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

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May 21st, 2009

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2009 US DOE Hydrogen Program and Vehicle Technologies Program
Annual Merit Review and Peer Evaluation Meeting
May 18-22, Washington D.C.

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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

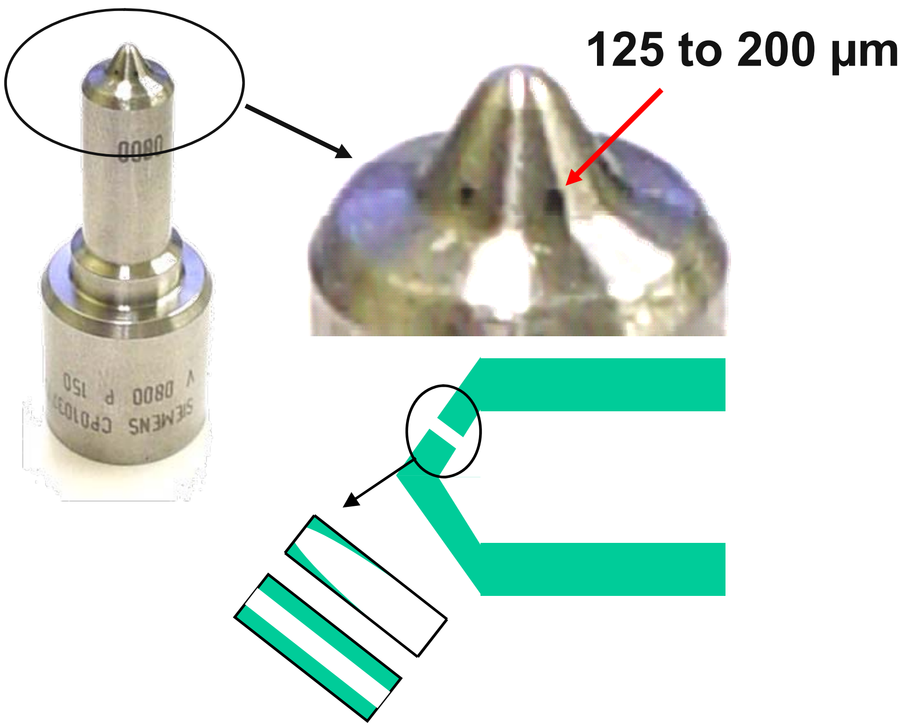
- Imagineering Finishing Technologies
- Fuel system OEMs
- Engine OEM
- Small business - integration of EN process into nozzle production line
- US EPA

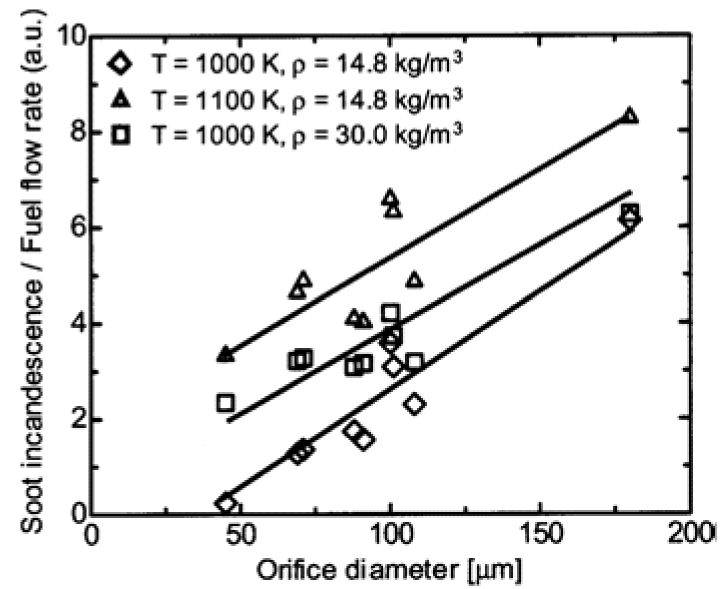
Relevance of Research to DOE Barriers

- 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)***





Pickett & Siebers, JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME 127 (1): 187-196 JAN 2005

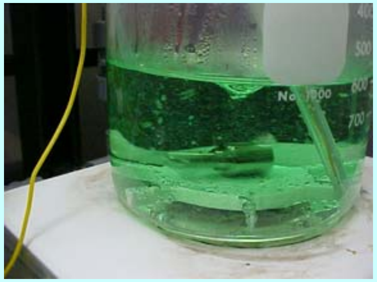
Approach

- 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)

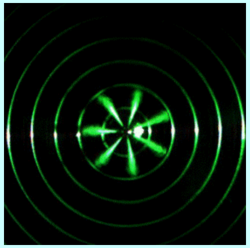
- Multi-Sized Orifices (e.g. 50 µm & 100 µm) orifices on the same nozzle to maintain overall fuel flow capability
  - Detailed microstructural analysis
  - Process re-optimization
- Engine emission & efficiency studies

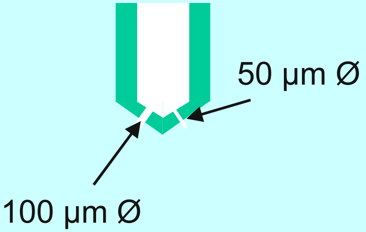
Electrodischarge (current process), Plating (**aqueous**, CVD/PVD), Laser-processing, LIGA, …

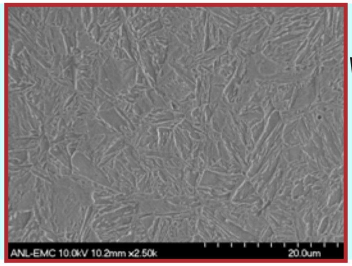
Electroless Nickel – autocatalytic deposition of Ni from aqueous solution

