Success Story

Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Ceramic Fuel Injectors Help Reduce Diesel Emissions

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

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.

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.

The Technology

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.

The Technology

The conversion of PAN to carbon fibers is normally made in four continuous stages:

- Oxidation followed by stabilization of the polymer
- Carbonization to convert the fibers to nearly 100% carbon
- Surface treatment to provide better adhesion to the resin
- Sizing to protect the fibers during further processing and to provide a resin-compatible interface

The carbonization step involves heating the fibers to 1000–1500°C in an inert atmosphere. Researchers at Oak Ridge National Laboratory (ORNL) are developing microwave-assisted plasma (MAP) technologies to carbonize and graphitize PAN precursor. Using continuous MAP processing creates a carbon fiber with very uniform properties, suitable for use by the automotive industry at a significantly reduced cost over conventionally produced fibers.

ORNL has also developed a novel method for producing an axially undulated surface on the carbon fibers using plasma technology and microwave radiation. The undulated surface allows the fibers to interlock mechanically with the resin matrix, thereby resisting fiber pullout. Mechanical properties that are compromised by fiber pullout, notably interlaminar shear strength and in certain cases axial compression strength, should be enhanced by producing fibers with axially undulated surfaces.

ORNL's initial continuous pilot unit was designed to achieve a line speed of 6 inches per minute to demonstrate technical feasibility. Recently, line speeds in excess of 200 inches per minute have been achieved. This exceeds most conventional processing line speeds.

ORNL's MAP carbon fibers have achieved a tensile modulus between 29–32 million pounds per square inch (Msi) and ultimate tensile strength of 342–424 thousand pounds per square inch (Ksi), exceeding the target values of the FreedomCAR Partnership. Comparable, conventionally manufactured carbon fiber attains 31 Msi modulus and 485 Ksi ultimate strength.

Commercialization

Two patents have been awarded and others are pending on this technology, which has the support of U.S. carbon fiber manufacturers. Considerable interest has been generated in industry and there have been many inquiries concerning technical and economic data from fiber and processing equipment manufacturers.

Benefits

- Savings of 40% in direct production costs and a reduction in the cost of finished carbon fiber of about 18%
- Faster processing speed over conventional production methods
- Reduced space requirements and capital outlay for plant and equipment
- More uniform product quality and reduced waste

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