Fabrication of Small-Orifice Fuel Injectors

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Outline

• Introduction & Background
  - The Need
  - A Path
  - The Concept
  - The Method

• Implementation

• Application

• Conclusions & Further Work
The Need

• Decrease emissions
  - 2007 EPA emissions guidelines for diesel engines are quite stringent
  - Further emission reduction mandates are likely
  - Diesel engines are more efficient than SI engines
  - Keeping diesel-powered vehicles on the road thus saves energy

• Increase fuel efficiency
  - Unburned fuel and incomplete combustion reduces engine efficiency
  - Improving combustion process will increase efficiency
A Path

- Many different strategies for reducing emissions are being tried
  - Aftertreatment devices
  - Changes in engine cycle
  - Changes in injector design
- EPA: PM emissions from an LD engine reduced by using 75 µm orifice injectors
- SNL: PM eliminated in bench tests by reducing injector orifice diameter to 50 µm

Problems with Small Orifices

• Decreased fuel delivery
  - Compensate by increasing injection pressure, number of spray holes, and/or discharge coefficient

• Sensitivity to plugging
  - Coking potentially a major issue, especially with alternative fuels such as biodiesel

• These must be considered
The Concept

• Economically fabricating 50 µm-orifice injectors on a commercial scale is currently impossible
  - Limit for economical EDM fabrication is 100 µm
  - Other technologies (laser drilling, LIGA, etc.) too difficult to scale up

• Solution: Reduce orifice diameter by coating the ID of a current-technology injector
  - Wide array of techniques for depositing material
  - Select an appropriate one
The Method

- After careful examination of the available techniques, we chose Electroless Nickel (EN) plating
  - Mature technology, inexpensive, widely commercialized
  - Highly conformal coatings of internal surfaces
  - Potential for depositing different alloys to tailor:
    - Mechanical properties: Erosion resistance
    - Chemical properties: Corrosion/Coking resistance
Potential Issues

- Hole size—is diameter reduction to 50 µm possible using EN plating?
- Uniformity—does the coating process change the circularity of the holes and/or the needle guide?
- Adhesion—will the coating come off in use?
- Durability—is the coating capable of resisting the impact loads in the needle seat and the possibility of cavitation erosion in the orifices?
- Surface finish—is the coating smooth enough in the as-deposited state, or will further processing be necessary?
Results: Hole Size & Uniformity

- We have reduced orifice diameter to 50 µm in bench-scale tests, and to 75-80 µm in commercial-scale tests.

- Circularity and uniformity also appear to be satisfactory.
Results: Hole Size & Uniformity (cont’d)

- Scatter in the diameter is due to a surface finish issue, since resolved
Results: Adhesion

- Initially we had problems with adhesion in our bench-scale coatings.
- Adhesion on the commercial-scale coatings is excellent, as shown by Rockwell indent tests.
Results: Durability

- In bench-scale tests, coating hardness ranged from HK$_{50}$ 400 to 800, depending on phosphorus level, vs. substrate hardness of ~700.
- Softer coatings generally have higher strain-to-failure.
- We can thus tailor the coating to give optimal durability in use.
- Impact tests for the needle seat are planned.
Results: Surface Finish

- Initial surface finish in as-received spray holes is $R_A$ ca. 0.5 µm
- In bench-scale tests, the best final spray hole $R_A$ was ca. 0.2 µm
- In bench-scale plating tests on flats with different $R_A$ values, the post-plating $R_A$ was always lower than the initial $R_A$

- Orifice interior micrographs before (L) and after (R) 15 min EN plating; image size 100 µm across
Results: Surface Finish (cont’d)

Surface Roughness

- Smoother surfaces should lead to higher discharge coefficients
Results: Surface Finish (cont’d)

- Initially there were problems with the commercial-scale coatings, caused by accumulation of hydrogen bubbles on the surface.

- These were solved in the most recent set of coatings.
Results: Combustion Deposit Resistance

- In bench tests, the commercial EN plating bath appears to be less prone to deposit formation than steel.
**Results: Combustion Deposit Resistance (cont’d)**

- PSMO tests are also encouraging
Results: Combustion Deposit Resistance (cont’d)

- Further bench tests at 250°C with high-oleic sunflower oil show even greater differences between steel and EN

High-Oleic Base Oil Deposit and Volatiles Mass% in Open Air at 250°C
Conclusions & Future Work

• Economical fabrication of fuel injector nozzles with orifice sizes 50-75 µm via EN plating has been demonstrated

• Further work is in progress or planned:
  - Spray visualization and LD engine testing
  - Impact resistance tests on coated needle seats
  - Spray tests with alternative fuels