Mechanism of Turbocharger Coking in Gasoline Engines

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F+L Week 2016
8-11 March 2016
Regent Hotel, Singapore
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2. Objectives
3. What is “Engine Oil Degradation”?
4. How Does Engine Oil Degradation Cause Coking?
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1. Background

Mechanism of Turbocharger Coking in Gasoline Engines

Fuel Economy

DI-SI

HV

Downsizing with Turbocharged DI-SI

Low Speed Pre-Ignition

Engine Oil Degradation

Turbocharger Coking

Fuel Economy

Engine Oil

- Low Viscosity
- Strong FM
(MoDTC, etc.)

Conflict?
1. Background

Mechanism of Turbocharger Coking in Gasoline Engines

Turbocharger System

- Compressor
- Bearing
- Coolant Passage
- Exhaust Turbine
- Oil Drain Passage
- Air
- Exhaust Gas

F+L Week 2016
1. Background

Example of Severe Driving Pattern for Turbocharger Coking

- **Vehicle Speed**
- **Engine Speed / Load**
- **Turbocharger Temperature**

**High Load Operation**

**Engine Shut Down after Short Idling**

**Heat Soak Back from Exhaust Parts**
1. Background
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3. What is “Engine Oil Degradation”?
4. How Does Engine Oil Degradation Cause Coking?
5. Reproduction of Turbocharger Coking by Engine Dyno Test
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2. Objectives

- Clarification of Turbocharger Coking Mechanism
- Development of Turbocharger Coking Screening Test
- Proposal of Effective Countermeasures
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Mechanism of Turbocharger Coking in Gasoline Engines
3. What is “Engine Oil Degradation”?

Designing Engine Oil = Design of Viscosity + Design of Additional Functions

Additional Functions = Dispersancy, Acid Neutralization, Anti-Wear, Anti-Oxidation, etc.
3. What is “Engine Oil Degradation”?

Degradation of Gasoline Engine Oil

Change of Physical Properties

Depletion of Additional Functions

Change of Viscosity

Shear of VII

Fuel Dilution

Depletion of Dispersancy

Depletion of Detergency

Depletion of TBN

Depletion of Anti-Wear

Depletion of Anti-Oxidancy

Etc.

Caused by loss of additives, or degradation of additives
3. What is “Engine Oil Degradation”?

Degradation of Gasoline Engine Oil

- Change of Physical Properties
- Depletion of Additional Functions
- Accumulation of External Materials
  - Un-burnt Fuel
  - Insolubles
    - PM
    - Acid
    - Wear Metals

Excessive Accumulation of Insoluble causes variety of Deposit issues.
3. What is “Engine Oil Degradation”? 

![Diagram of Engine Oil Degradation Mechanism](image)

**Fuel (Gasoline)** → **Combustion** → **Degraded Fuel (C=O)** → **Accumulation in Engine Oil** → **Polymerization** → **Insoluble**

* Insoluble: - Polymer compound containing polar functional group,
  - Poor thermal stability than engine oil
1. Background
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4. How Does Engine Oil Degradation Cause Coking?
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Turbocharger Coking Mechanism

Working Hypothesis:

1) Accumulation of degraded fuel molecules in engine oil
2) Insoluble formation by polymerization of degraded fuel molecules
3) Formation of deposit from insoluble by thermal stress

When this process occurs in the turbocharger, it is observed as turbocharger coking
4. How Does Engine Oil Degradation Cause Coking?

Investigation of Engine Oil Coking Tendency by Thermal Stress

- Used Oil
- Coking Test (HTT)
- Deposit
- Fresh Oil
  - Laboratory Oxidation Test (ISOT)
  - Degraded Oil
  - Coking Test (HTT)
  - Deposit
- Fresh Oil
  - Coking Test (HTT)
  - Deposit
### 4. How Does Engine Oil Degradation Cause Coking?

#### Test Oil Samples for HTT (Laboratory Coking Test)

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Depletion of TBN Increase of TAN</th>
<th>Accumulation of Insoluble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh oil samples</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Degraded oil samples by high temperature oxidation laboratory test</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Diesel used oil samples from engine dyno tests</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gasoline used oil samples from vehicles in the field</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- TBN: Total Base Number
- TAN: Total Acid Number
4. How Does Engine Oil Degradation Cause Coking?

**Gasoline:** Hydrocarbon structure with carbonyl and ester functional groups

**Diesel:** Soot (graphite-like carbonaceous particle)
4. How Does Engine Oil Degradation Cause Coking?

Characteristics of Different Insolubles

<table>
<thead>
<tr>
<th>Gasoline engine oil</th>
<th>Diesel engine oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymerized compound derived from oxidized gasoline molecules</td>
<td>Mainly diesel soot</td>
</tr>
<tr>
<td>Lower coking temp.?</td>
<td>Higher coking temp.?</td>
</tr>
</tbody>
</table>
4. How Does Engine Oil Degradation Cause Coking?