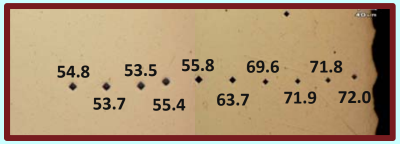


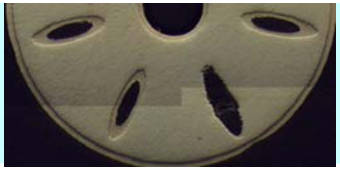
USEPA NVFEL











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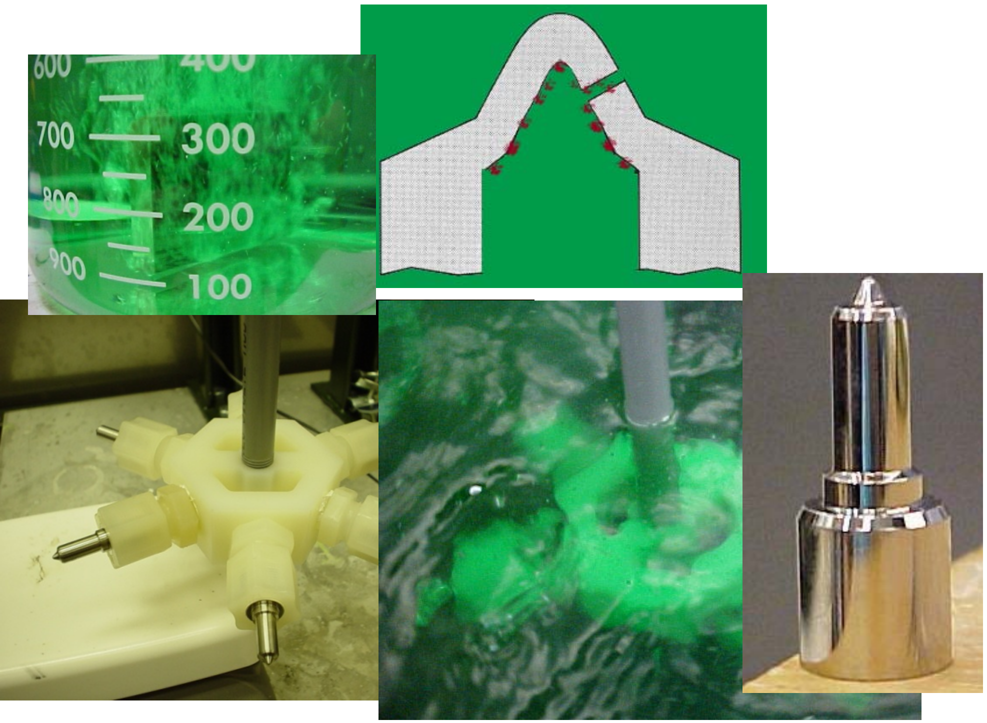
Milestones/Decisions

- 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*
  - Characterization of laser-fabricated micro-orifices.
    - *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*

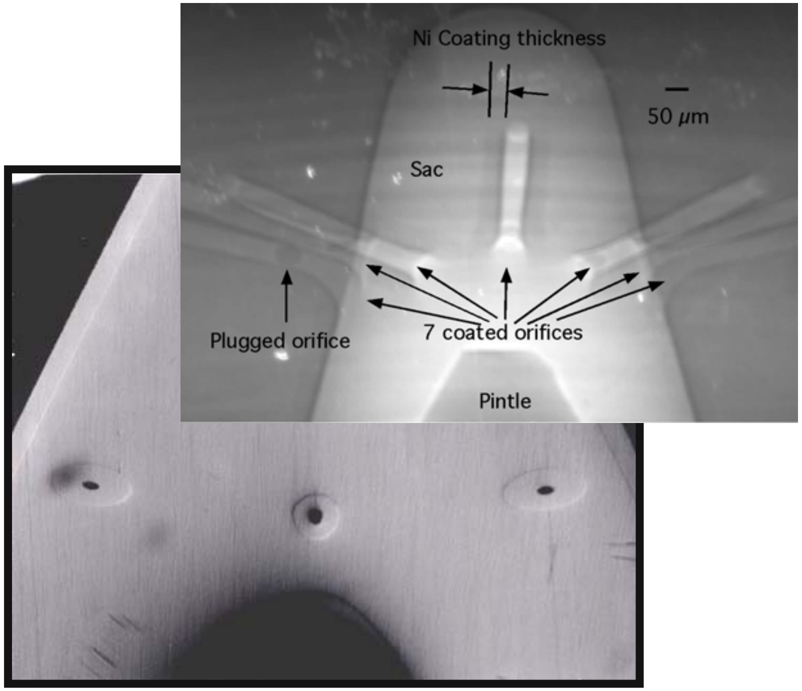
Progress/Accomplishment: Ability to coat interior of injector orifices requires process optimization to remove hydrogen gas bubbles

