Agreement 9440 - Fabrication of Micro-orifices for Diesel Fuel Injectors

George R. Fenske and Nicholaos Demas
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
(630)252-5190; fax (630)252-4798; e-mail: gfenske@anl.gov

DOE Technology Manager: Jerry Gibbs
(202) 586-1182; fax: (202) 586-1600; e-mail: jerry.gibbs@ee.doe.gov

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Objectives

- Develop a methodology for reducing the diameters of fuel injector orifices to 50 μm by applying material to the internal diameter (ID) of the orifice. Micro-orifices should improve fuel distribution, increase efficiency, and reduce emissions in compression-ignition, direct-injection (CIDI) engines.
- Characterize the spray and combustion properties of the fuel injector system coated with electroless nickel (EN) and other advanced ID coating processes.
- Transfer the developed technology to DOE industrial partners.

Approach

- Reduce the orifice diameter by coating its interior with EN plating for improving the surface finish and reducing deposit formation on injector nozzles.

Accomplishments

- In collaboration with the U.S. Environmental Protection Agency (EPA), characterized the spray characteristics of EN-coated commercial nozzles.
- In concert with Imagineering, Inc. (a commercial plating company), developed a method for improving the surface finish of commercial-scale plated nozzles.
- Used x-ray phase imaging for nondestructive examination of thin EN coatings applied onto the nozzles.
- Examined the microstructure and micro-hardness of commercial nozzles.
- Evaluated coating integrity using micro-indentation and examined the variation of coating thickness as a function of depth using non-destructive x-ray imaging analysis.
- Established collaboration with injector manufacturer (Robert Bosch GmbH) to perform engine testing of plated nozzles for deposit mitigation.
- Simulated cavitation erosion and evaluated the impact of EN plating on erosion.

Future Direction

- Characterize spray properties of EN-coated multi-sized orifice nozzles in collaboration with the U.S. EPA.
- Explore establishing a consortium with industrial partners to integrate EN process into a production setting.
- Evaluate EN-plated nozzles under actual engine testing conditions.

Introduction

In 2007, EPA regulations mandated reduction in diesel engine emissions to 0.01 grams of particulate matter (PM) per engine horsepower per hour and 0.2 grams of nitrogen oxide (NO_x) per engine horsepower per hour. Further reductions are expected for 2012. To achieve these levels, CIDI engines are being redesigned to reduce in-cylinder soot production. One design change under consideration is the reduction of the diameter for the fuel injector orifice.

Pickett and coworkers[1,2] demonstrated significant reductions of soot in a test cylinder using experimental injectors with orifice diameters of 50 μm, even with high levels of exhaust gas recirculation and concomitant reduction in NO_x emissions. National Vehicle and Fuel Emissions Laboratory (NVFEL) researchers observed reduced PM emissions from a light-duty diesel engine equipped with 75-μm-diam injector orifices. These reductions arise from increases in fuel atomization efficiency, leading to more complete combustion.[3] Although 100-μm-diam orifices can now be economically mass produced by electrical discharge machining (EDM), further reductions in hole size are accompanied by unacceptable fabrication error rates.

Reducing the orifice diameter (e.g., from 150 to 50 μm) carries with it a number of other penalties. It will reduce the amount of fuel that can be delivered to the combustion chamber without increasing the number of spray holes, the injection pressure, and/or the discharge coefficient. The potential impact of coking on smaller orifices is also much greater, as smaller holes will be more readily blocked by coking deposits on the injector tip and in the spray holes themselves. Coking deposits are a particular problem with tapered-orifice nozzles, another technique for increasing fuel atomization and thus reducing PM emissions.

Another issue is alternative fuels. One method to minimize dependence on foreign oil is the increased use of bioderived fuels, such as vegetable oil esters. Because of the presence of carbon-carbon double bonds in the carboxylic acid chain precursors, these fuels readily form coking deposits in the combustion chamber—a major problem in concert with smaller spray holes. Other alternative fuels include alcohols such as methanol or ethanol. These are not typically used neat but are blended with conventional diesel fuel. One emissions reduction strategy is to inject an ethanol/water mixture along with conventional fuel, reducing the combustion temperature and NO_x emissions. However, alcohol partial oxidation products can include corrosive carboxylic acids, which will damage the steel nozzles over time.

