Fuel injector Holes

(Fabrication of Micro-Orifices for Fuel Injectors)

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PM003

Overview

Timeline

- Project start date FY04
- Project end date FY12
- Percent complete 70%

Barriers

- Emissions – reduction of in-cylinder formation of particulates
- Efficiency – improved combustion & mitigation of aftertreatment fuel consumption

Budget

- Total Project Funding ~$1.6M
  - DOE Share ~$1.5M
  - Collaborator Share ~$0.1M

- FY09 $350 K
- FY10 $400 K

Partners

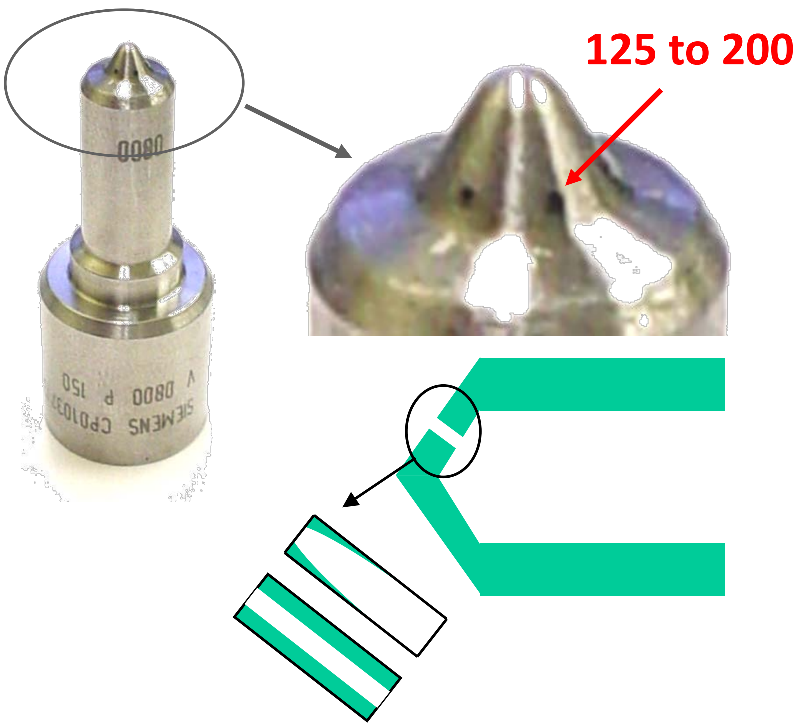
- Imagineering Finishing Technologies
- Fuel system OEMs
- Engine OEM
- Small business - integration of electroless nickel (EN) process into nozzle production line
- U.S. EPA

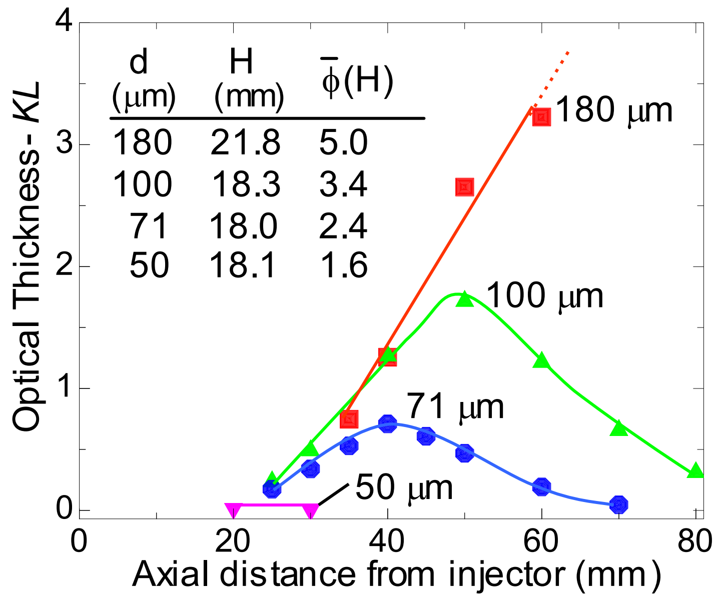
Project Objectives - Relevance

- Main objective/goal of the project is the development of fuel injector manufacturing technology to **reduce diesel emissions** by reducing in-cylinder production of particulates.
  - Potential secondary benefits to improve fuel efficiency through improved fuel atomization & combustion, and, reduction in the use of fuel for regeneration of particulate matter (PM) traps
- Multiple paths being pursued by DOE & industry to reduce emissions
  - Aftertreatment devices (NO_x & PM traps)
  - Alternative combustion cycles (homogeneous charge compression ignition, low temperature combustion)
  - **Improved fuel injector designs – fuel atomization (in-cylinder reduction of particulates)**
- DOE Workshop "**RESEARCH NEEDS RELATED TO FUEL INJECTION SYSTEMS IN CIDI AND SIDI ENGINES**" identified specific needs:
  - **Manufacturing technologies** that would be used for cost effectively producing ultra-small holes and controlling dimensions with ultra precision
  - Materials and coatings to resist fatigue, wear, and corrosion; sensors and controls; non-traditional fuel injection; modeling & simulation, etc.

Objective of Work

- Combustion studies have demonstrated that reducing the orifice diameter on an injector decreases the amount of particulates formed during combustion
- Objective of research is to develop technologies to fabricate **50-µm diameter (or less) micro-orifices** for high-pressure diesel injectors
  - Reduce in-cylinder production of particulates ***(lower emissions)*** **with no fuel economy penalty**
  - Improve combustion of fuel ***(improved fuel efficiency)***





Courtesy L. Pickett SNL-Livermore

Project Milestones

- **FY 2009**
  - Preparation of multi-sized (40/145 µm) micro-orifices on commercial nozzles for spray visualization studies at the U.S. EPA (completed)
  - Establishment of collaborative agreements with engine and nozzle OEMs to accelerate technology validation
    - Negotiating level and type of effort between Argonne and nozzle OEM – level and effort negotiations completed, publication rights under negotiation

- **FY 2010**
  - Demonstration of x-ray absorption imaging technique for nondestructive evaluation (NDA) of internal coated orifice surfaces (completed)
  - Evaluation of ASTM Method G32-09 to determine cavitation erosion performance of plated nozzles (in progress)
  - Preparation of 2^{nd} generation multi-orifice nozzles (50/110 µm) for nozzle OEM evaluation (in progress)