- 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



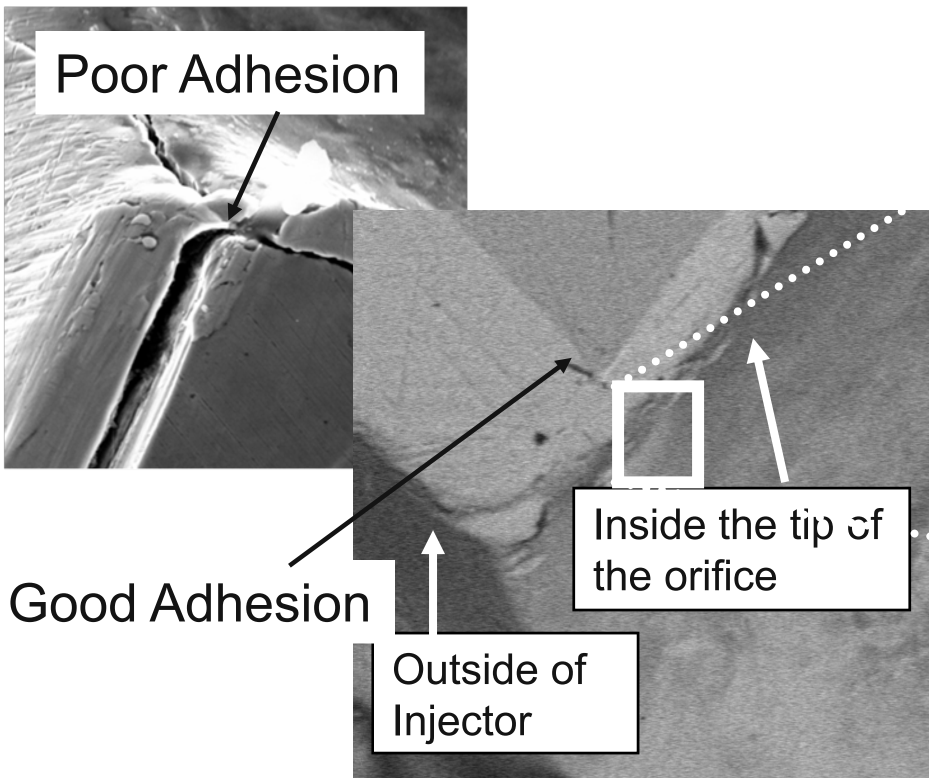
Progress/Accomplishment: Developed and applied advanced analytical techniques to characterize coating uniformity

- 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



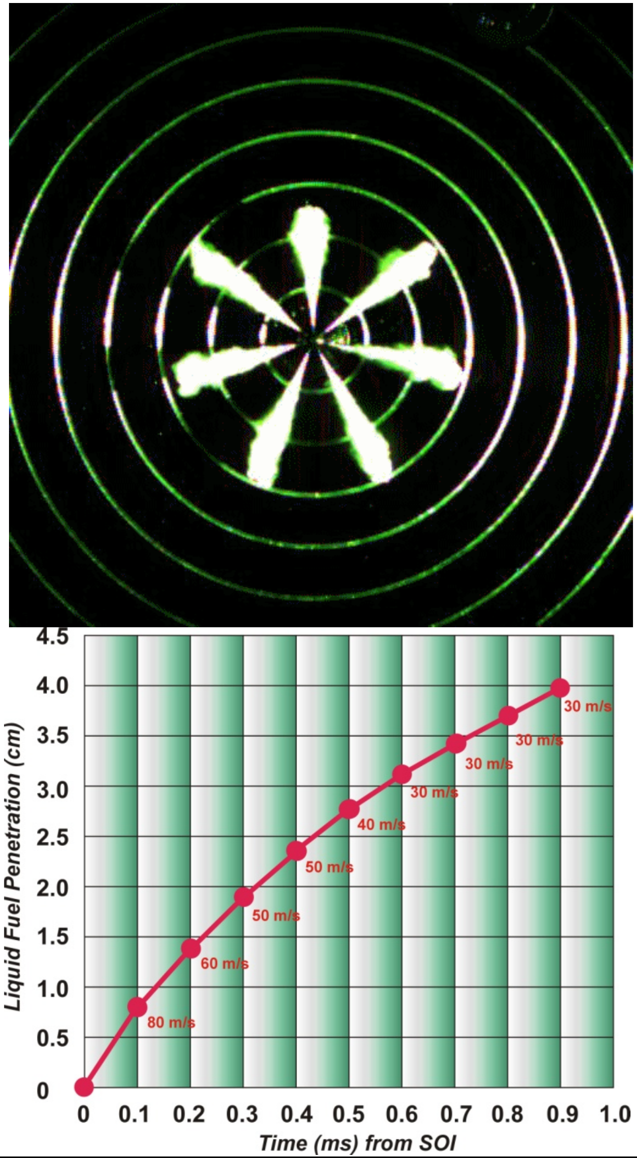
Progress/Accomplishment: Transferred concept/technology to industrial plater/coater

- Lab-scale process transferred to commercial size operation

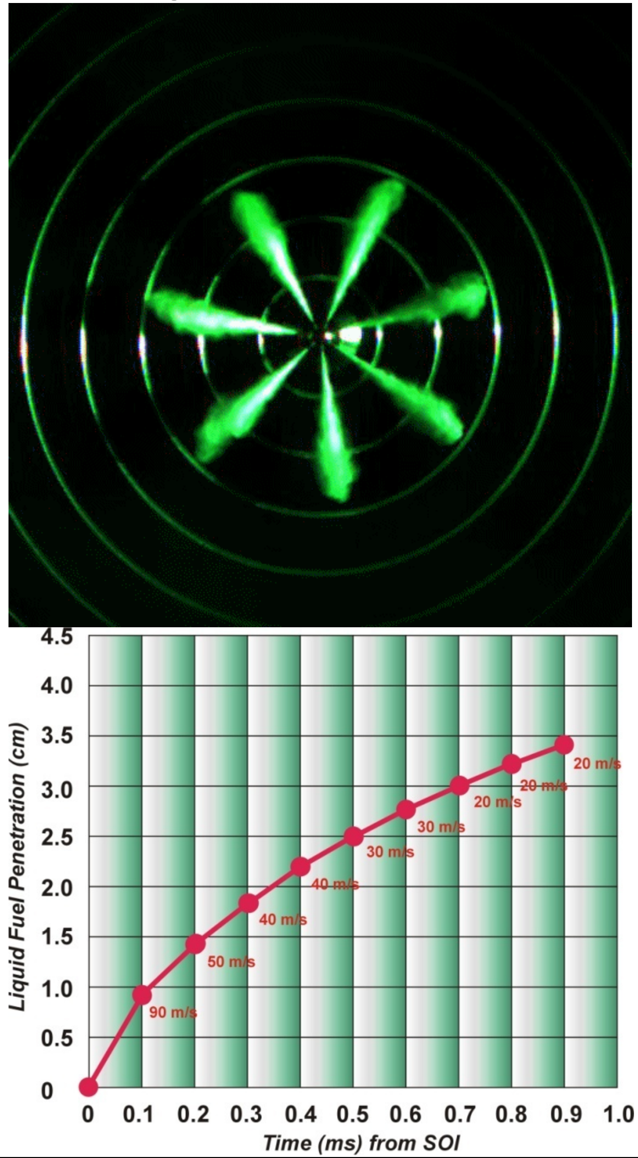
  - Reduce small-batch chemistry variations
  - Standardized cleaning and post-deposition treatments
  - Access to knowledgebase