In concert with more commonly used fabrication techniques, EN plating has been used to prepare fuel injector nozzles with orifice diameters as small as 50 μm.[4,5] EN plating promises to mitigate or solve all of the difficulties described above. The plated surface is corrosion-resistant and smoother, and the discharge coefficient of the plated orifices is higher. This method can be used to deposit a wide variety of alloys, offering the possibility of tailoring surface chemistry to reduce or eliminate deposit formation.

Approach

As described in previous progress reports, the diameter of an orifice can be reduced by coating its interior with EN plating. This technique has been used to deposit nickel/phosphorus or nickel/boron alloys onto metallic surfaces from aqueous solutions. It has been successfully used in previous years to reduce the orifice diameter from 200 to 50 μm on a bench scale, and from 180 to 75–80 μm on a commercial scale. Other metal alloys have been deposited by the same technique.

Having demonstrated that EN plating reduces the orifice diameter to the desired size, we next sought to demonstrate the usefulness of EN-plated nozzles for solving the challenges described in the Introduction: improving spray properties and discharge coefficients, reducing deposit formation, and resisting corrosion. To this end, phase-

contrast x-ray imaging at Argonne's Advanced Photon Source (APS) was explored for nondestructive examination of plated nozzles.[6] This technique is capable of measuring coating thicknesses on internal passages and was applied as a quality check on nozzles that were sent to the EPA for engine tests.[7]

In collaborative studies with the EPA, fuel sprays produced with EN-coated commercial nozzles yielded encouraging results, and during FY10, we explored the application of EN plating to produce multi-sized orifices (e.g., 50 μm and 125 μm) on a given nozzle. Research also continued to evaluate the use of EN coatings as an approach to mitigate erosive wear.

Results

In FY11, activities were continued to develop/demonstrate the ability to fabricate multi-sized orifices that improve the ability to direct fuel to a broader area in the combustion chamber, as well as to evaluate the potential of EN platings for mitigating orifice erosion. The microstructure and composition of the nozzles were characterized using secondary electron microscopy (SEM) and energy dispersive x-ray (EDX) analysis, respectively. EDX analysis near the orifices revealed the presence of tungsten, which originated from the wire used to EDM the holes. This impurity compromised coating integrity in some samples and was responsible for cosmetic surface blemishes on the nozzles. Mechanical polishing removed the blemishes and resulted in a greatly improved surface around the holes.

Our latest work has involved a coordinated effort between various industrial partners to fabricate multi-sized orifice nozzles. During FY11, coated nozzles consisting of 12 orifices (six 50-μm holes and six 120-μm holes) were sent for regrinding. During the regrind, the interior surface of the nozzle-body collar was out-of-round, which made it difficult to be matched to the needle guide. To overcome these unforeseen issues and prepare the matched assembly for testing, all the nozzles were ground to a larger ID bore size, and new needles were manufactured to fit the nozzle. After significant delay, the nozzles were received and prepared for spray visualization studies. To address the issues encountered during the regrinding, a masking process during EN plating is being pursued, in which the interior surface of the nozzle-body collar is protected by Teflon® tubing. Positive results have been obtained when using the mask. However, additional work is required to determine the optimum length to be masked and to address adhesion issues that have arisen when trying to mask the interior surface of the nozzle body.

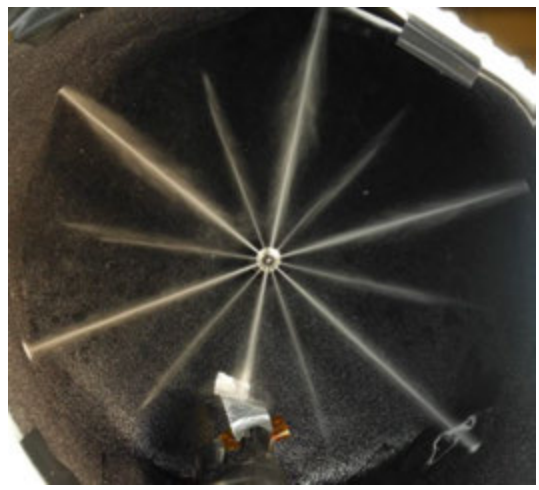


Figure 1. Photograph of the spray of a nozzle with two sets of holes mounted into a pop-tester used for spray tests

