EGR Cooler Deposit Analysis

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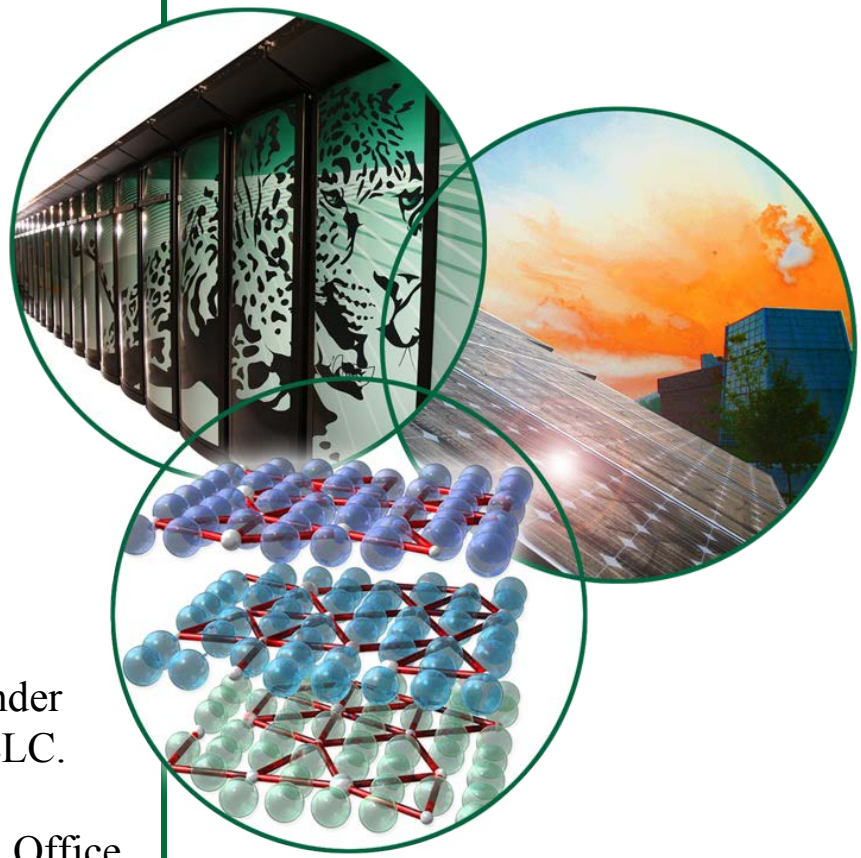

Research sponsored by WFO sponsor John Deere under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

Techniques developed through a Department of Energy, Office of Vehicle Technologies project sponsored by Jerry Gibbs.

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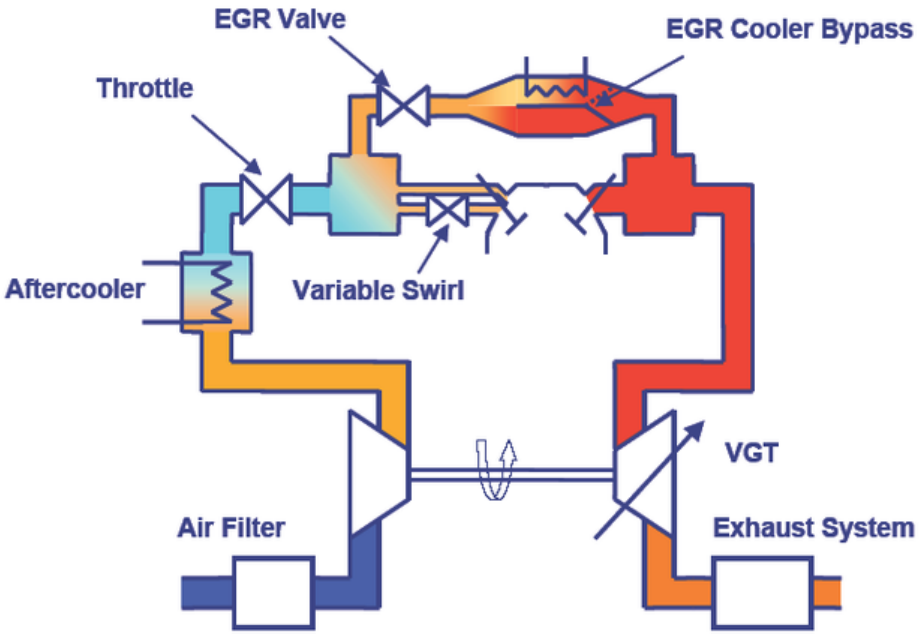
Background: Exhaust Gas Recirculation Cooler Fouling



- High-pressure exhaust gas recirculation (EGR) is the dominant NO_X-reduction technology.
- Exhaust gas laden with PM flows through the EGR cooler which causes deposits to form through thermophoresis and HC condensation.
- The deposit thermal conductivity is very low, which reduces the effectiveness of the EGR system.
- EGR cooler fouling has become a significant issue for compliance with NO_X emissions standards and has negative impacts on cooler sizing and engine performance.

Experimental Approach

- 21 tube-in-shell EGR coolers were fouled using a 5-factor, 3-level design-of-experiments (DoE) with the following variables:
  1. EGR flow rate
  2. EGR inlet gas temperature
  3. Soot (PM) level
  4. Hydrocarbon (HC) concentration.
  5. Coolant temperature
- A 9-liter engine and ULSD fuel were used to form the cooler deposits.
- Coolers were run until the effectiveness stabilized (typically 40-70 hours), were then cooled down to room temperature and then run for an additional few hours in order to measure the change in effectiveness (regeneration) due to shut down.
- Samples were cut and milled open and the mass per unit area of the deposit was measured as a function of distance down the tube.
- Microstructural analyses using both optical and electron microscopy were conducted to better understand deposition and removal processes.