Progress/Accomplishment: Flow Visualization - demonstrated enhanced flow characteristics

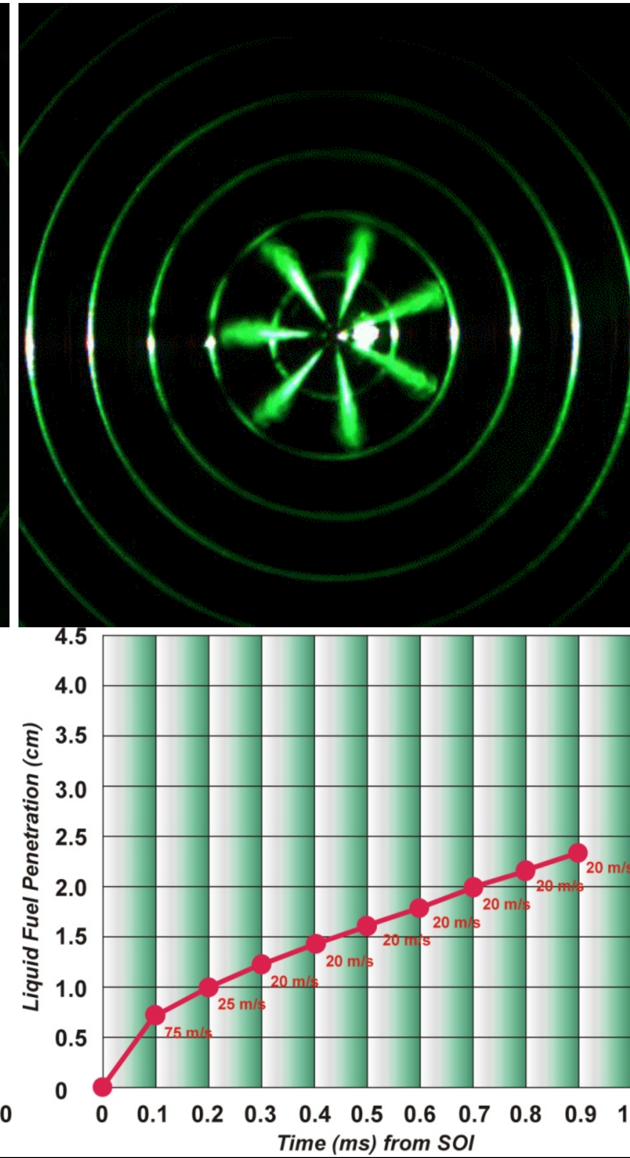
Ann Arbor Nozzle: 7X0.10mmx160



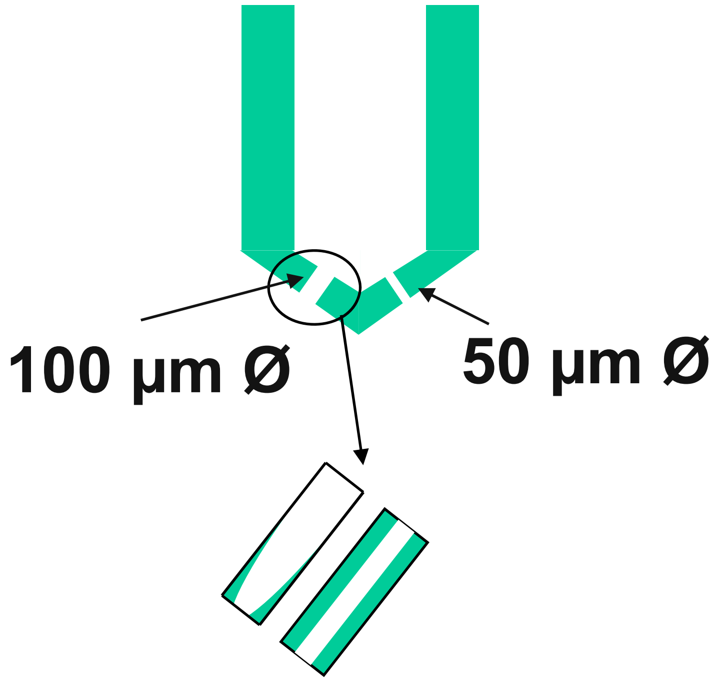
Argonne Nozzle: 7x0.075x157



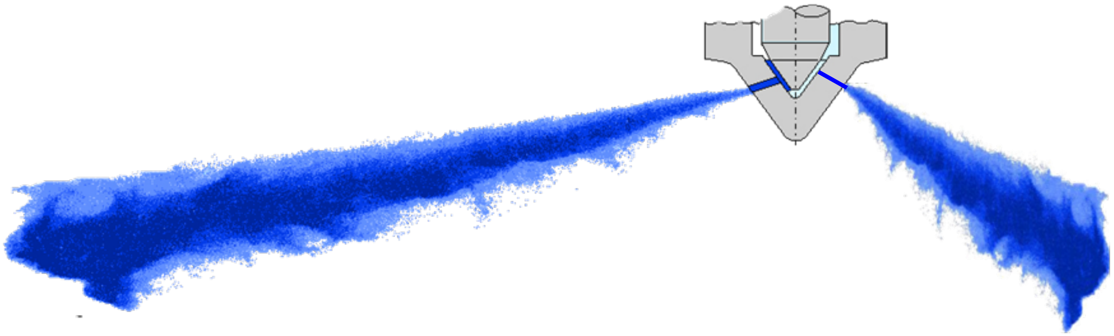
Argonne Nozzle: 7x0.05x157



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



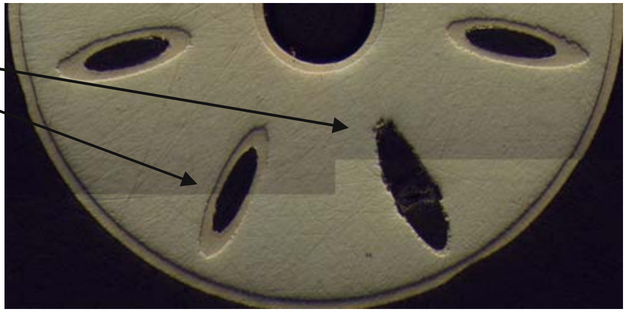
Progress/Accomplishment: *Approach - multiple pathways to obtain multi-sized orifice considered.*