**Gasoline Engine Used Oils from Vehicles**
- Collected from customer vehicles in the US market in 2009
- Engine: 2GR-FE (3.5L, V-6, PFI, N/A)
- ILSAC GF-4 5W-30

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Insoluble*, mass%</th>
<th>TAN, mgKOH/g</th>
<th>TBN, mgKOH/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentane-B</td>
<td></td>
<td>ASTM D664</td>
<td>ASTM D4739</td>
</tr>
<tr>
<td>No.1</td>
<td>0.9</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>No.2</td>
<td>1.9</td>
<td>3.1</td>
<td>0.6</td>
</tr>
<tr>
<td>No.3</td>
<td>3.8</td>
<td>4.1</td>
<td>1.0</td>
</tr>
<tr>
<td>No.4</td>
<td>5.0</td>
<td>4.6</td>
<td>0.1</td>
</tr>
<tr>
<td>No.5</td>
<td>5.9</td>
<td>6.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* With Pentane B Solvent at 30,000G acceleration.
4. How Does Engine Oil Degradation Cause Coking?

**Diesel Engine Used Oils from Fired Engine Test**
- Collected from diesel engine dyno tests
- Engine: Turbocharged, L-4 Common rail, Direct Injection

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Performance Level</th>
<th>Soot*, mass% Pentane-B Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.6</td>
<td>ACEA B1</td>
<td>2.4</td>
</tr>
<tr>
<td>No.7</td>
<td>ACEA B1</td>
<td>2.7</td>
</tr>
<tr>
<td>No.8</td>
<td>ACEA C2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

* With Pentane B Solvent at 30,000G acceleration.
Hot Tube Test (HTT) (JPI-5S-55-99)
Convenient lab. test to check coking tendency of oils. Deposit weight method is applied.
4. How Does Engine Oil Degradation Cause Coking?  TOYOTA

HTT on Gasoline Engine Used Oils from Vehicles

- Similar coking start temp. regardless of their insoluble levels.
- Deposit weight showed correlation to the insoluble level.
- No good correlation between soot content and deposit weight.
- ACEA C2 showed clearly better deposit control.
4. How Does Engine Oil Degradation Cause Coking?

Comparison of Coking Start Temperature

**Gasoline Engine Used Oils**

- No.1 [0.9]
- No.2 [1.9]
- No.3 [3.8]
- No.4 [5.0]
- No.5 [5.9]

**Diesel Engine Used Oils**

- No.6 [2.4]
- No.7 [2.7]
- No.8 [2.2]
4. How Does Engine Oil Degradation Cause Coking?

Investigation of Engine Oil Coking Tendency by Thermal Stress

- Used Oil
- Coking Test (HTT)
- Deposit
- Fresh Oil
- Laboratory Oxidation Test (ISOT)
- Degraded Oil
- Coking Test (HTT)
- Deposit
- Fresh Oil
- Coking Test (HTT)
- Deposit
### Coking Start Temperature in HTT

<table>
<thead>
<tr>
<th></th>
<th>Depletion of TBN</th>
<th>Increase of TAN</th>
<th>Accumulation of Insoluble</th>
<th>Coking Start Temp., degC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline used oil samples from vehicles in the field</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>180</td>
</tr>
<tr>
<td>Diesel used oil samples from engine dyno test</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>240</td>
</tr>
<tr>
<td>Degraded oil samples by high temp. oxidation lab. test</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Fresh oil samples</td>
<td>No</td>
<td>No</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Fresh Oil Samples for HTT and ISOT

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Performance Level</th>
<th>Elemental Content, mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Zn</td>
</tr>
<tr>
<td>No.9</td>
<td>ILSAC GF-3, API SL/EC</td>
<td>0.10</td>
</tr>
<tr>
<td>No.10*</td>
<td>ILSAC GF-4, API SM/EC</td>
<td>0.08</td>
</tr>
<tr>
<td>No.11</td>
<td>ILSAC GF-5, API SN/RC</td>
<td>0.08</td>
</tr>
<tr>
<td>No.12</td>
<td>ACEA B1</td>
<td>0.11</td>
</tr>
<tr>
<td>No.13*</td>
<td>ACEA C2</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* These samples contain MoDTC
4. How Does Engine Oil Degradation Cause Coking?

TEOST 33C (ASTM D6335)

- Developed as simulation laboratory test for gasoline turbocharger coking
- Required as a part of ILSAC GF-5 except SAE 0W-20
- MoDTC is known to increase TEOST 33C deposit formation
  (Ref. : SAE 2008-01-2480)
No. 10 showed high amount of deposit in TEOST 33C.
4. How Does Engine Oil Degradation Cause Coking?