Design of Experiments Summary

H = High
L = Low
M = Middle

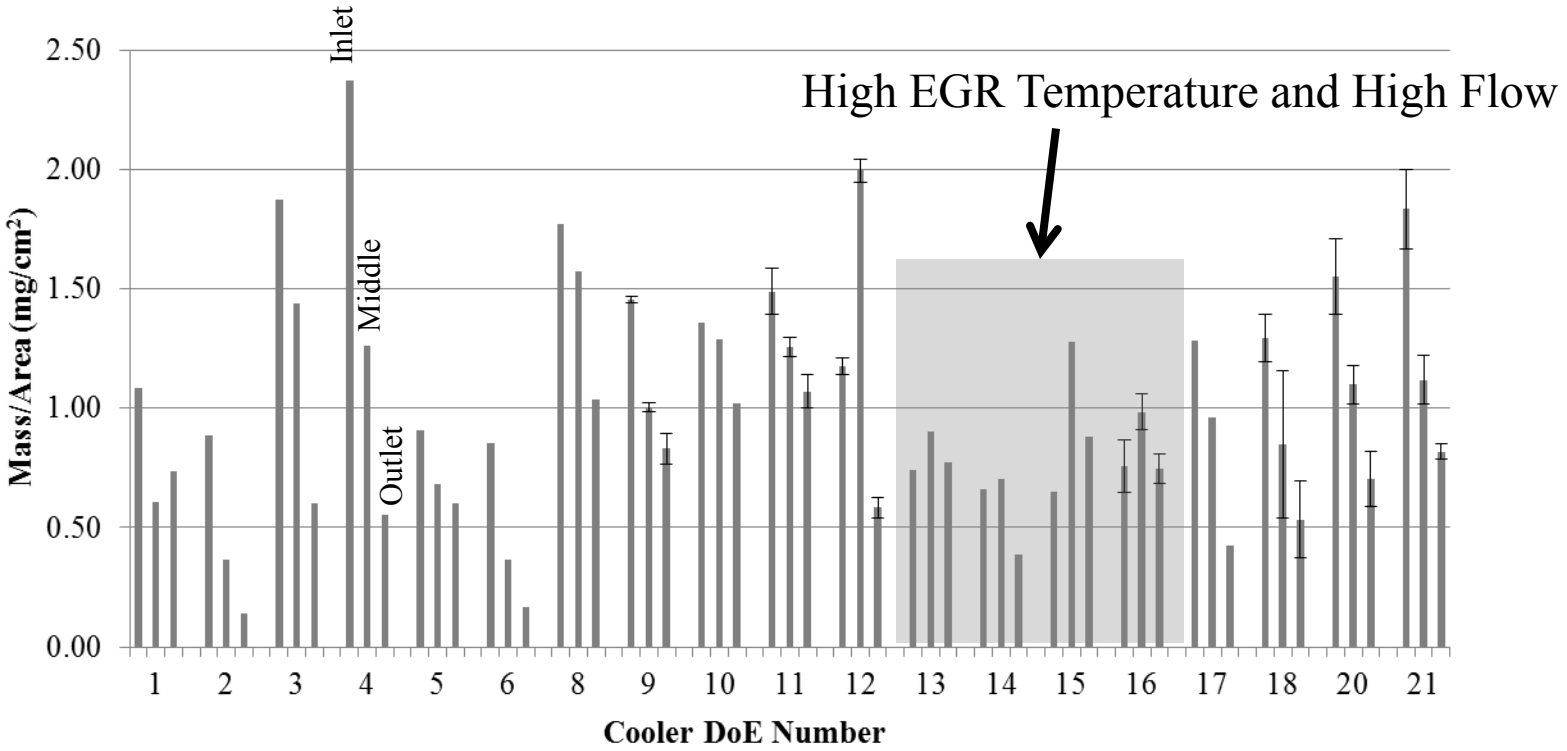
DoE #	EGR rate	EGR Temp	Smoke	HC	Coolant Temp
1	L	L	L	H	L
2	L	L	L	L	H
3	L	L	H	L	L
4	L	L	H	H	H
5	L	H	L	L	L
6	L	H	L	L	H
7	L	H	H	L	L
8	L	H	H	L	H
9	H	L	L	L	L
10	H	L	L	H	H
11	H	L	H	H	L
12	H	L	H	L	H
13	H	H	L	L	L
14	H	H	L	L	H
15	H	H	H	L	L
16	H	H	H	L	H
17	M	L	L	L	M
18	M	M	M	M	M
20	H	M	M	M	M
21	M	L	M	H	M

Best Performing

Worst Performing

- Coolant Temperature had no effect on performance.
- High EGR temperature always produced low HC.