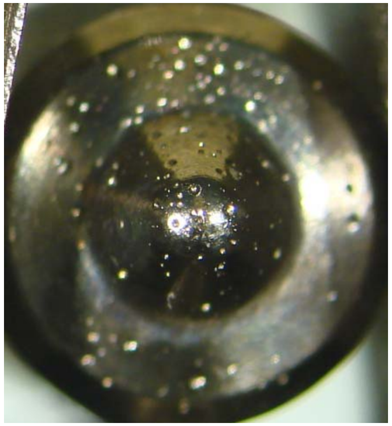
- Two approaches were considered to fabricate nozzle with multiple sized orifices
  - Approach 1 - take commercial nozzle, reduce orifices to 50 µm, then EDM in larger holes (100 µm)
  - Approach 2 - EDM 150 µm and 100 µm size holes, then plate to reduce orifices to 100 µm and 50 µm

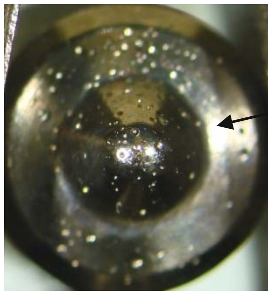
  - Approach 1 selected because it minimized upfront preparation efforts for the nozzle
  - Approach 2 may be more appropriate for eventual production, however, approach 1 is being developed because of availability of nozzles

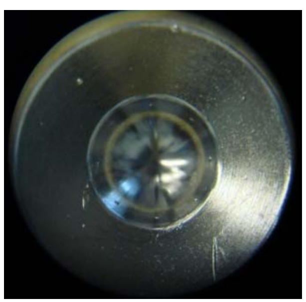
Progress/Accomplishment: Multi-Sized Orifice Nozzles (cont'd)

- 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





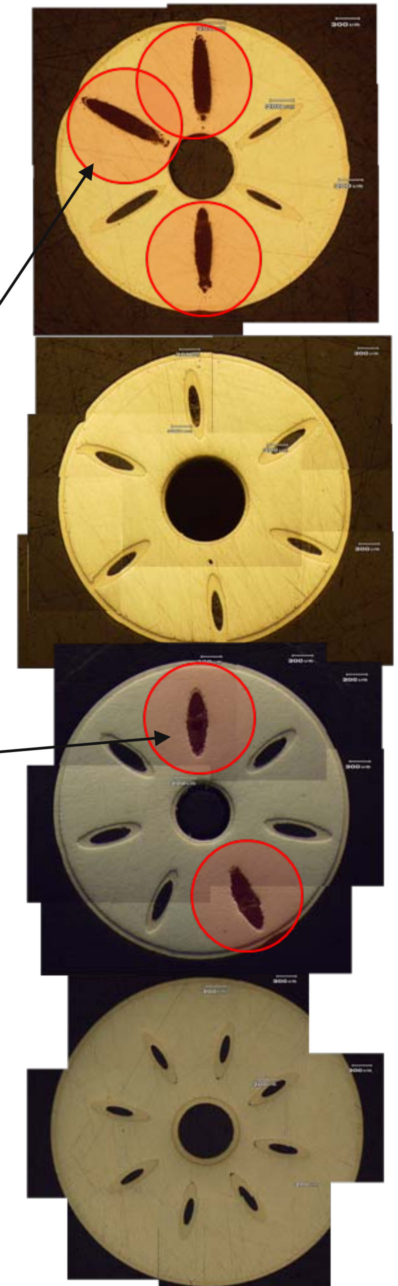




Progress/Accomplishment: Coating Uniformity & Surface Pitting After First trial Run