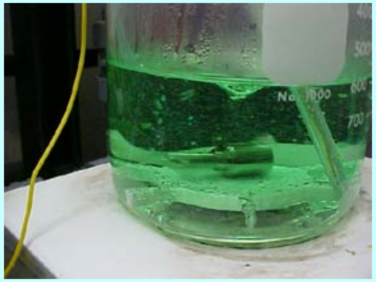
Approach

- Identify potential micro-orifice fabrication techniques
  - No technology exists to economically produce robust 50 µm orifices
- Down select – 50 µm, maturity, cost, scale-up
- Demonstrate feasibility (lab)
- Identify and resolve technical barriers
  - Uniformity, adhesion, deposit formation, hardness, fatigue, reduced flow, etc.
- Treat prototypic components (Tech Transfer)
- Spray visualization studies (EPA)
  - Single-size orifices (50 µm)
- Multi-sized orifices (e.g. 40 µm & 145 µm) orifices on the same nozzle to maintain fuel flow capability and improve combustion
  - Detailed microstructural analysis

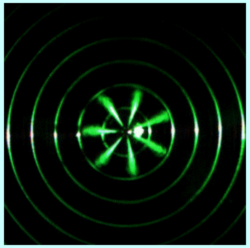
- NDE of multi-size orifices (x-ray imaging)
- Cavitation erosion studies
- Engine emission & efficiency studies

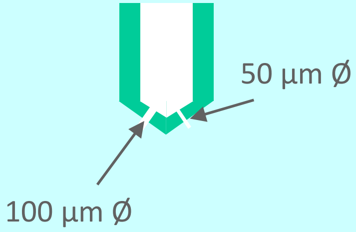
Electrodischarge (current process), plating (**aqueous**, CVD/PVD), laser processing, LIGA, …

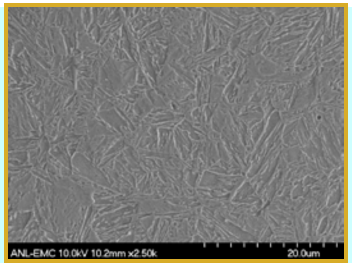
Electroless Nickel (EN) – autocatalytic deposition of Ni from aqueous solution

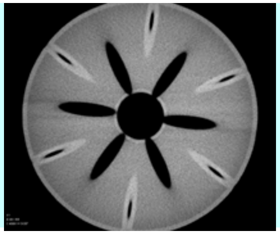


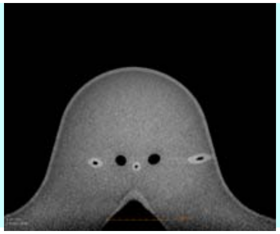
USEPA NVFEL





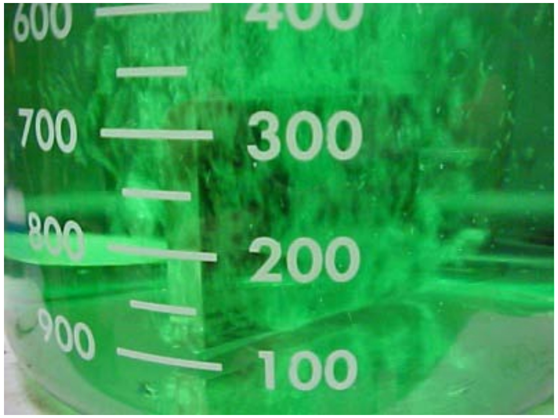


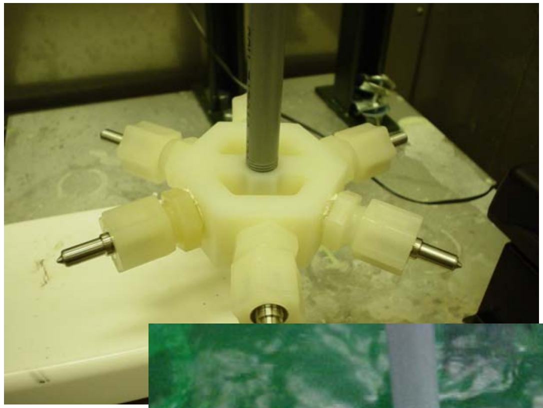


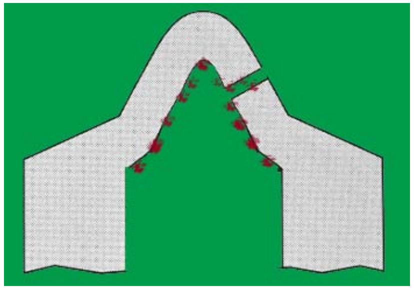


Accomplishment – Demonstrated feasibility to coat interior surfaces of small injector orifices using EN.

- Autocatalytic EN process generates hydrogen bubbles that adhere to surface and prevent uniform coverage.
- Multiple mechanical techniques pursued to mitigate adhesion of H_2 bubbles successfully.