Mass/Area: Measured at Inlet, Middle and Outlet

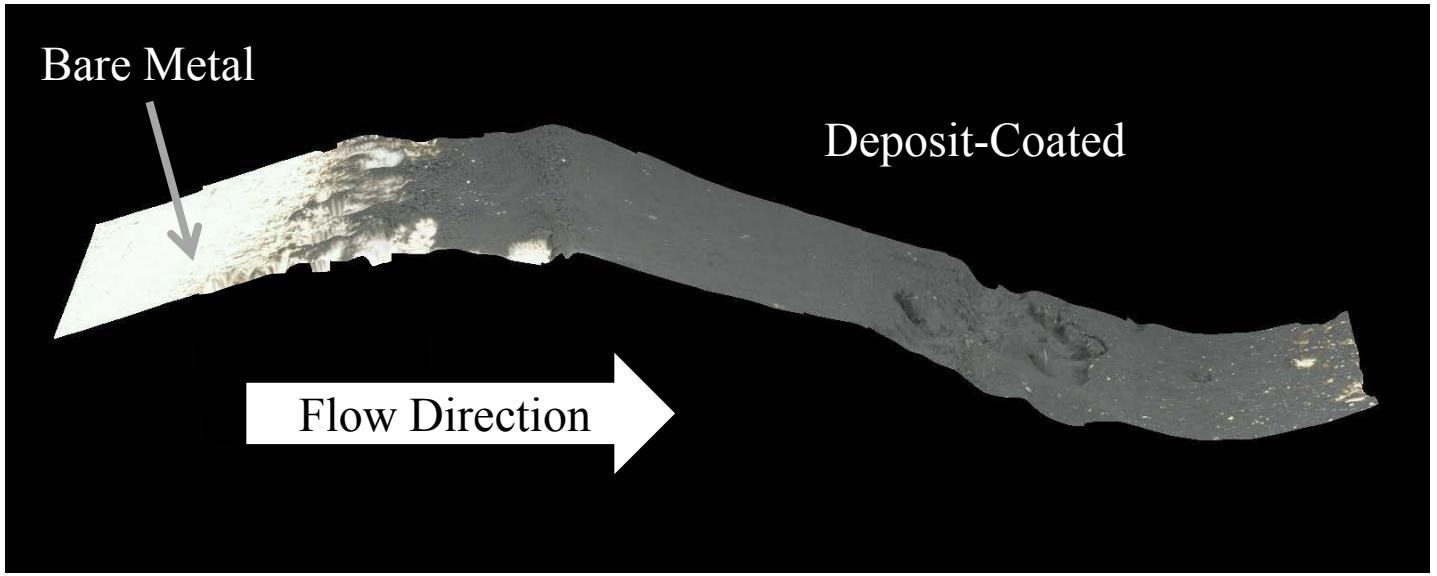


- The deposit mass decreases down the length of the cooler because as the gas is cooled, the thermophoretic velocity, which is proportional to the temperature gradient, decreases.
- Inlet had the highest mass except when both the EGR inlet temperature and flow rate was high.

Deposit Thickness Varies with Fin Geometry

Outlet : Mid-Point Sample

DOE	EGR rate	EGR Temp	Smoke	HC
18	M	M	M	M

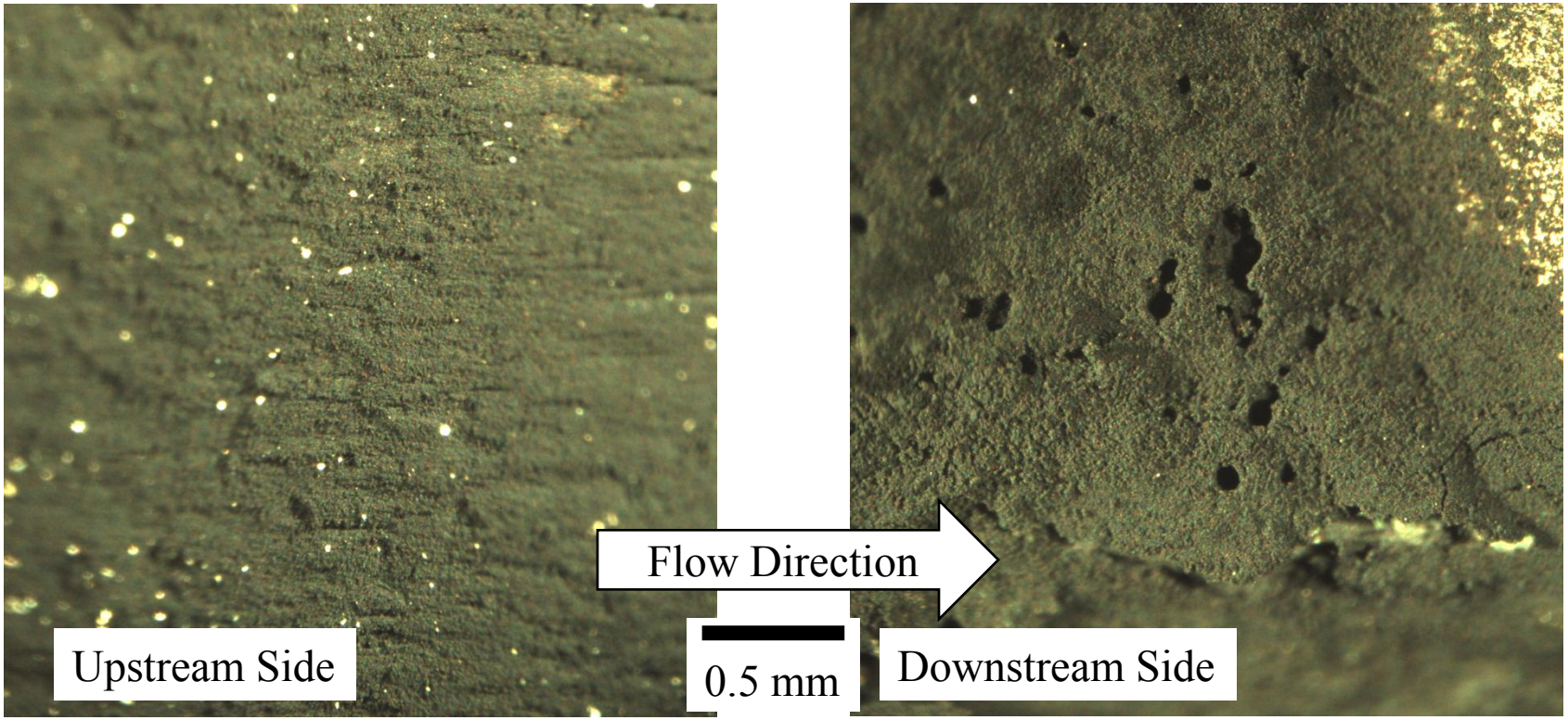


- There is always more deposit on the downstream side of the peak of the fin where the local residence time of the PM increases allowing for more deposition.
- Deposit removal can also occur on the upstream side.