- 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

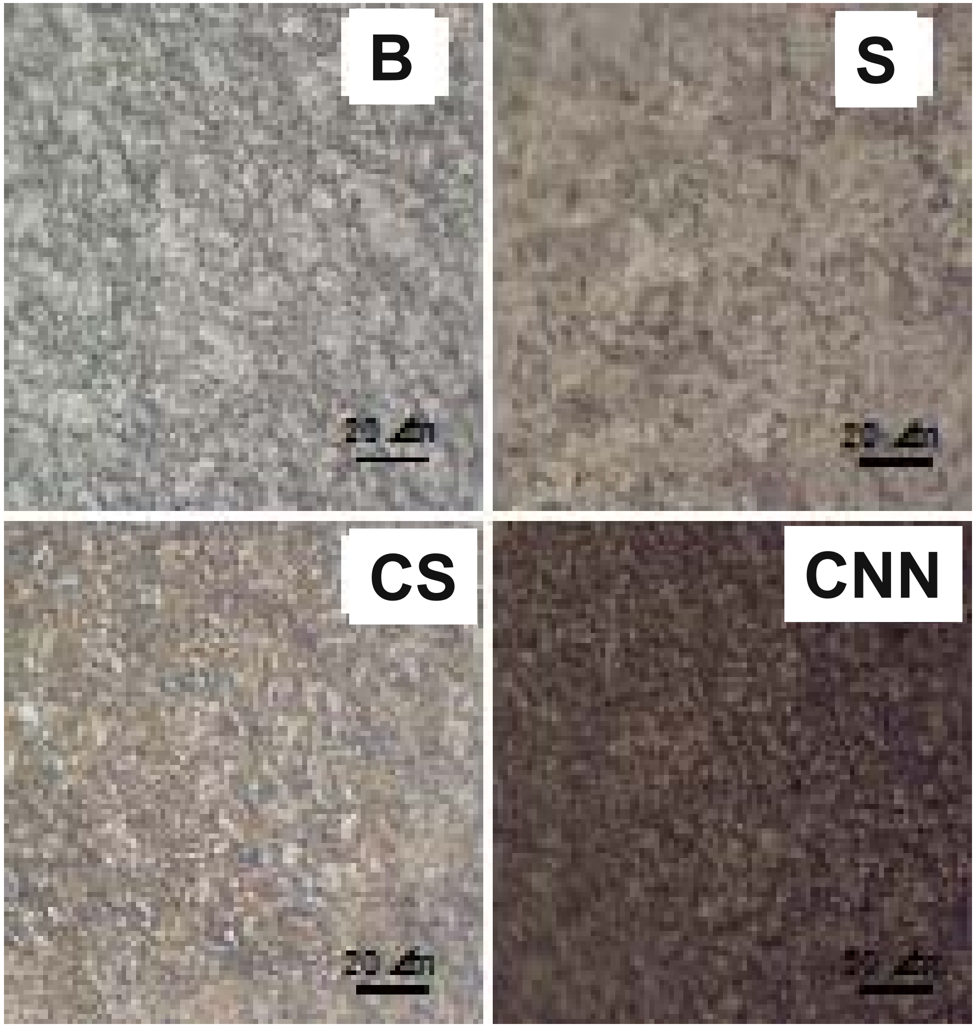


Progress/Accomplishment: *Two-steps forward, one-step back……*

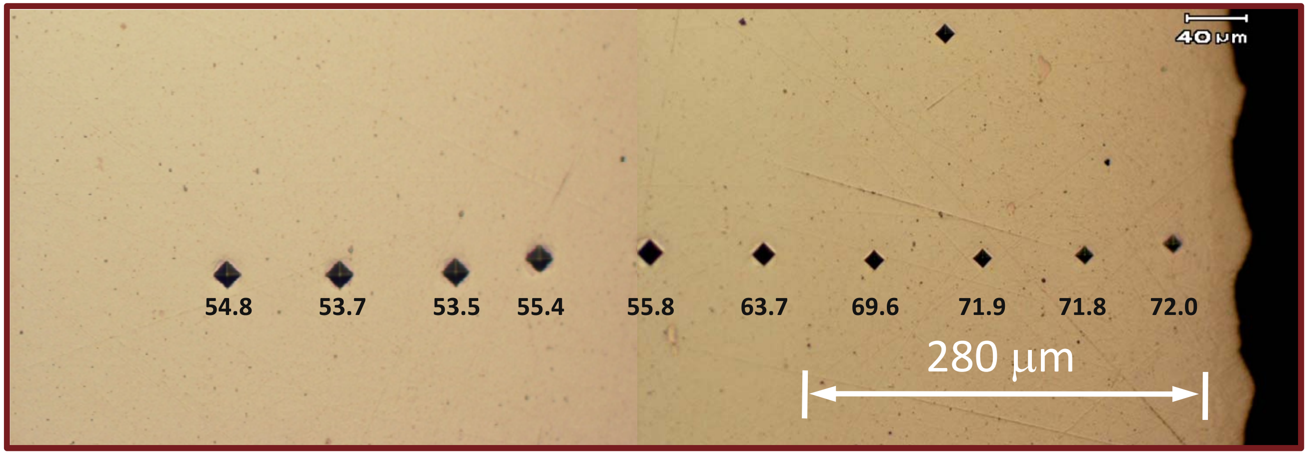
- Concerns over the different alloy chemistry and heat treatment raised concerns regarding the applicability of the original costing protocols
- Preliminary test (previous page) confirmed this concern regarding surface pitting and coating uniformity
- A decision was made to go back and perform detailed 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

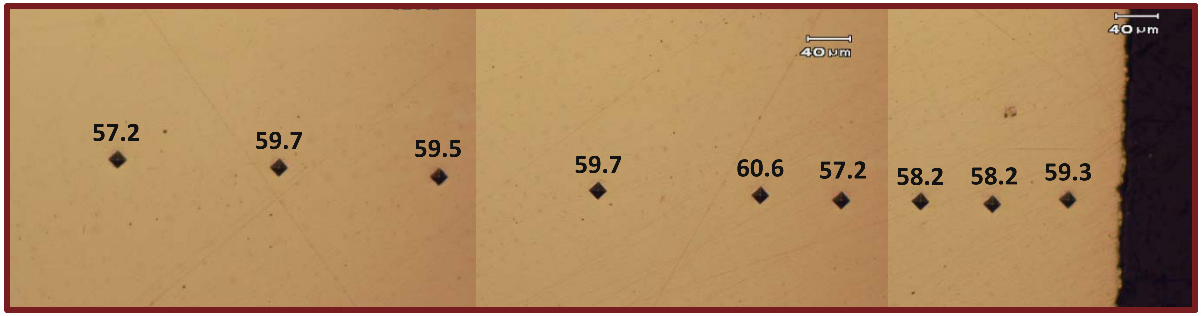
- Optical microscopy revealed different microstructures:
  - nozzle B consisted of tempered martensite,
  - nozzle S consisted of martensite,
  - nozzle CS consisted of tempered martensite with nitride precipitates located along prior austenitic grain boundaries, and
  - nozzle CNN contained bainite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