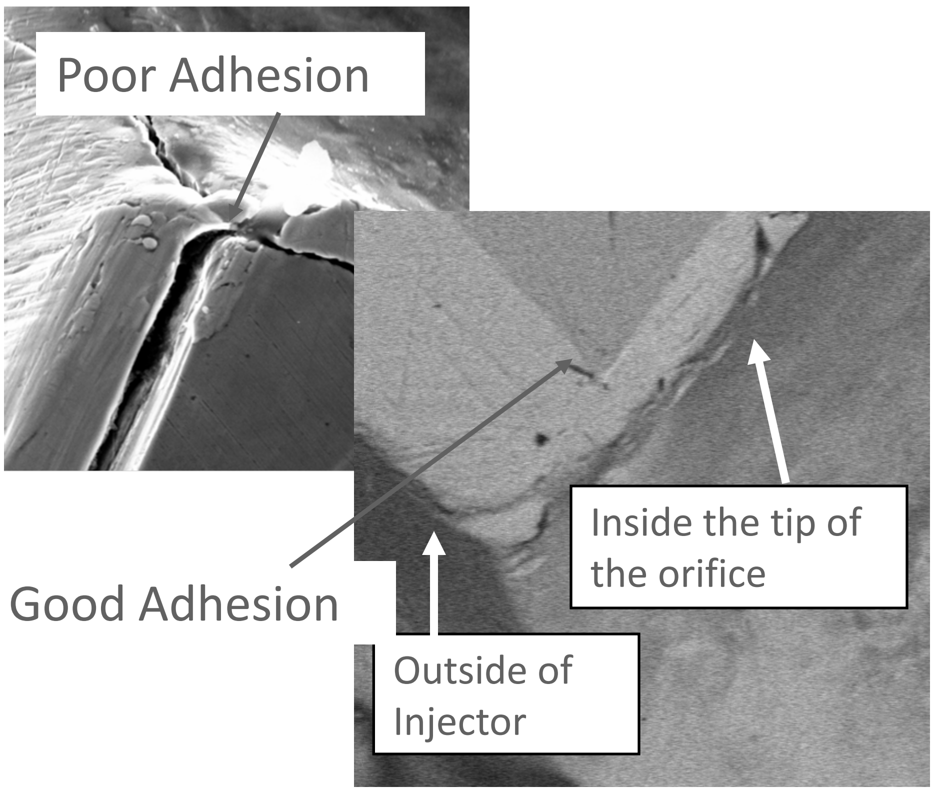






Accomplishment: *Addressed and resolved early issues related to coating adhesion.*

- Initial adhesion issues were addressed and resolved with proper control of precleaning/etching, control of solution chemistry, and post-deposition annealing.



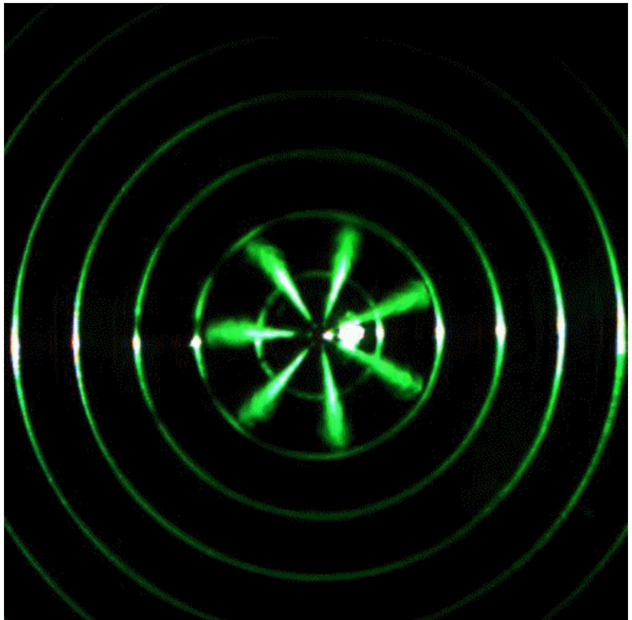
Accomplishment: *Transferred concept/technology to industrial plater/coater.*

- Lab-scale process transferred to commercial size operation.

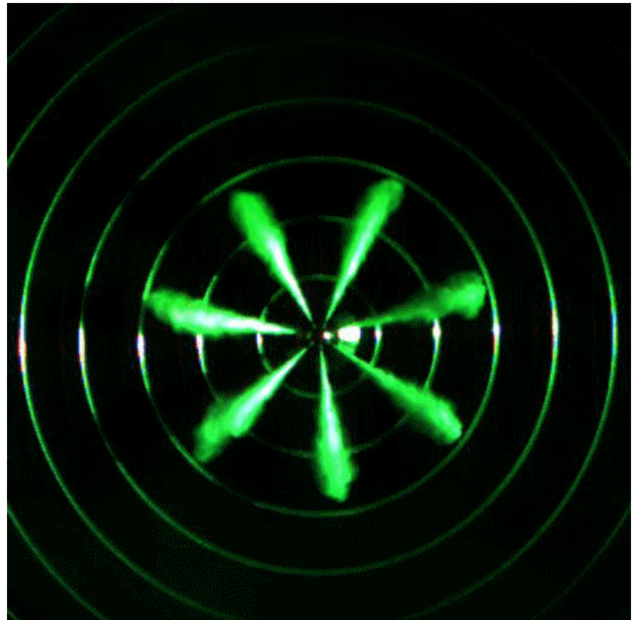
  - Reduced small-batch chemistry variations.
  - Standardized cleaning and post-deposition treatments.
  - Access to knowledge base.

Progress/Accomplishment: *Flow Visualization - Demonstrated enhanced flow characteristics in single size orifices (100, 75, and 50 µm) at 3000 bar.*