Common Deposit Surface Features

DOE	EGR rate	EGR Temp	Smoke	HC
3	L	L	H	L

DOE	EGR rate	EGR Temp	Smoke	HC
4	L	L	H	H



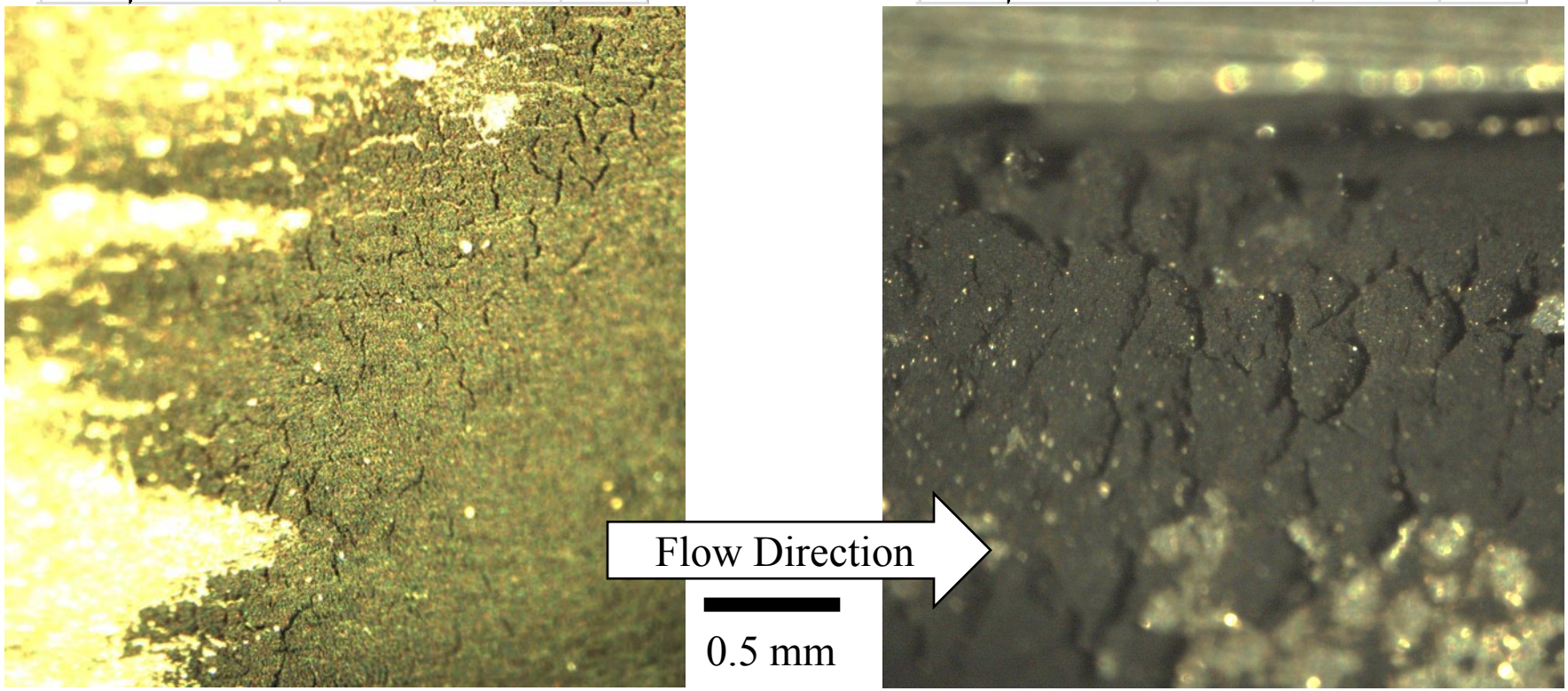
- All the deposits had grooves on the upstream side of the fin peak indicating deposit removal either due to debris hitting the deposit or the gas flow.
- All the deposits had irregular structures on the downstream side of the fin peak.

Effect of High Temperature (Inlet)

