**Fuel injector Holes**  
*(Fabrication of Micro-Orifices for Fuel Injectors)*

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Overview

Timeline
- Project start date: FY 04
- Project end date: FY 12
- Percent complete: 60%

Barriers
- Barriers addressed: FCVT/VT Materials Technologies (3.4.7 & 3.4.8)
  - Cost
  - Manufacturability
  - Performance

Budget
- Total Project Funding: ~1.6M
  - DOE Share: ~1.5M
  - Collaborator Share: ~0.1M
- FY 08: 350 K
- FY 09: 350 K

Partners
- Imagineering Finishing Technologies
- Fuel system OEMs
- Engine OEM
- Small business: integration of EN process into nozzle production line
- US EPA
**Relevance of Research to DOE Barriers**

- This project addresses the development of fuel injector technology to **reduce diesel emissions** by reducing in-cylinder production of diesel particulates.
  - Potential secondary benefits to improve fuel efficiency through improved fuel atomization & combustion

- Multiple paths being pursued by DOE & industry to reduce emissions
  - Aftertreatment devices (NOx & PM traps)
  - Alternative engine cycles (HCCI, LTC)
  - **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, …
Relevance/Purpose/Objective of Work

- Combustion studies demonstrate that reducing the diameter of injector orifice 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*)

**Approach**

- Identify potential micro-orifice fabrication techniques
  - No technology exists to economically produce robust 50 µm orifices
- Downselect – 50 µm, maturity, cost, scale-up
- Demonstrate feasibility (lab)
- Identify and resolve technical barriers
  - Uniformity, adhesion, deposit formation, hardness, fatigue, reduced flow …
- Treat prototypic components (Tech Transfer)
- Spray visualization studies (USEPA)
  - Single-size orifices (50 µm)

- Multi-Sized Orifices (e.g. 50 µm & 100 µm) orifices on the same nozzle to maintain overall fuel flow capability
  - Detailed microstructural analysis
  - Process re-optimization
- Engine emission & efficiency studies

**Electroless Nickel**

- Autocatalytic deposition of Ni from aqueous solution

**Electrodischarge (current process), Plating**

- (aqueous, CVD/PVD), Laser-processing, LIGA, …

** USEPA NVFEL**

50 µm Ø

100 µm Ø

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**Argonne National Laboratory**
Milestones/Decisions

- FY08 (completed)
  - Preparation of EN coated nozzles to mitigate cavitation erosion
    - *Work with OEM to deposit EN on experimental nozzles to improve cavitation performance at elevated pressures*
  - Characterization of NVD coated nozzles (coating uniformity, surface finish, and adhesion)
    - *Evaluate potential of alternative coating process (NVD - nickel vapor deposition) process to deposit uniform coatings on nozzles*
    - *Perform preliminary assessment of uniformity of laser processed orifices*
- FY09
  - Preparation of multi-sized micro-orifices on commercial nozzles for spray visualization studies at the US-EPA (in-progress)
  - Establish collaborative agreement with nozzle OEM to accelerate technology validation (in-progress)
    - *Negotiating level and type of effort between ANL and partner*
**Progress/Accomplishment:** Ability to coat interior of injector orifices requires process optimization to remove hydrogen gas bubbles

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

**Progress/Accomplishment:** Developed and applied advanced analytical techniques to characterize coating uniformity

- Metallography and phase-contrast X-Ray imaging (NDE) of EN - coated nozzles provide quantitative information on coating uniformity
  - Coating uniformity within 5% achieved
Progress/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.

Progress/Accomplishment: Transferred concept/technology to industrial plater/coater

- Lab-scale process transferred to commercial size operation
  - Reduce small-batch chemistry variations
  - Standardized cleaning and post-deposition treatments
  - Access to knowledgebase
Progress/Accomplishment: Flow Visualization - demonstrated enhanced flow characteristics

Ann Arbor Nozzle: 7X0.10mmx160

Argonne Nozzle: 7x0.075x157

Argonne Nozzle: 7x0.05x157

[Images of flow visualization data]

Liquid Fuel Penetration (cm)

Time (ms) from SOI

 Courtesy – Ron Schaefer, USEPA/NVFEL
**Progress/Accomplishment: Initiated development of process to fabricate multisized orifices**

- Following demonstration of flow characteristics of micro-orifice nozzle, plans were initiated to fabricate nozzles with multi-sized orifices (e.g. 50 µm and 100 µm)
  - Compensate for loss of flow when orifice area is reduced by a factor of 4
  - Compensate for reduced penetration distance of smaller orifice
  - Enable greater flexibility to control distribution of fuel within the combustion chamber
Progress/Accomplishment: Approach - multiple pathways to obtain multi-sized orifice considered.