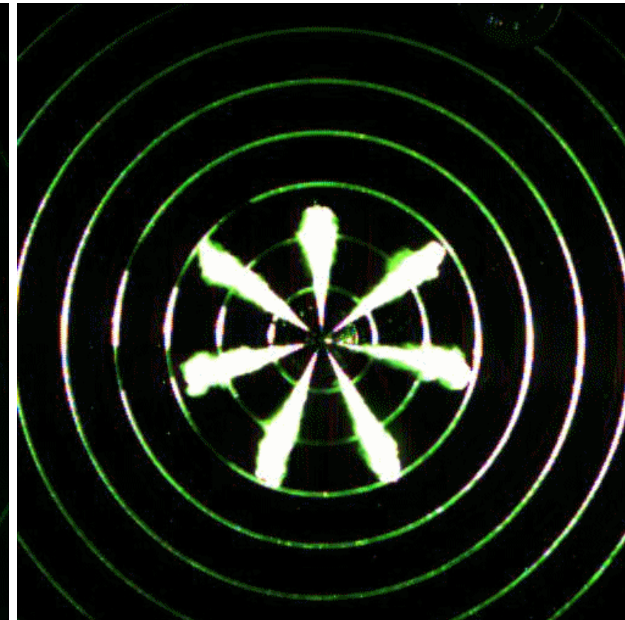
Argonne Nozzle: 7x0.05x157

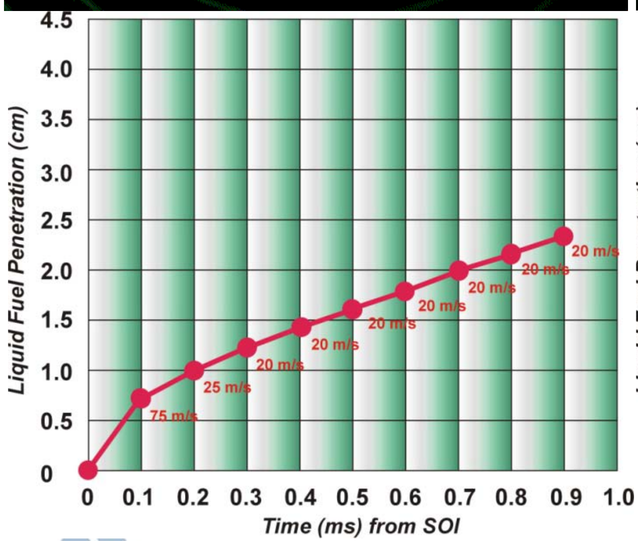


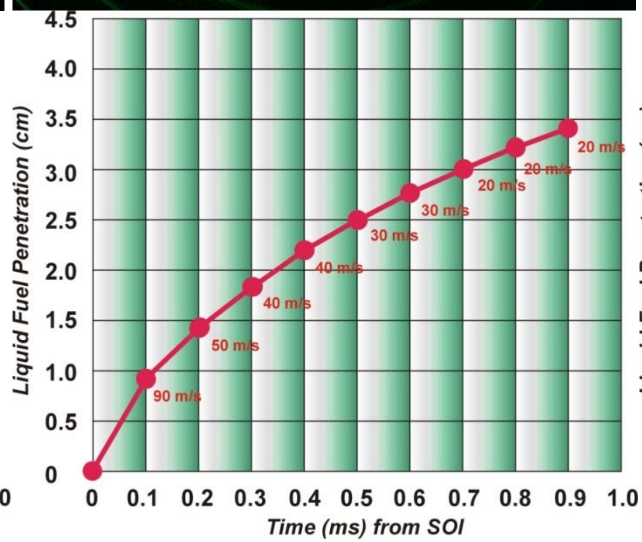
Argonne Nozzle: 7x0.075x157

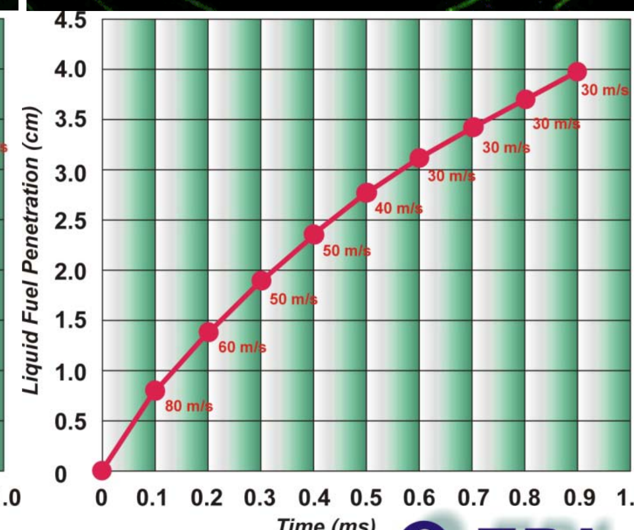


Ann Arbor Nozzle: 7X0.10mmx160





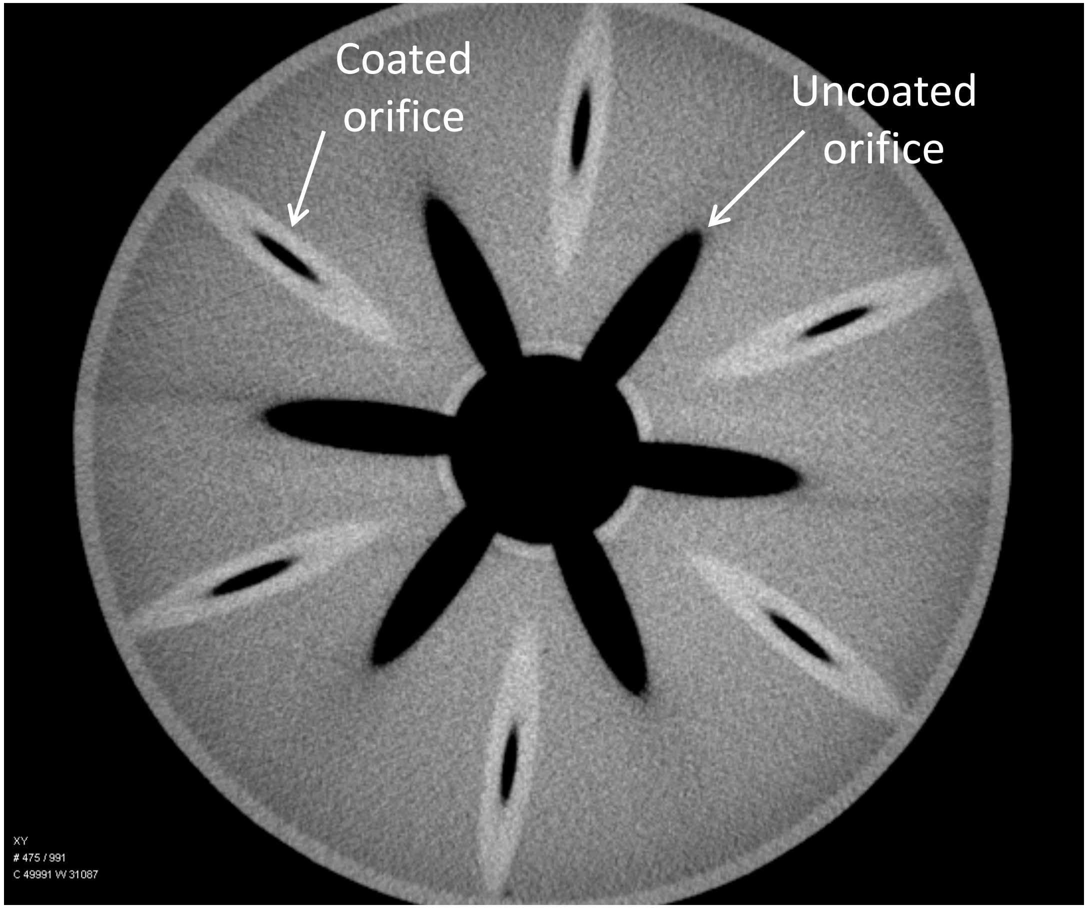




Courtesy – Ron Schaefer, USEPA/NVFEL

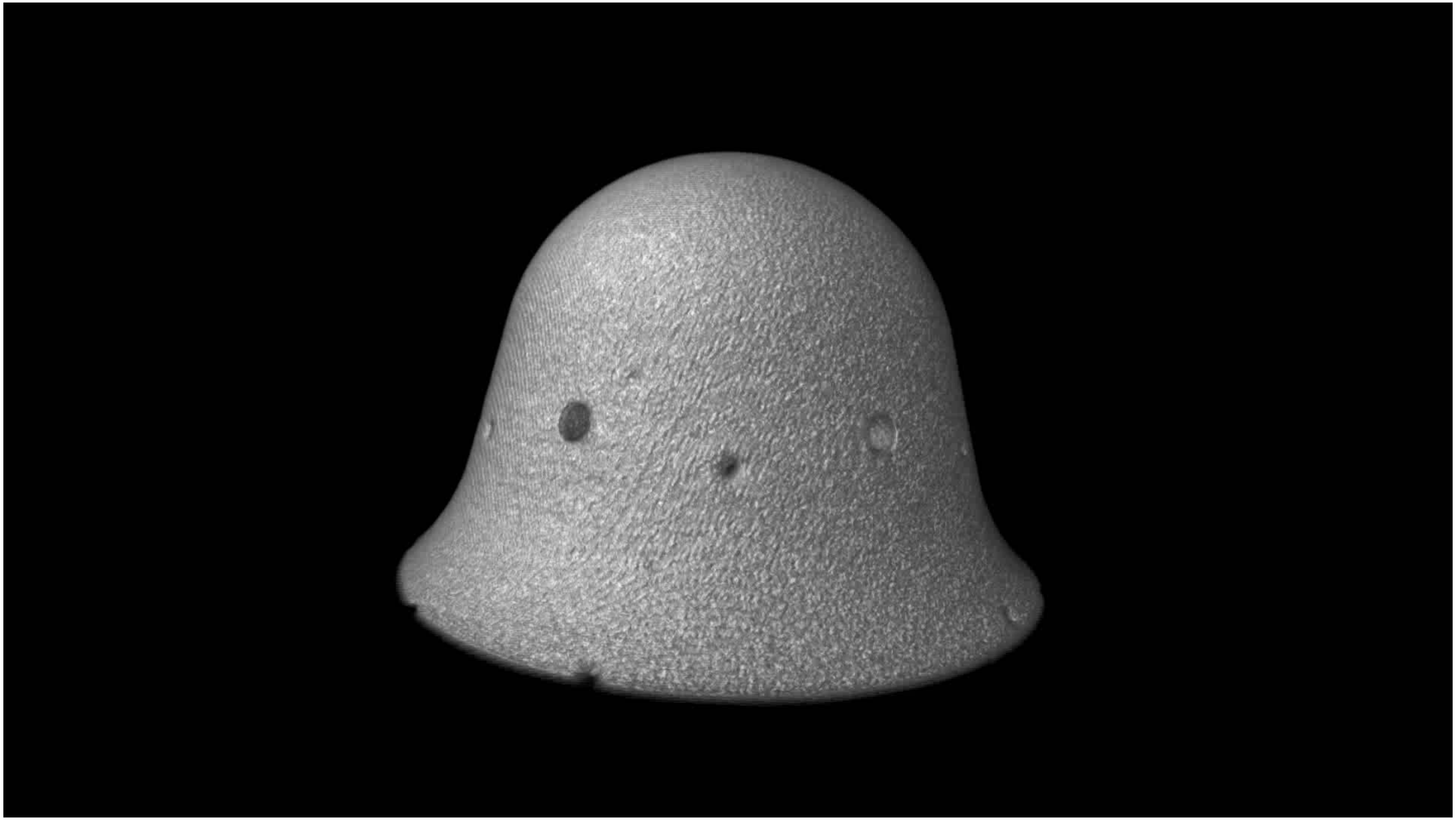
Accomplishment – Demonstrated feasibility of 3-D x-ray imaging to examine the uniformity of EN coatings applied to commercial fuel injectors (multi-size orifice).

- Potential of a high-resolution (< 2 µm) x-ray absorption technique was investigated to image the internal volume of the orifices after plating.
  - Original expectation was to image the void regions only.
- Imaging capabilities exceed original expectations.
  - In addition to imaging the void region, the technique was also able to delineate the coating (Ni-P alloy) from the ferrous injector alloy.