Best Performing

DOE	EGR rate	EGR Temp	Smoke	HC
8	L	H	H	L

DOE	EGR rate	EGR Temp	Smoke	HC
6	L	H	L	L

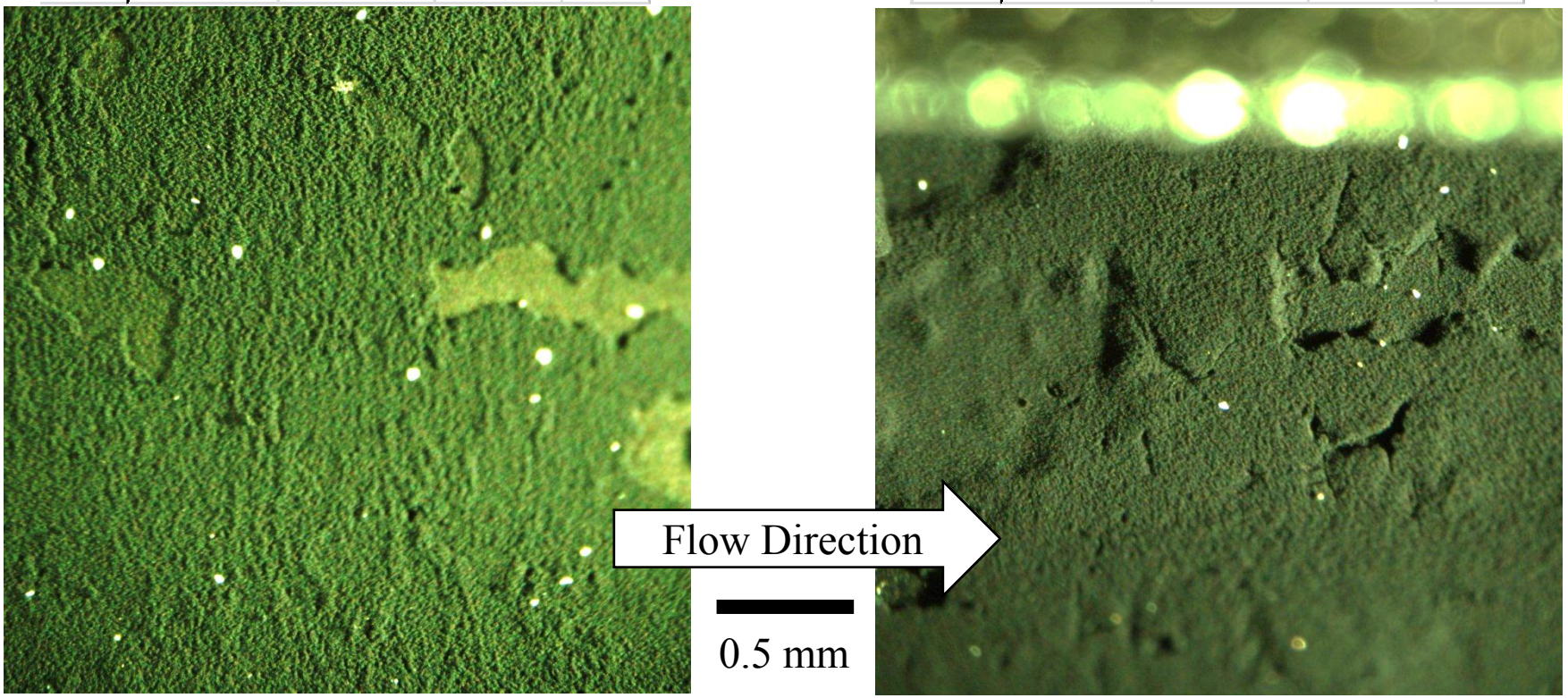


- All high temperature samples had mud-cracking at the inlet.
- The cracks themselves will aid in heat transfer and may lead to deposit spallation.
- Thermochemical effects dominate the deposition and removal mechanisms at these temperatures.

High Temp and High Flow Rate at Inlet

DOE	EGR rate	EGR Temp	Smoke	HC
14	H	H	L	L

DOE	EGR rate	EGR Temp	Smoke	HC
15	H	H	H	L

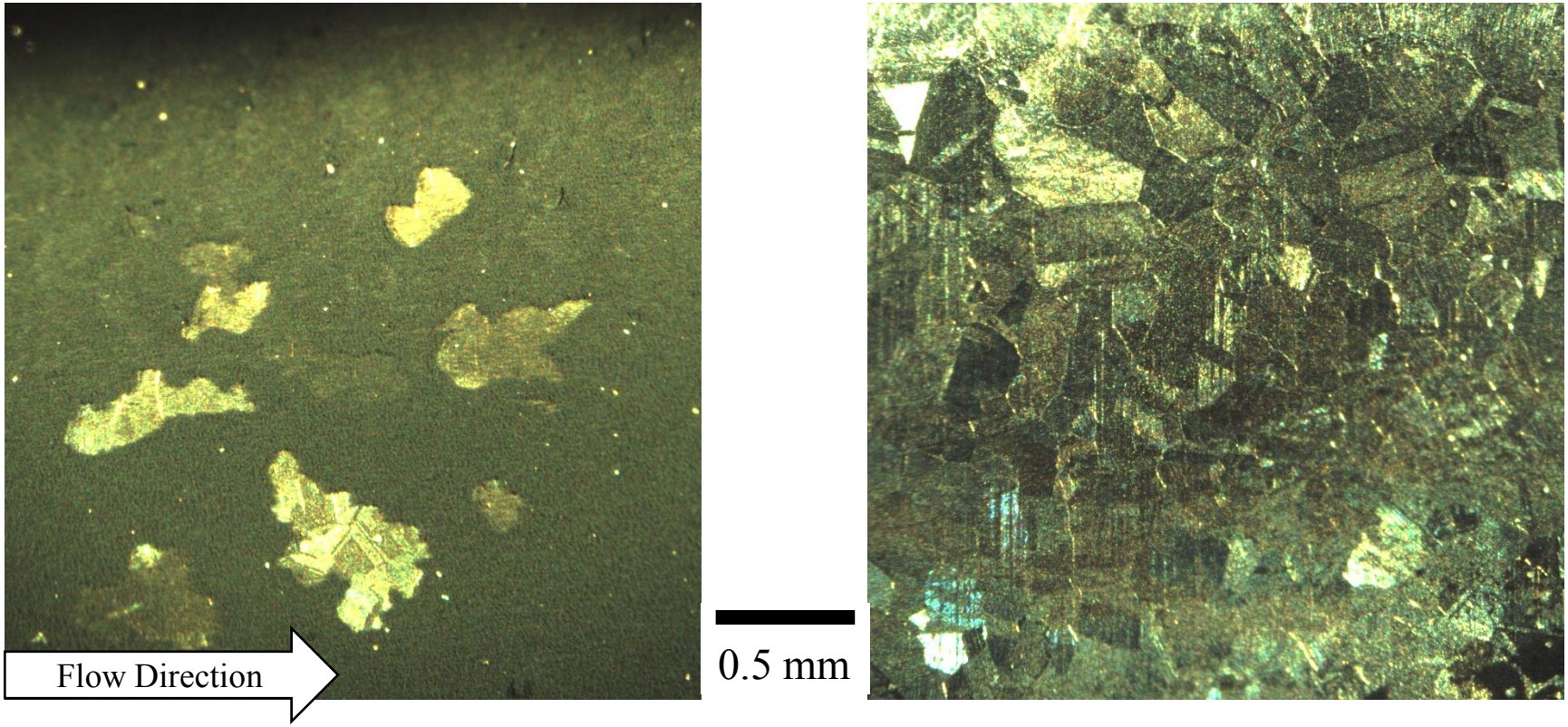


- High rate and high EGR temp correlated with a lower inlet mass.
- Spalled regions are clearly observed. Once spallation occurs, fresh PM will deposit on the bare metal.
- This removal mechanism may be counteracting the higher mass expected at the inlet under this high flow condition. Spallation is aided by the fast-flowing exhaust gas.
- Metal surface appeared to be free of an HC film.