Progress/Accomplishment: Nozzle Hardness

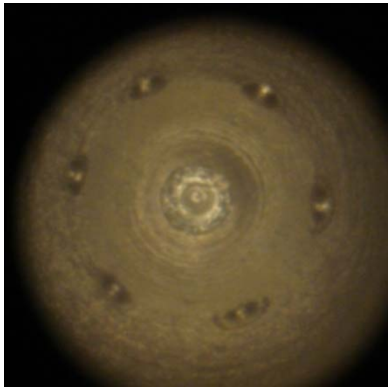
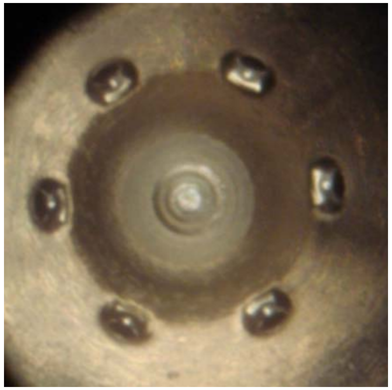
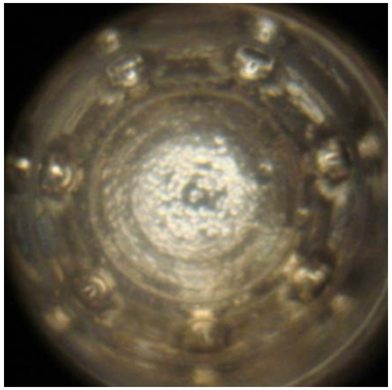
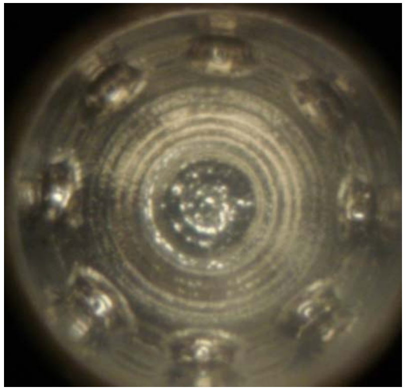


- Due to different alloy chemistries and heat treatments (hardened, case hardened, nitrided, etc.) significant differences in alloy hardness were observed.
- Hardness (Rc) ranged from 50 to over 70 depending on nozzle treatment and position

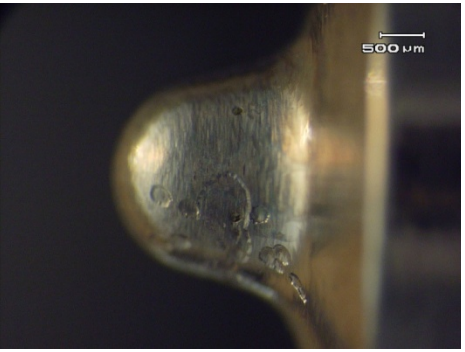


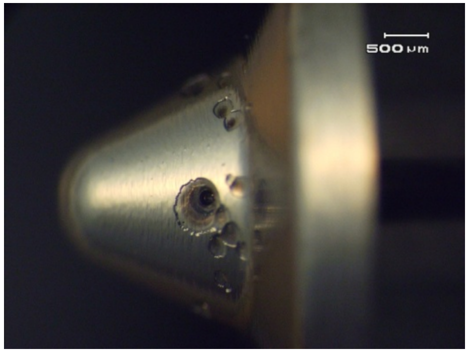
Progress/Accomplishment: ***2nd Trial run of samples was degreased before plating, used a ‘low surface tension’ bath formulation, and, aggressive bath agitation to improve infiltration of solution into orifices***

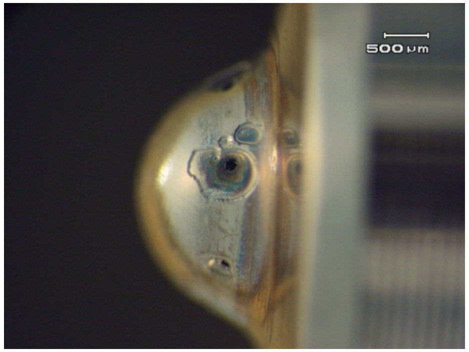
- Boroscope images after plating showed uniform coverage inside of nozzle