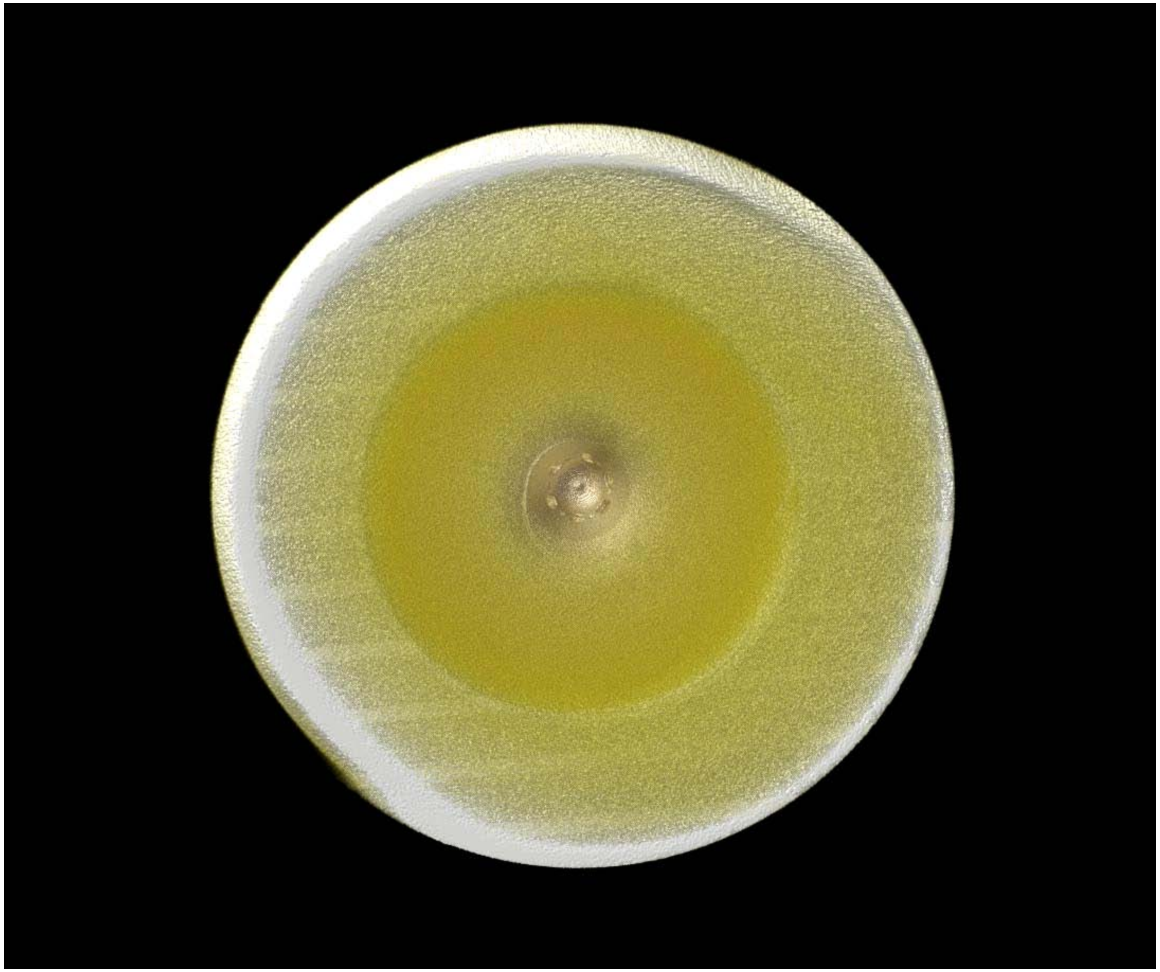


X-ray absorption image of commercial nozzle containing coated and uncoated orifices

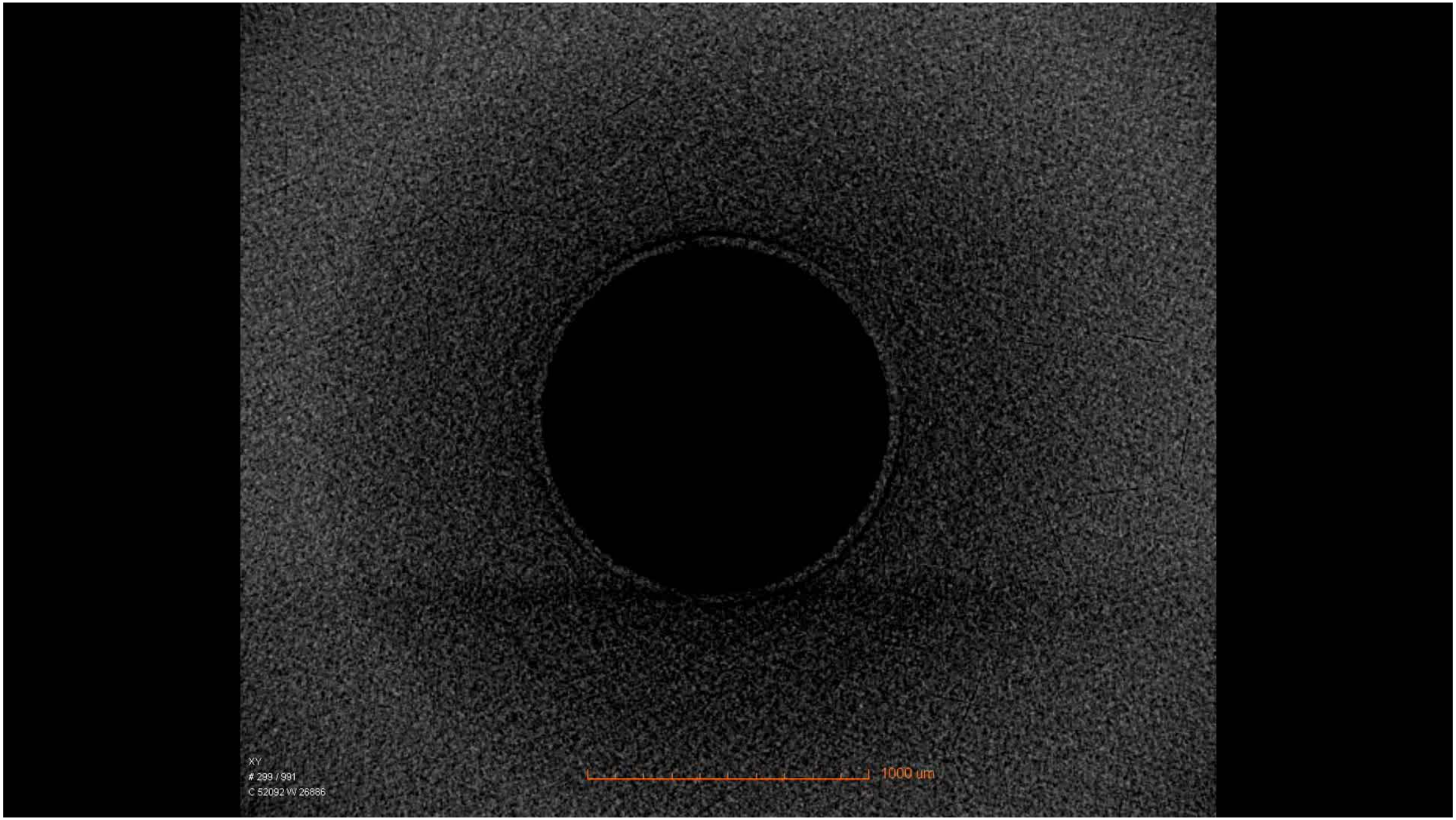
3-D x-ray movie of coated injector (showing outer surface)