High Temperature Oxidation Test: Indiana Stirring Oxidation Test (ISOT)

- Stirring Speed: 1,300rpm
- Temperature: 165.5°C
- Duration: 72hrs
Degraded Oils by ISOT
- Balance between TBN and TAN is similar to vehicle used oils recovered from the market.
- Almost no insoluble was observed.
4. How Does Engine Oil Degradation Cause Coking?

**Hot Tube Test with Fresh Oils and Degraded Oils by ISOT**

**Degraded Oils by ISOT**

**Fresh Oils**

Engine oil degradation lowered the coking start temperature slightly.
4. How Does Engine Oil Degradation Cause Coking? **TOYOTA**

Hot Tube Test with Gasoline Engine Used Oils and Degraded Oils by ISOT

- **Degraded Oils by ISOT**
- **Gasoline Engine Used Oils from Vehicles**

Insoluble decreases coking start temperature drastically.
### Coking Start Temperature Summary

<table>
<thead>
<tr>
<th></th>
<th>Degradation Level</th>
<th>Coking Start Temp., degC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depletion of TBN</td>
<td>Increase of TAN</td>
</tr>
<tr>
<td>Fresh oil samples</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Diesel used oil</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>samples from</td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine dyno test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degraded oil samples</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>by high temp. oxidation lab. test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline used oil</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>samples from vehicles in the field</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. How Does Engine Oil Degradation Cause Coking?
1. Background
2. Objectives
3. What is “Engine Oil Degradation”? 
4. How Does Engine Oil Degradation Cause Coking?
5. Reproduction of Turbocharger Coking by Engine Dyno Test
6. Summary and Discussion
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5. Reproduction of Turbocharger Coking by Dyno Test

Main Factors of Gasoline Turbocharger Coking are...

- Accumulation of insoluble in gasoline engine oil
  ➔ Fired engine operation is needed.

- Exposure to high temperature around 180 degC or higher
  ➔ Presence of insoluble is necessary.
5. Reproduction of Turbocharger Coking by Dyno Test

Turbocharger Coking Test Cycle

- Engine Speed: 2800
- Torque: Idle

- Adjust torque and idle time after high load operation to get target temperatures.
5. Reproduction of Turbocharger Coking by Dyno Test

**Engine Cooling Circuits**

(a) High Temperature Cooling Circuit

(b) Low Temperature Cooling Circuit
### Test Engine Specification

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Prototype</td>
</tr>
<tr>
<td>Displacement</td>
<td>2.0L</td>
</tr>
<tr>
<td>Air Intake System</td>
<td>Turbocharged</td>
</tr>
<tr>
<td>Fuel Injection System</td>
<td>Direct Injection (Lateral)</td>
</tr>
<tr>
<td>Number of Cylinder</td>
<td>L-4</td>
</tr>
<tr>
<td>Fuel Quality</td>
<td>98 RON</td>
</tr>
</tbody>
</table>

### Cross Section of Turbocharger

- **Bearing**
- **Oil Slinger**
- **Temperature (Near Bearing)**
- **Temperature (Drain Wall)**
5. Reproduction of Turbocharger Coking by Dyno Test

Test 1 Condition:
Drain Wall = 203degC, Bearing = 186degC, Test Duration = 40hrs (High Temp. Cooling Circuit)

- Oil Slinger near by Turbine
- Outer Side of Bearing
- Oil Drain Wall

Mechanism of Turbocharger Coking in Gasoline Engines
5. Reproduction of Turbocharger Coking by Dyno Test

<table>
<thead>
<tr>
<th>Engine Cooling Circuit</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain Wall Temp.</td>
<td>203</td>
<td>172</td>
<td>143</td>
<td>230</td>
</tr>
<tr>
<td>Bearing Temp.</td>
<td>186</td>
<td>160</td>
<td>142</td>
<td>n/a (214) Estimation</td>
</tr>
</tbody>
</table>

Oil Slinger

Bearing
5. Reproduction of Turbocharger Coking by Dyno Test

<table>
<thead>
<tr>
<th></th>
<th>Diesel Engine</th>
<th>Gasoline Engine, Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing</td>
<td>220degC</td>
<td>214degC (Estimated)</td>
</tr>
<tr>
<td>Oil Drain Wall</td>
<td>239degC</td>
<td>230degC</td>
</tr>
<tr>
<td>Duration</td>
<td>600 hours</td>
<td>40 hours</td>
</tr>
<tr>
<td>Insoluble/Soot</td>
<td>0 – several %</td>
<td>7.5 mass%</td>
</tr>
</tbody>
</table>