Also, in FY11, high-speed photography of the spray patterns produced by nozzles with multi-sized orifices was performed using a pop-tester setup specifically developed for this purpose. The spray of one of the nozzles obtained with the pop-tester is shown in Figure 1. The injection pressure for all nozzles was 200-400 bar (the spray was injected into lab air at 1 bar). This rig is used to confirm that the orifices are not blocked. As seen in this figure, all 12 orifices are open, and one can discern a difference between the small and large orifices.

A set of commercial-size nozzles containing eight 119-µm orifices was sent to an outside company that specializes in EDM processing of nozzles. This company completed EDM processing of 178-µm orifices equally spaced between the 119-µm orifices. Upon close examination of the inside of the nozzle using a boroscope, we noted that the orifices were not placed precisely. Figure 2 illustrates the problem.

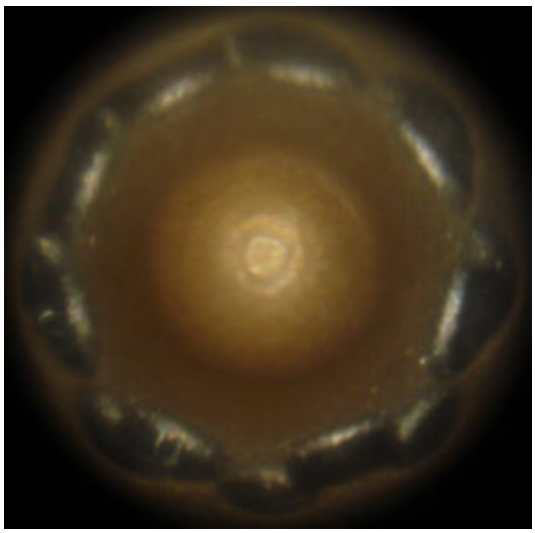
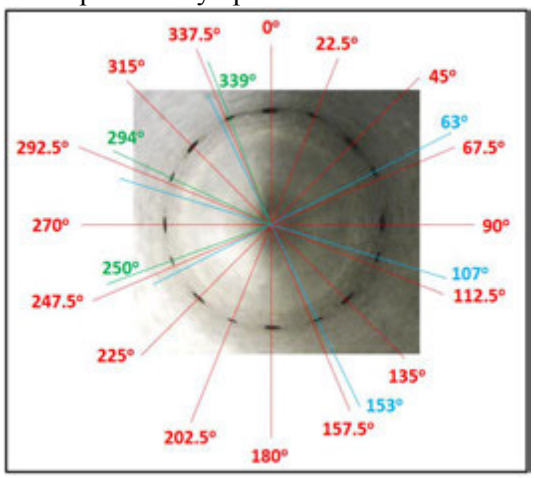


Figure 2. Boroscope image of the nozzle interior after EDM

Examination of the pre-existing orifices on a number of nozzles indicated that the orifices were not at the locations specified in the schematics that were provided by the manufacturer. Using one of the orifices as a reference point, we located the remaining orifices and found that the remaining 7 orifices were out of position up to 6°. This discrepancy would account for the overlap of the holes on the inside of the nozzle bore observed in Figure 2.

Figure 3 shows a micrograph of the top-view of a nozzle. The red lines denote the proper orifice locations. At 0° there is the first 178-µm orifice placed by our EDM industrial partner. Every 45 °, the rest of the 178-µm orifices can be seen, and it is obvious that they have been placed correctly. However, the 119 µm orifices, which would be expected at 22.5 ° and every 45 ° after that, have not been placed correctly. The blue and green lines show actual locations. The 119-µm orifices are out of position by up to 5.5°.