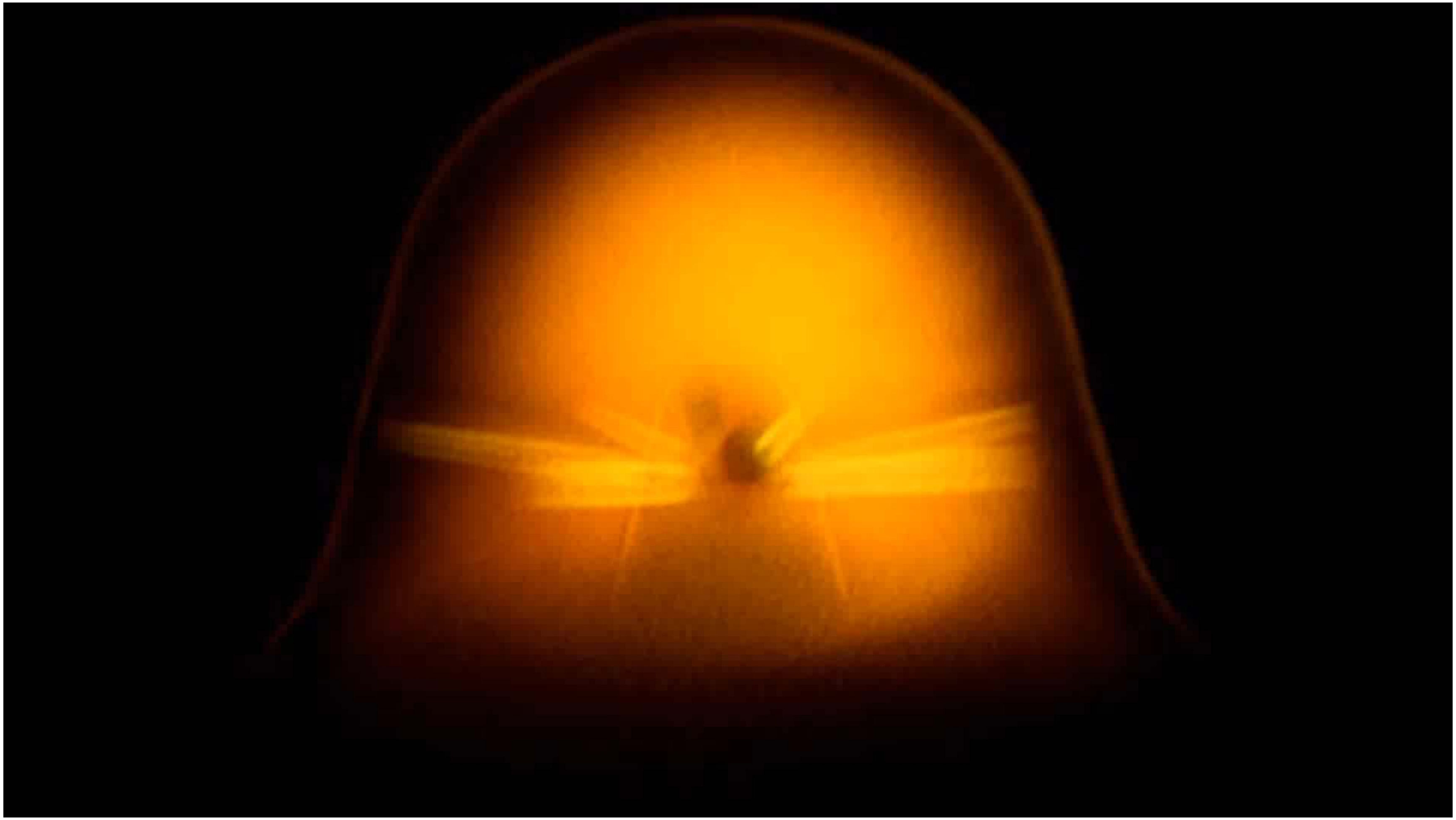
3-D x-ray movie of coated injector (showing outer surface)



3-D x-ray movie of coated injector (illustrating interior of injector – bottom/up scan)



3-D x-ray movie of coated injector (illustrating EN coating on interior orifices)



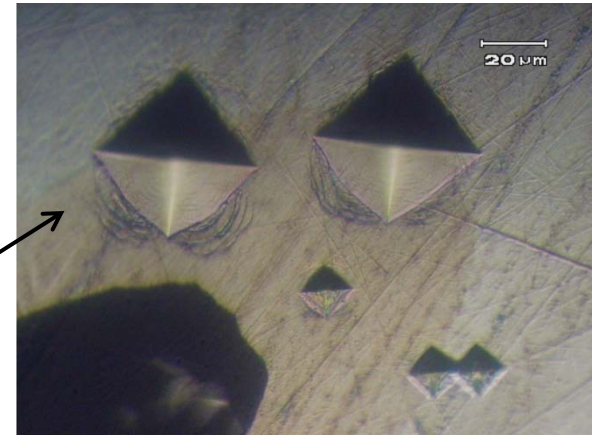
Accomplishment - Currently fabricating 2nd generation multi-sized orifice nozzles for OEM evaluation.

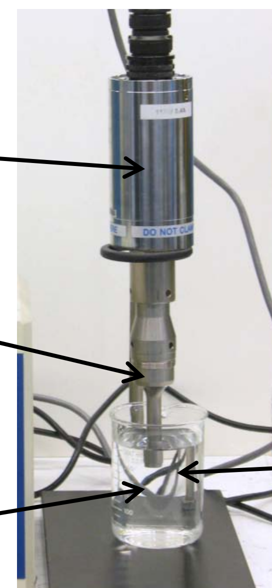
- Current multi-size orifice nozzles fabricated for EPA testing used commercial nozzles with pre-existing orifices
  - 120-µm orifices (6)
  - EN plating (to 40 µm) orifices
  - Electrodischarge machining (EDM) larger orifices (145 µm)
  - Abrasive slurry honing
  - EPA testing

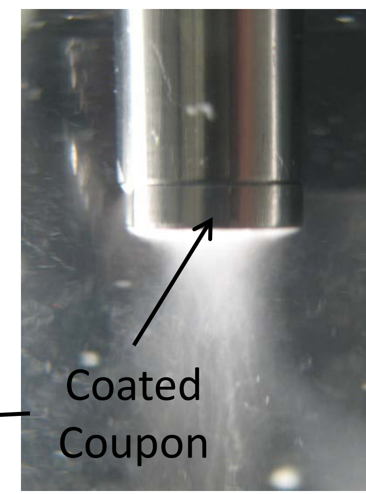
- Second generation design starting with blank nozzles (no orifices)
  - EDM 120-µm and 180-µm orifices (completed)
  - Abrasive slurry honing (in progress)
  - EN plating (to 50 and 110 µm) orifices (July 2010)
  - OEM evaluation

Accomplishment – Evaluated application of high-frequency vibratory technique to simulate cavitation erosion.