Metal Surface Effect on High Temp, High Flow Rate Deposits

DOE	EGR rate	EGR Temp	Smoke	HC
14	H	H	L	L

Inlet Deposit-Coated Bare Metal

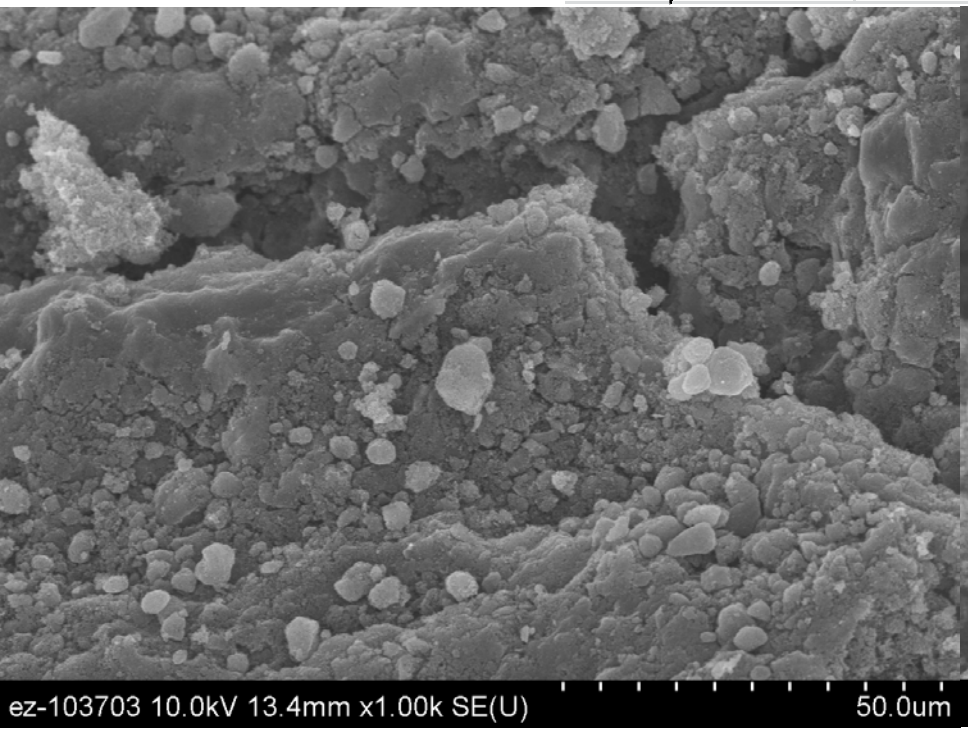


- Faceted spalled regions correspond to the underlying metal grain microstructure.
- Perhaps delamination is influenced by different oxide scales forming on different metal orientations?
- The oxide scale may influence deposit adherence when there is no HC to coat the metal.

Micron-sized Rounded Agglomerates in High Smoke Coolers

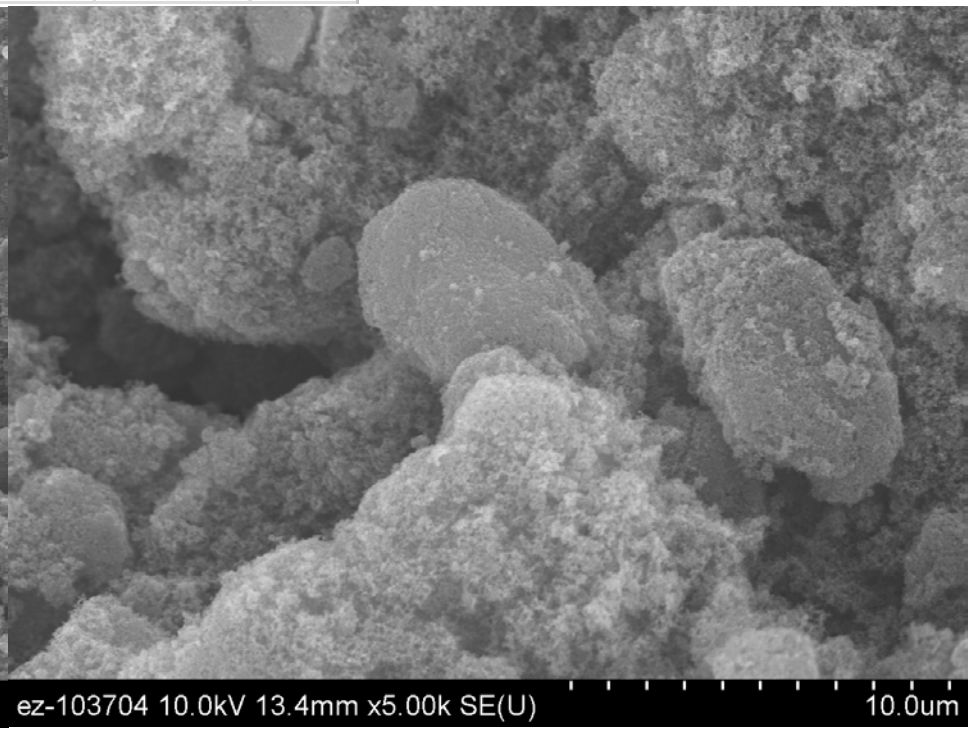
DOE	EGR rate	EGR Temp	Smoke	HC
8	L	H	H	L