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Micrograph of nozzle showing orifice locations and deviations of the pre-existing orifices from schematics provided by the manufacturer

We are in communication with the nozzle manufacturer to circumvent this issue by either starting with blank nozzles or determining whether there was an error in the batch of nozzles we received.

During FY11 we examined a limited number of nozzles using a 3-D X-ray imaging system. We are using this non-destructive analysis supplemented by microscopy measurements to look for surface defects and coating uniformity, and to measure the sizes of the holes. As previously mentioned, the technique allows for 3-D rendering so that areas of interest may be targeted, as well as selective 2-D imaging. Figure 4 shows a top-down "slice" of one of the latest eight-orifice nozzles after EN plating using this technique.

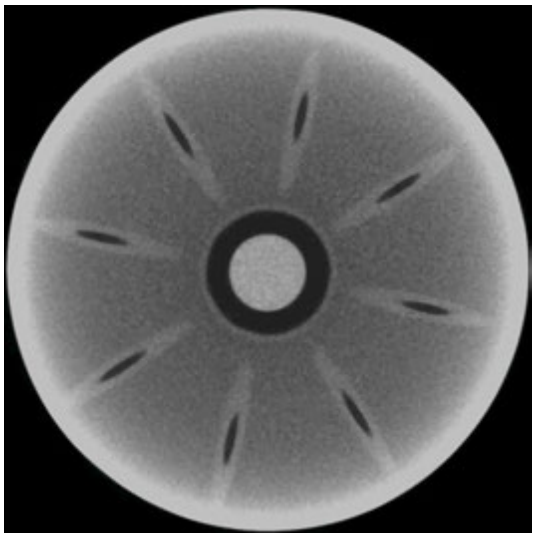

Figure 4. X-ray top-down slice of a multi-orifice nozzle

Plating can be seen around the holes as a lighter shade of gray. A single frame of a 3-D rendered video is shown in Figure 5. Using this technique, we can examine interior passages during the 3-D rendering "mode," as seen in this figure.

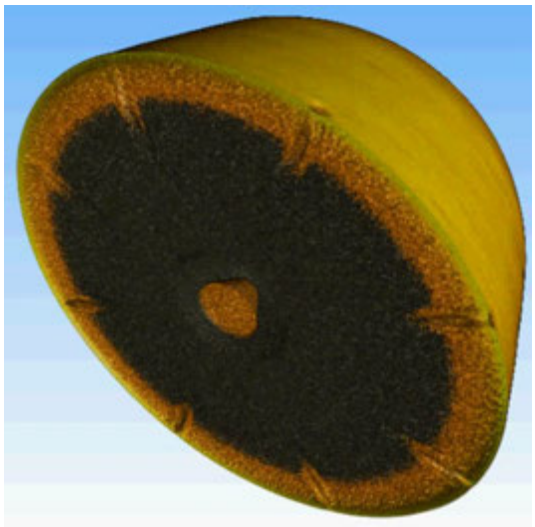

Figure 5. Snapshot of a 3-D rendering showing the tip of a nozzle

Using a micro-indentation technique at the coating/substrate interface, we demonstrated that the adhesion of the EN coatings to the orifices is very good. A benchtop ultrasonic apparatus was developed to simulate cavitation erosion and evaluate the impact of different alloy compositions and treatments on erosion. Specimens were machined out of a very similar material in composition to that of a nozzle and tested according to the ASTM G32-09 standard ("Standard Test Method for Cavitation Erosion Using Vibratory Apparatus"). A test coupon is shown in Figure 6.