- Cavitation phenomena can lead to accelerated erosion of injector orifices and alter the spray characteristics of fuel entering the combustion chamber.
- EN coatings must be adherent and resistant to cavitation erosion over the lifetime of the injector.
- Recent efforts (FY09) demonstrated excellent adhesion of EN coatings to fuel injector orifices (using a micro-indentation technique at coating/substrate interface – see photo at right).
- During FY10, a cavitation erosion test rig was developed based on ASTM Test Method G 32-09

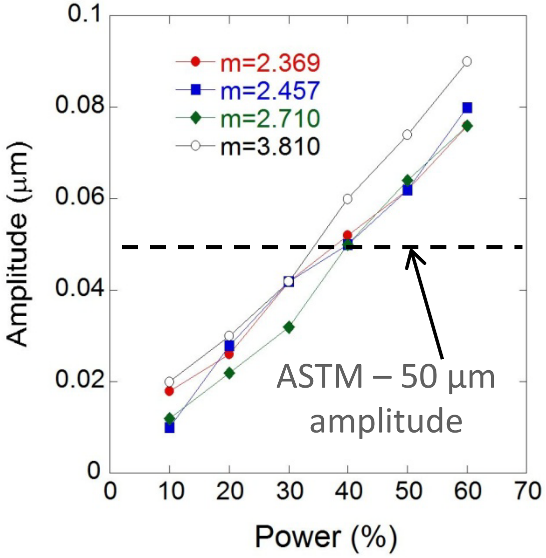






Accomplishment – Cavitation erosion (cont'd)

- ASTM G32-09: Method to simulate cavitation damage in a benchtop rig
- Quantify change in mass (mass loss) and erosion rate of test coupon as a function of time
  - Impact of different alloy composition and treatment on erosion
  - ASTM G32-09 will be used to evaluate adhesion and erosion properties under conditions that simulate cavitation
- Current activities:
  - Evaluating peak amplitude characteristics of test rig as a function of transducer power and coupon mass
  - Preliminary results demonstrate technique is capable of producing measurable erosion in reasonable time.
  - Designing coupon fixture to accommodate coated fuel injector coupons



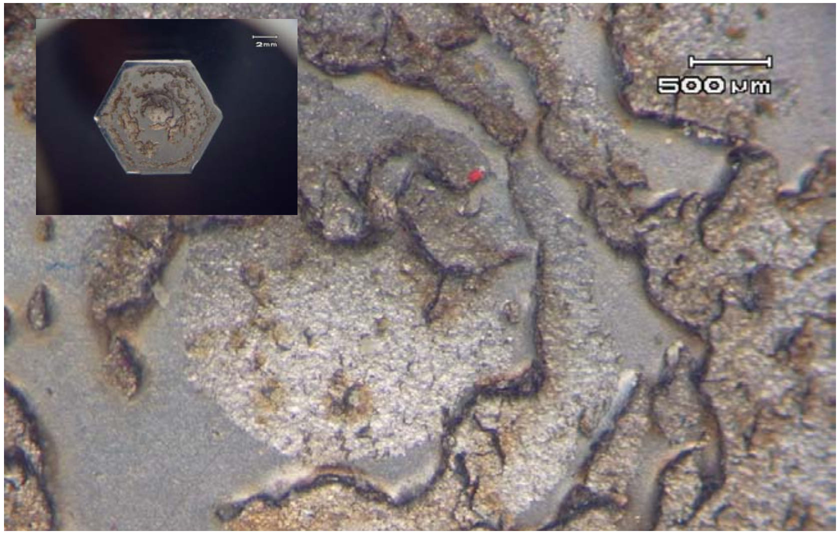


Image of polished steel sample illustrating cavitation erosion induced by ultrasonic agitation

Collaborations/Coordination with Other Institutions

- Development of processes to fabricate micro-orifices on commercial nozzles involves coordination of different manufacturing steps:
  - Electrodischarge machining (EDM) of orifices on existing commercial nozzles (either nozzle blanks or nozzles with pre-existing orifices) [LEER (industry)]
  - High-pressure abrasive honing of EDM orifices to increase flow characteristics [Extrude Hone (industry)]
  - Electroless nickel plating of nozzles [Imagineering (industry)]

- Evaluation of micro-orifice nozzles
  - Spray visualization studies [U.S. EPA (government)]
  - Fuel injector OEM [industry – NDA]
  - Engine OEM [industry – confidentiality]

Proposed Future Work

- Near Future (FY10/11)
  - Flow visualization studies by U.S. EPA
  - Preparation of 2nd generation multi-size orifice nozzles for nozzle OEM
  - Cavitation erosion studies
  - Development of 3-D x-ray imaging for in-situ characterization of orifice surfaces and cavitation erosion

- Longer Term (parallel) Activity (FY 10/12)
  - Combustion studies on instrumented single-cylinder rigs (national labs)
  - Engine emission studies
    - National labs
    - Engine OEM
  - Integration of overall fabrication processes
    - Nozzle and/or engine OEM

Summary

- Based on studies that demonstrated significant reductions in soot production with decreasing orifice diameter, initiated efforts to identify and develop processes to fabricate micro-orifices on commercial nozzles.
  - Improved fuel atomization reduces soot/particulate formation and improves air entrainment, thereby improving combustion efficiency.
- Examined multiple approaches early in the project with a down selection to EN.
- Demonstrated the EN process for fabricating micro-orifices on commercial fuel injectors.
- Worked with industry: technical barriers were identified and resolved (uniformity, adhesion, hardness).
- Completed spray visualization studies in collaboration with the U.S. EPA :
  - Smaller orifices resulted in shorter liquid penetration length and an appreciably shorter spray core length.
  - Smaller orifices enhanced atomization.
- Successfully demonstrated ability to fabricate multi-size orifices 6 @ 40 µm + 6 @ 145 µm.
- Demonstrated 3-D x-ray NDE technique to image orifice and coating on treated nozzles.
- Efforts in FY10/11 will focus on spray visualization studies of multi-sized orifices (EPA) and performance evaluation with nozzle OEM.
- Future efforts will focus on engine emission studies.