Cross-section



Cross-section

Inlet

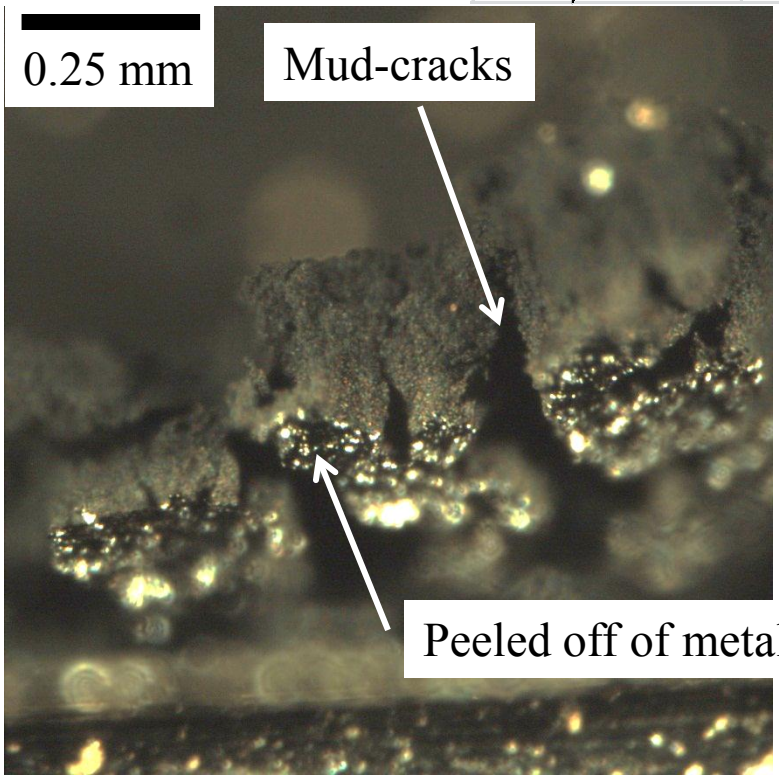


- Only carbon and oxygen were detected.
- The agglomerates were present across the thickness.
- Also found in the inlet diffuser.

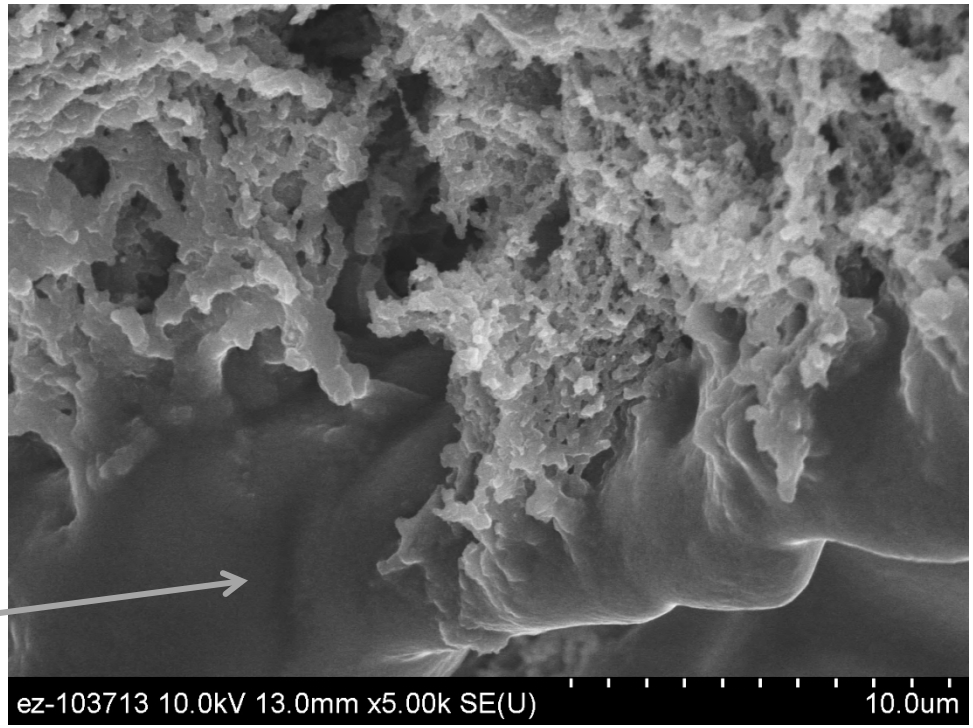
Highest HC Deposit Microstructure

DOE	EGR rate	EGR Temp	Smoke	HC
10	H	L	L	H

Cross-section



Cross-section Inlet



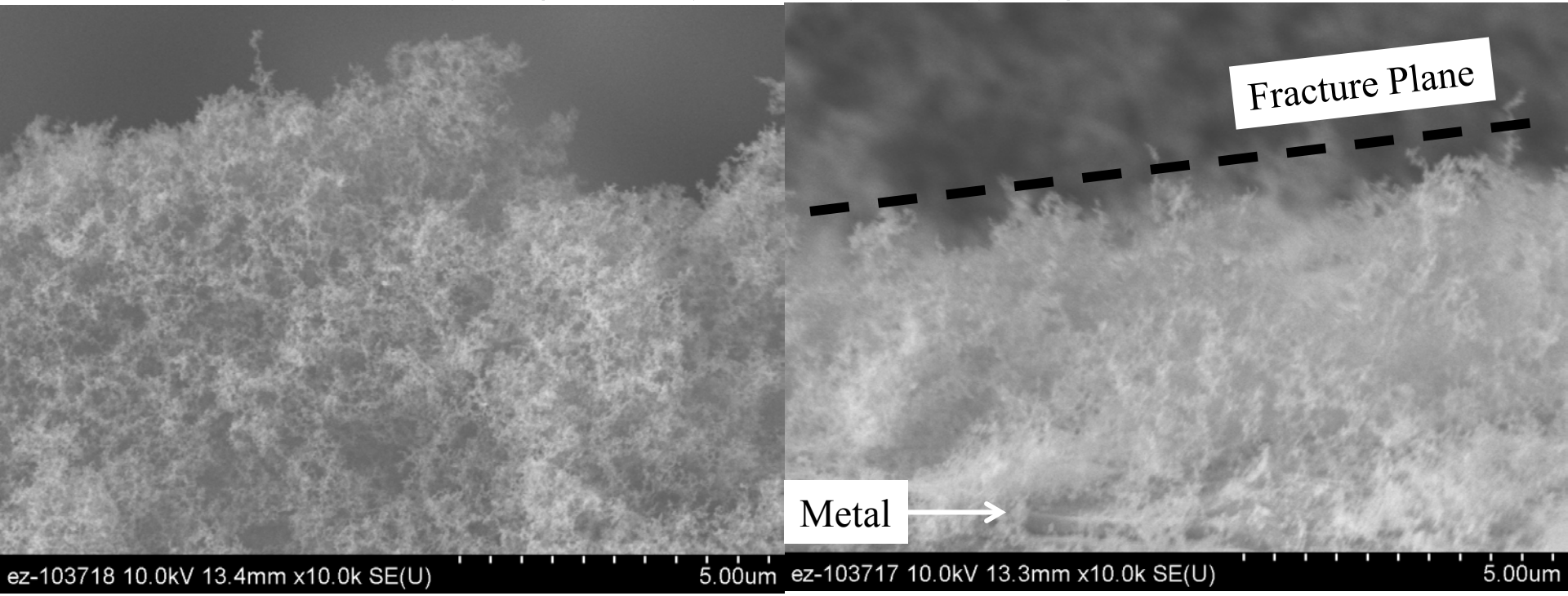
- At least two layers are observed in the deposit: a dense HC layer coating the metal and a PM deposit with an HC gradient moving away from the metal.
- The presence of high amounts of HC appears to densify and coarsen the deposit producing mud-cracks.
- Can HC diffuse through the deposit?