Result: No thick deposit formation on bearing, slinger, drain wall.
1. Background
2. Objectives
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6. Summary and discussion

- Main source of gasoline turbocharger coking is insoluble derived from fuel.
- Coking start temperature is constant regardless of quantity of insolubles (as long as there are some insolubles).
- Coking start temperature of gasoline engine used oil is lower than that of diesel engine used oil.
- Engine dyno test with used oil containing insolubles showed coking deposit with only 40hr operation.
6. Summary and discussion

Countermeasure
- **Temperature control ➔ Prevention of deposit formation**
- **Anti-oxidancy ➔ Inhibition of polymerization ➔ Deposit amount reduction**

![Diagram showing the mechanism of turbocharger coking in gasoline engines]

- **Fuel (Gasoline)**
- **Air**
- **Energy**
- **Exhaust Gas**

**Combustion**

- **Degraded Fuel (C=O)**
  - Precursor of Insoluble

**Accumulation in Engine Oil**

- **Polymerization**
  - **Insoluble**

- **Coking**

- **Deposit**
  - (Piston Deposit, Turbocharger Coking)

**In Engine Oil**

- **Unavoidable**

- **Anti-Oxidancy**
  - **Heat**

**Temperature control**

- **Promote**
  - Degrade
- **Prevent**
Contents

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7. Conclusion

- To reproduce turbocharger coking with an engine dyno test, used engine oil containing insolubles generated by a fired engine is essential.
- Laboratory thermal stress test with fresh oil will not reproduce the true mechanism of coking.
- MoDTC does not seem to be a concern based on our investigation. It can be utilized for further fuel economy improvement.
- To prevent coking, temperature control is most effective.
- From the viewpoint of engine oil design, improvement of anti-oxidancy is probably effective to reduce deposit formation. Better anti-oxidant formulation and higher quality base stock are desirable to reduce coking deposit.
Thank you for your attention!!
Appendix
4. How does engine oil degradation cause coking?

To clarify the difference between gasoline used oil and diesel used oil, insoluble was analyzed.

- **Used Oil Sample (Gasoline / Diesel)**
  - Dilution with n-Pentane
    - Ultracentrifuge
      - Residue (Insoluble)
        - Dried at 50degC for 3 hours
          - FT-IR Micro-pectroscopy with Pressed Powder on Diamond Plate
            - (1)
          - TGA
            - (2)

2 Times
4. How does engine oil degradation cause coking?

(1) Insoluble Analysis by FT-IR

Diesel: Soot (graphite-like carbonaceous particle)
Gasoline: Hydrocarbon structure with carbonyl and ester functional groups
4. How does engine oil degradation cause coking?

(2) Insoluble Analysis by Thermogravimetric Analysis (TGA)

<table>
<thead>
<tr>
<th>Analysis Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample Quantity</strong></td>
</tr>
<tr>
<td><strong>Sample Pan</strong></td>
</tr>
<tr>
<td><strong>Atmospheric gas</strong></td>
</tr>
<tr>
<td><strong>Temperature program</strong></td>
</tr>
</tbody>
</table>

![Graph showing analysis conditions with temperature in °C and time in min]
4. How does engine oil degradation cause coking?

(2) Insoluble Analysis by Thermogravimetric Analysis (TGA)

Difference of thermal decomposition characteristics between insoluble in gasoline used oil and one in diesel used oil
4. How does engine oil degradation cause coking?

Mechanism of insoluble accumulation

FT-IR analysis of used oil from vehicle field test

- Carbonyl peak (IR58, oxidation peak) increased linearly by mileage.
- Nitro ester peak (IR61, nitration peak) showed take-off from certain mileage.
- Insoluble started to increase after approximately 5,000km
4. How does engine oil degradation cause coking?

Mechanism of insoluble accumulation

- Carbonyl peak (IR58, oxidation peak) is observed in residue (insoluble).
- Nitro ester peak (IR61, nitration peak) is observed in supernatant fraction.
4. How does engine oil degradation cause coking?

Mechanism of gasoline engine oil degradation

- Promote Degrade
- Preventive

**In Engine Oil**

- Degraded Fuel (C=O) = Sludge Precursor
- Polymerization
- Insoluble
- Coagulation
- Coking
- Deposit (Turbocharger Coking)

**Mechanism Summary**

1. Fuel (Gasoline) + Air → Combustion
2. Degraded Fuel (C=O) → Sludge Precursor
3. Sludge Precursor → Accumulation in Engine Oil
4. Engine Oil Oxidation
   - Generation of alcohol
   - Nitro-ester (-O-NO₂)
5. NOx Generation

**Antioxidancy**

- Promotes degradation
- Prevents coking