

Investigation and Analysis of Wear in a 3.6L V6 Gasoline Engine: Phase I - Use of Radioactive Tracer Technology

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ABSTRACT

Piston ring and liner wear measurements and analyses were performed in a production 3.6L V6 gasoline engine with radiolabelled engine parts. Three isotopes were generated: one in the engine liner using surface layer activation; one each in the top ring face and top ring side using bulk activation. Real-time wear measurements and subsequent rates of these three surfaces were captured using the radioactive decay of the isotopes into the engine oiling system. In addition, surface roughness and wear profile measurements were carried out using white light interferometry. The results from Phase I provided insights on evolution of wear and wear rates in critical engine components in a gasoline engine.

Phase II will extend this work further and focus on evaluating the fuel additive effects on engine wear.

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INTRODUCTION

Wear is ever present in any engine - it is important to understand a) the mechanism of wear and wear rates of critical engine parts and b) can the wear effects be mitigated by using the right fuel additive chemistry. The objective of this study was to investigate and analyze wear in a commercially available 3.6L V6 gasoline engine and evaluate the wear of the piston rings and piston ring/liner interface with a market representative fuel containing a generic additive using radioactive tracer technology (RATT) and white light interferometry (WLI). The study was designed to generate the baseline data, establish "size of the prize" and perform method development and optimization for the subsequent testing.

Bulk activation and surface layer activation methodologies were utilized to generate isotopes in the piston rings and liners respectively. The activities and decay of these isotopes were then monitored simultaneously to identify the source and the amount of wear at these surfaces in real time using germanium detectors. At the end of the test, WLI was used to "visualize" wear on the used piston and piston ring surfaces as compared to the references (new - "unworn" reference and sequence IIIH - "worn" reference).

This article is the first in a series of intended publications to determine the protection mechanisms of gasoline additives against engine wear. The current article discusses the techniques and methodology used to assess the engine wear for liner and piston ring surfaces in a gasoline engine and provides preliminary wear results. RATT and WLI techniques made it feasible to measure real-time wear and generate high resolution surface topography information for new and worn engine parts respectively.

EXPERIMENTAL DETAIL

Vehicle and Engine

The main objective of this work was to evaluate wear at engine surfaces using a Pentastar 3.6L V6 engine with an eight-speed transmission. In order to achieve this goal, a 2015 Dodge Charger equipped with the same Pentastar 3.6L V6 engine was used on the mileage accumulation dynamometer (MAD) for developing a test cycle. The vehicle was driven on a MAD using the US06 cycle (Appendix, [Figure A1](#)), and engine data was recorded to generate the desired test cycle for the program. Afterward, two Pentastar 3.6L V6 engines were purchased - one was used to simulate the test cell installation and for tuning the test cycle and the second engine was disassembled and the various components were sent out for irradiation.

Drive Cycle Development

A 2015 Dodge Charger equipped with a 3.6L V6 Pentastar engine and an eight-speed transmission (identical to the test engine) was run on a MAD for several days using the US06 drive cycle to generate the engine data outlined in Table 1.

Table 1. On-board Diagnostics Data from the 2015 Dodge Charger.

OBD Data
Engine RPM
Engine coolant temp.
Intake manifold absolute pressure
Absolute throttle position
Ignition timing degrees
Long term fuel trim bank 1
Trouble code MIL
Calculated load value
Long term fuel trim bank 2
Intake air temp.
O2 sensor V/trim bank 1-sensor1
O2 sensor V/trim bank 2-sensor1

The engine data was processed to identify a series of operating conditions that could be used on the dynamometer. Specifically, the engine RPM versus intake manifold absolute pressure (MAP) data is shown in Figure 1.

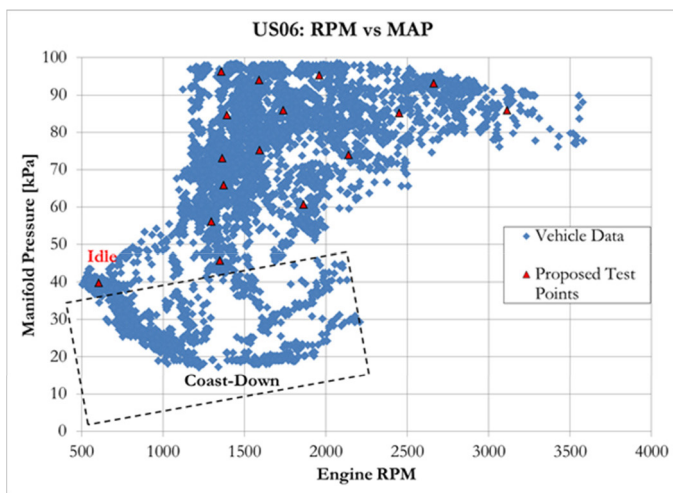


Figure 1. Engine RPM versus MAP Data for the 2015 Dodge Charger with a Pentastar 3.6L V6 Engine on US06 Drive Cycle.