Low HC Deposit Microstructure (Best Performing Cooler)

DOE	EGR rate	EGR Temp	Smoke	HC
6	L	H	L	L

Deposit-Gas Interface

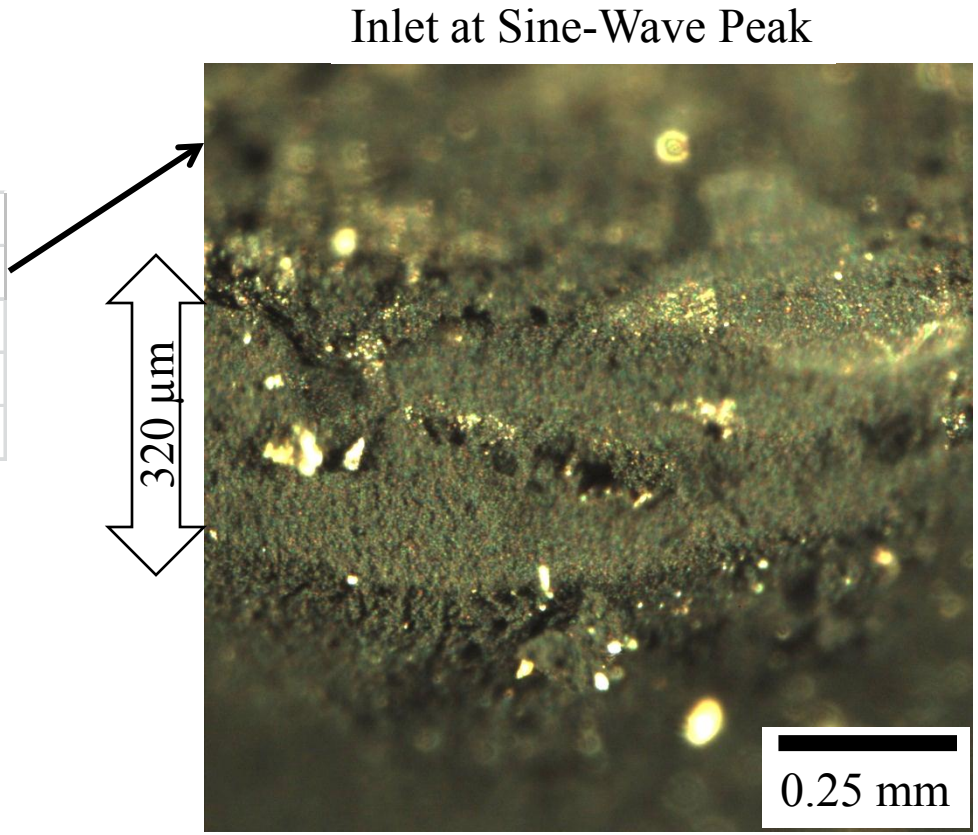
Deposit-Metal Interface



- The PM appears the same across the entire cross-section of the deposit.
- No HC gradient or high smoke agglomerates are observed.
- After delamination, some PM remains on the metal which suggests that, for these conditions, the weakest layer of the deposit is within the deposit, not at the deposit-metal interface.

Four Worst Performing Coolers: High Rate & Low Temp

DOE	EGR rate	EGR Temp	Smoke	HC
12	H	L	H	L
11	H	L	H	H
10	H	L	L	H
9	H	L	L	L



- High rate and low temperature deposits appeared much thicker.
- The high rate introduces more PM and HC for deposition.
- Low gas temperature turns off the spallation observed at the inlet with high gas temperature.

Summary

- Deposit mass and thickness was generally lowest at the outlet of the coolers due to a lower temperature gradient hence a lower thermophoretic velocity.
- Deposit mass and thickness was lowest on the upstream side of the peak of the fin for all of the coolers.
- EGR Temperature
  - Low EGR temperature combined with High EGR rate produces the most deposit.
  - High EGR temperature removes most (all?) HC on the metal surface which possibly reduces PM adherence.
  - High EGR temperature produces thermochemical effects that correlates with deposit mud-cracking.
  - Metal surface comes into play with high EGR temperature.
- EGR Rate
  - High EGR rate is bad because it increases the total PM and HC flowing into the cooler.
  - However, high EGR rate may be beneficial when combined with high EGR temp by aiding in deposit removal at the inlet.
- Smoke
  - High smoke produces PM agglomerates.
- HC
  - High HC deposits have a dense HC layer on the metal and an HC gradient in the PM deposit.
  - In some cases, high HC may densify the deposit and produce mud-cracks though in a different way than high EGR temp.