- Two approaches were considered to fabricate nozzle with multiple sized orifices
  - Approach 1 - take commercial nozzle, reduce orifices to 50 µm, then EDM in larger holes (100 µm)
  - Approach 2 - EDM 150 µm and 100 µm size holes, then plate to reduce orifices to 100 µm and 50 µm

- Approach 1 selected because it minimized upfront preparation efforts for the nozzle
- Approach 2 may be more appropriate for eventual production, however, approach 1 is being developed because of availability of nozzles
Progress/Accomplishment: Multi-Sized Orifice Nozzles (cont’d)

- New set of nozzles procured for multi-sized orifice task. The new set of nozzles were produced by the same OEM as those used in the spray-visualization studies, however, they were fabricated from more current (different) alloy.
  - Information on alloy composition and heat treatment and how they differed from original series of nozzles was unknown and proprietary
  - Because of the unknown alloy composition and heat treatment, a series of scoping runs were performed to determine deposition rate and quality (coating uniformity, adhesion, hardness)
- Initial EN deposition runs performed using original deposition protocols developed for the spray-visualization nozzles indicated further optimization was required.
  - Presence of surface pits on outer surfaces
  - Poor coating uniformity
Progress/Accomplishment: Coating Uniformity & Surface Pitting After First trial Run

- 1 out of 4 nozzles experienced severe surface pitting. Minor pitting observed on remaining 3 nozzles.

- 2 out of 4 nozzles exhibited non-uniform coating on internal orifices - suggesting poor mechanical agitation of nozzles.
Progress/Accomplishment: Two-steps forward, one-step back……

- Concerns over the different alloy chemistry and heat treatment raised concerns regarding the applicability of the original costing protocols
- Preliminary test (previous page) confirmed this concern regarding surface pitting and coating uniformity
- A decision was made to go back and perform detailed characterization on the chemistry and microstructure of the different nozzles that were being studied in this project:
  - 4 different nozzles - Nozzle ‘B’, Nozzle ‘S’, Nozzle ‘CS’, and Nozzle ‘CNN’
- Nozzles were coated, then sectioned for detailed microstructural and chemical analysis
  - Note: nozzle chemistry and microstructures are considered proprietary and the results presented below on structure, hardness, and composition will not be linked to a specific nozzle
Progress/Accomplishment: Microstructure - tempered martensite, nitride precipitates, bainite and pearlite

- Optical microscopy revealed different microstructures:
  - nozzle B consisted of tempered martensite,
  - nozzle S consisted of martensite,
  - nozzle CS consisted of tempered martensite with nitride precipitates located along prior austenitic grain boundaries, and
  - nozzle CNN contained bainite and fine pearlite
Progress/Accomplishment: Nozzle Hardness

- Due to different alloy chemistries and heat treatments (hardened, case hardened, nitrided, etc.) significant differences in alloy hardness were observed.
- Hardness (Rc) ranged from 50 to over 70 depending on nozzle treatment and position.
Progress/Accomplishment: 2nd Trial run of samples was degreased before plating, used a ‘low surface tension’ bath formulation, and, aggressive bath agitation to improve infiltration of solution into orifices

- Boroscope images after plating showed uniform coverage inside of nozzle

- However, outer surface exhibited surface imperfections
Forward 2 steps, back-1, sideways 1...

- Surface imperfections
- Some of the holes near the surface have been slightly affected
- Complete hole coverage
- Uniform thickness through entire depth of orifice
Progress/Accomplishment: Micro-Vickers indentation of coatings on internal surfaces demonstrated excellent adhesion of the coatings to the orifice (after 2\textsuperscript{nd} trial run)

- A Micro-Vickers hardness tester was used to apply a load at the interface between the plated region and the substrate in order to test the plating integrity
- Good adhesion
Summary - 2nd trial run with low-surface tension bath, degreasing of the orifices, and aggressive agitation resolved issue of internal coating uniformity, however, some external surface flaws appeared.

Visual examination of the surface flaws reveal they occurred at regions that exhibited ‘staining’ under the coating - suggesting poor adhesion due to surface contamination.

While the quality of the coatings produced using the protocols developed for the 2nd trial run should be sufficient to proceed to the next stage of research, a 3rd trial run will be performed to eliminate surface flaws and assure uniform internal coverage.

- Lower the level of surface tension modifier to mitigate internal coating stresses while still maintaining good coverage
- Aggressive pre-cleaning and etching to assure surface cleanliness and mitigate ‘staining’
Future Work - Pathway Forward

- **Near-Future (FY09)**
  - Re-fine coating protocols to assure defect-free, uniform coatings on new nozzle alloys
  - Deposition of coatings on new nozzles for US EPA flow studies
  - Return nozzles to shop to EDM large (100 µm) in between 50 µm orifices, slurry polish holes, regrind needle seat, and return to EPA
  - EPA flow studies (FY 09/10)

- **Longer term (parallel) Activity**
  - Establish collaboration with injector OEM on durability and emission studies
  - Develop team to integrate process into injector manufacturing process
Collaborations

- Imagineering Finishing Technologies
  - Development & application of commercial plating bath technologies to coat nozzles
- Fuel system OEMs
  - Provide commercial nozzles for research activities
  - Consulting and planning for durability and engine studies
- Engine OEM
  - Cavitation studies
- Small business
  - Integration of EN process into nozzle production line
- US EPA
  - Spray visualization studies
Summary

Based on studies that demonstrated significant reductions in soot production with decreasing orifice diameter, efforts were initiated 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

Multiple approaches were examined 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)

Internal LDRD funding supported development of advanced x-ray imaging techniques for NDE characterization of coating uniformity and orifice blockage

Spray visualization studies in collaboration with the USEPA demonstrated:

- Smaller orifices resulted in shorter liquid penetration length and an appreciably shorter spray core length.
- Smaller orifices enhanced atomization.

Efforts in FY09 to focus on spray visualization studies of multi-sized orifices

- New nozzle alloys require re-optimization of coating protocols

Future efforts to focus on engine emission studies