These highlighted (in red) test points in Figure 1 were then used to develop a test cycle for use on the cell for the Pentastar 3.6L V6 engine. First, the engine data collected was reduced by eliminating the coast down portion of the operating map. Furthermore, as an absorption dynamometer was used for this test, the engine braking

portion of the data was accounted for by adding time to the idle. The data was divided into 16 operating bins and the test cycle used for the program is outlined in Figure 2.

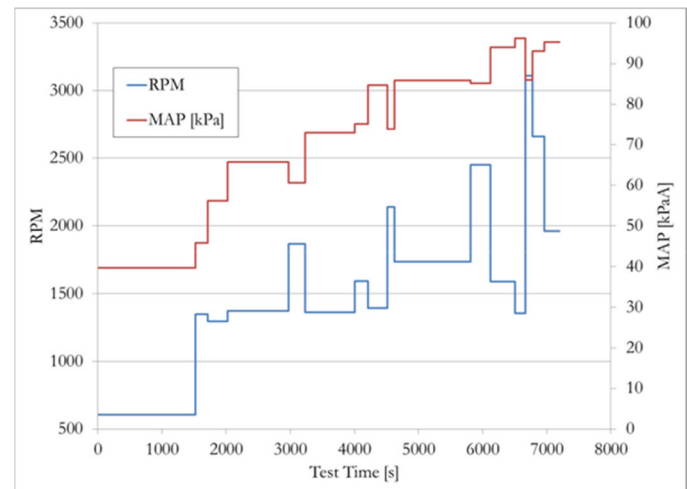


Figure 2. Test Cycle used for Mileage Accumulation.

Each test cycle, which is composed of 16 operating points, runs for two hours at an average speed of approximately 48.4 mph. The engine data was collected for a total of 104 cycles (equivalent to 10,061 miles).

RATT and Irradiation of Engine Parts

RATT has been used extensively for several decades to measure engine wear [1] [2] [3] [4] [5] [6]. It involves labeling engine parts with radioactive isotopes and subsequently using the isotopes as a tracer for real-time wear measurements. Depending on the activation technique used, a wide variety of unique radioactive isotopes corresponding to different engine parts can be generated - this permits simultaneous wear measurement from different engine parts in a single test.

For this study, six masked areas (one per cylinder) with an area of $10 \times 15 \text{ mm}^2$ at the top ring reversal region were activated in the cylinder liner using a particle accelerator utilizing a proton beam. The resultant activation produced Cobalt 56 from iron in the cylinder bore. The beam angle was chosen to generate $100 \mu\text{Ci}$ of activity within 40 microns of the bore surface, and a linear profile of activity per depth was maintained to a minimum of 40 microns of depth from the unworn surface.

The six top piston rings (one in each cylinder) were bulk activated via thermal neutron bombardment within a research reactor. Bulk activation created radioactive labeling material throughout the thickness of test parts, so some radioactive iron was generated away from the contact surfaces of the test parts. However, the isotopes to be monitored during testing are Chromium 51 and Iron 59. Chromium 51 was generated from the stable chromium in the top ring insert on the face of the ring. Iron 59 was created from the parent top ring material and represents the ring side and corner wear during

testing. The irradiation of these parts is not expected to affect the surface finish, hardness or any other properties that could potentially affect the results.

The half-lives and decays are as follows:

Liner: Cobalt 56 - 77 days (decays to stable Iron)

Top Ring Face: Chromium 51 - 28 days (decays to stable Vanadium)

Top Ring Side: Iron 59 - 45 days (decays to stable Cobalt)

Radioactivity Measurements

Both bulk and surface layer activation create gamma ray emitting radionuclides. These nuclides, which are in an excited state, transition to lower energy and a more stable state over time by emitting gamma ray photons. This gamma ray photon emission has two characteristics:

- **Specific energy** - It is characteristic of the parent element and helps identify the engine radiolabeled components where the wear is being generated.
- **Intensity** - It is proportional to the amount of element present at any time during the measurement. It is a characteristic probability of an isotope to decay with the emission of a gamma ray photon at a specific energy for the unique isotope.