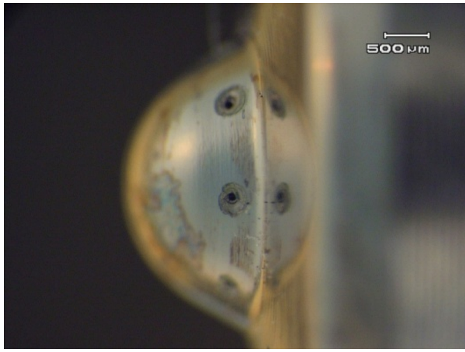





- However, outer surface exhibited surface imperfections



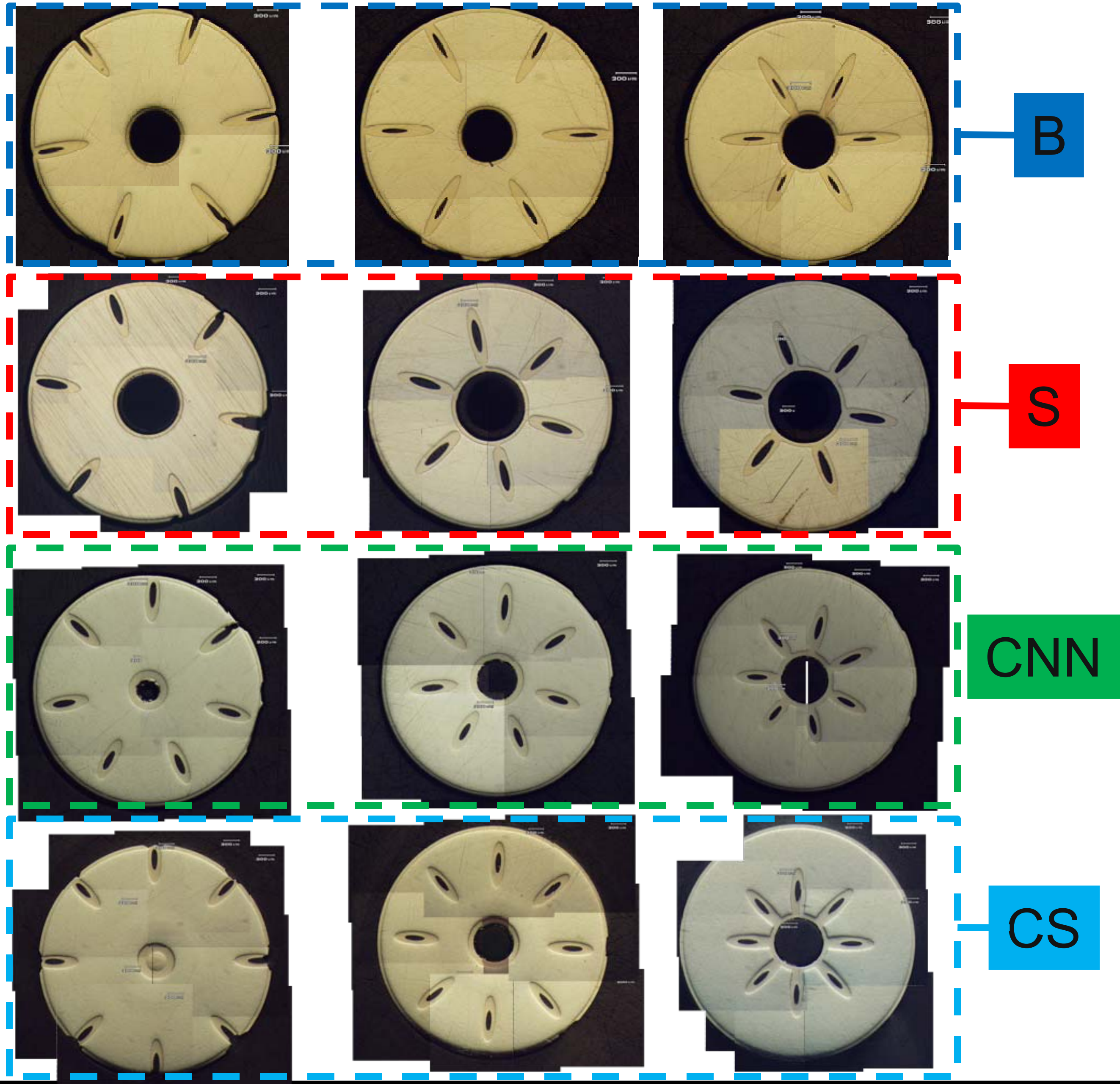






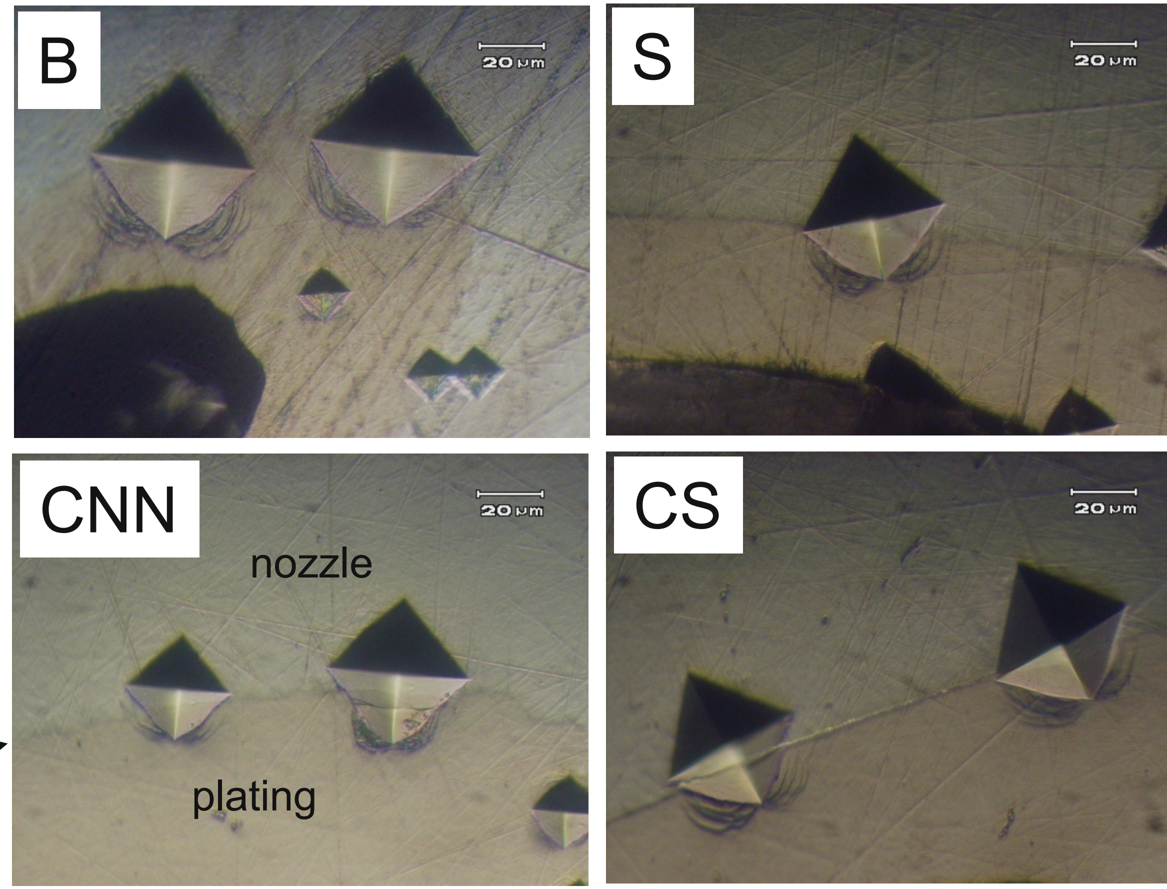
Forward 2 steps, back-1, sideways 1….

- 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 2nd 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



Interface between nozzle (top) and EN coating (bottom)

Forward 2 steps, back-1, sideways 1…. Pathforward

- 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 trail 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