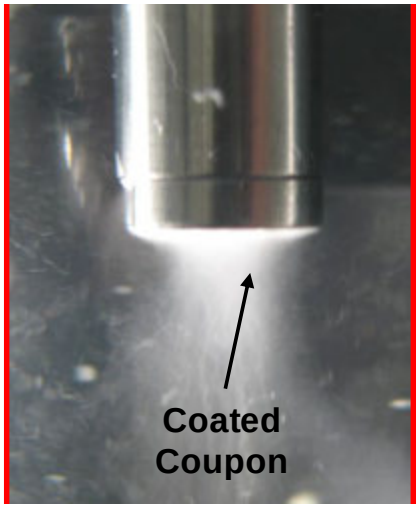

Figure 6. Photograph of an H13 coupon during cavitation erosion test

This method produces cavitation damage on the face of the specimens vibrated at high frequency while immersed in liquid (distilled water). The vibration induces the formation and collapse of cavities in the liquid, and the collapsing cavities produce erosion of the specimen. A specimen is attached by threading into the tip of a horn, which is then attached to the ultrasonic transducer. The specimen is immersed into a container with distilled water, which must remain at a specified temperature during operation while the specimen is vibrated at specified amplitude. The test specimen is weighed before and during testing to quantify mass loss as a function of time. Figure 7 shows cumulative mass loss versus time vibrated at 50% amplitude. From this figure we can see that the plated samples lose mass significantly faster than their bare metal counterparts. Tests were repeated for the first 4 hours, showing similar results. These are also included in Figure 7.

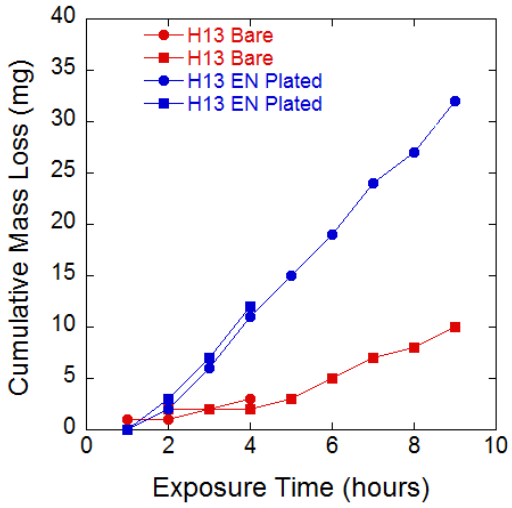

Figure 7. Cumulative mass loss versus time for bare and coated H13 coupons

Photographs of the H13 bare and plated samples are shown in Figure 8 before and after 9 hours of exposure.

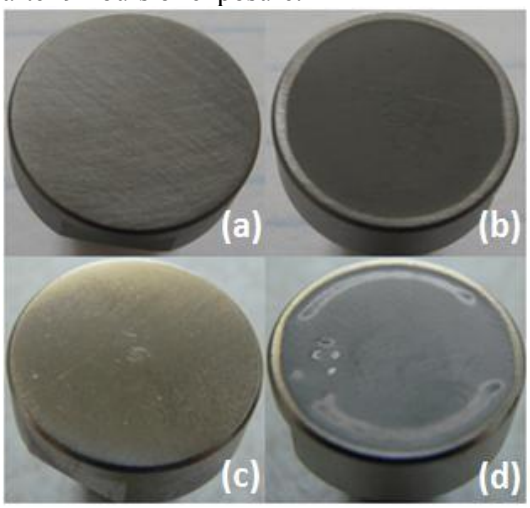

Figure 8. Photographs of bare H13 specimens before (a) and after (b) 9 hours of exposure, and EN-plated H13 samples before (c) and after (d) 9 hours exposure

It is evident that the tests caused some surface damage in both cases. After testing, the bare specimen exhibited a discolored concentric circle, and the EN-plated coupon had surface blemishes in addition to discoloration.

Conclusions

Through a collaborative effort, multi-sized orifices have been fabricated starting with blank nozzles or nozzles with a set of holes, adding holes by an EDM process, honing, grinding and EN plating. Development of the EN aqueous-based plating process has advanced to the stage where commercial nozzles can be treated. Furthermore, an advanced phase-contrast x-ray imaging technique can be used for the non-destructive evaluation of finished nozzles and examination of EN plating.

During FY11, unforeseen manufacturing issues delayed x-ray imaging and spray visualization. A pop tester setup was used to test the nozzles for blockage using high-speed spray photography and ensure spray pressures between 200-400 psi. Cavitation erosion tests were also performed.

Efforts will continue, based on funding availability during FY12, to fabricate large batches of multi-sized orifices in preparation for flow-spray studies.

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