CELECTtm zirconia metering plunger was introduced in 1997. This component displayed an increased level of complexity requiring sharp metering edges in two locations. The grinding and handling operations were improved to maintain these edges.

In 1998, Cummins introduced the CAPStm common rail fuel system for mid-range engines. The new fuel system contained a zirconia pumping plunger, and was the first system at Cummins to be introduced into production with a ceramic component included in the design and development process.

Cummins is constantly seeking to improve the performance of its new ceramic injectors. In 2001 a new, higher strength zirconia showing improved robustness and closer matching under operating conditions was introduced for all three applications.

Benefits

- Zirconia injectors resist scuffing and wear caused by the reduced lubricity of low-sulfur fuel
- Close cooperation among ORNL, Cummins, and ceramic suppliers has resulted in the development of improved zirconia ceramics
- The successful incorporation of zirconia injectors will allow the further advancement of emission reduction technologies for diesel engines

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