Therefore, in combination, specific energy and intensity can help identify the source and the amount of wear in real time using germanium detectors. Germanium detectors provide well resolved energy detection, thereby helping to better discriminate between individual radionuclides as compared to standard scintillation counter-methodologies. This allows for an accurate measurement of wear from multiple engine parts in one experiment, for example allowing us to readily measure wear from liner, ring face, ring side, and bearings in parallel. The assembly is shown in [Figure 3](#).

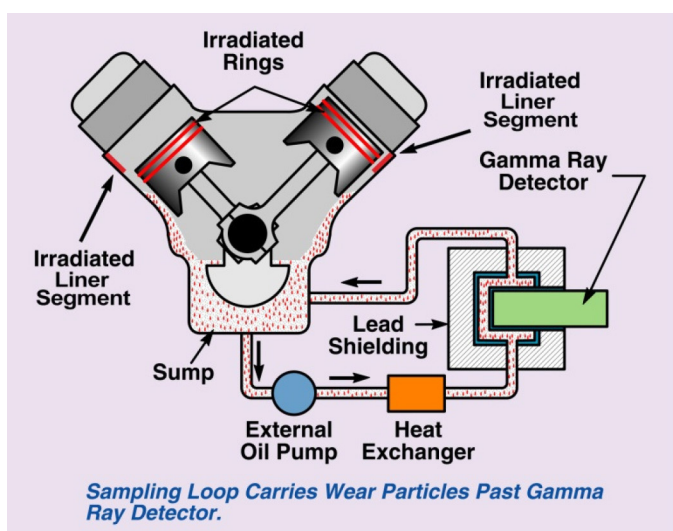


Figure 3. Illustration of an Irradiated Engine Showing Radiolabeled Parts and a Gamma Ray Detector. [2]

Calibration pieces of small segments of top rings were activated along with the test parts submitted for bulk neutron activation. The calibration pieces complete the activation with the equivalent specific activity to the test components. The calibration pieces were digested in sulfuric acid to create calibration solutions of 5, 10, 50, 100, and 1000 $\mu\text{g/L}$ concentrations. The solutions were introduced into the detection circuit and acquisitions were taken to measure the decay rate of each solution. The decay rate per mass became the calibrating factor that is reported as a mass loss for the measured decay counts measured at the detector. The top ring side and face calibration data is summarized in [Figure A4](#) and [A5](#) respectively.

The SLA liners calibration is a calculated profile based on particle beam incident angle, isotope production rate, and the duration of exposure. Interrogating the activated part is not possible without removing material, therefore the mathematical model that produces the activity profile production is validated using thin film stacks of material that represent part metallurgy of the test specimens. The thin film stacks undergo activation. To quantify the activity produced per depth in the thin film stack, the material stack is interrogated with detection equipment while layers are subsequently removed from the material stack. The activity versus depth profiles from the thin film stacks are used to generate profiles for test specimens of like materials. Profile corrections for necessary beam angles and energies can be made with the analytical tool generated from the empirical data collected via the thin film stacks. A linear fit to the thin film data depicts the slight rise and fall of activity along the depth profile of the thin film stacks as outlined in [Figure 4](#).

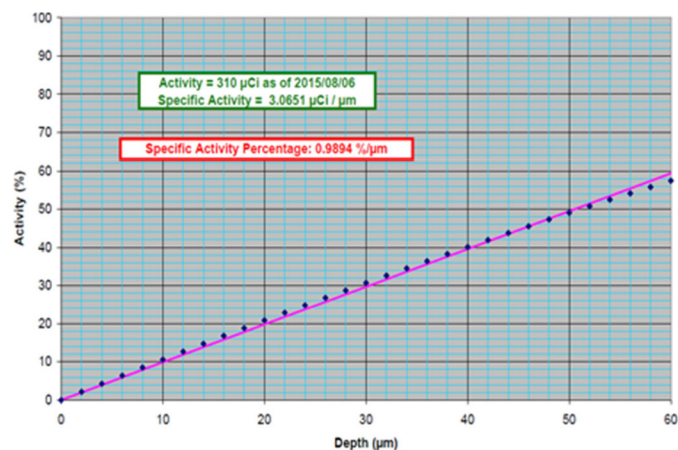


Figure 4. Illustration of an Irradiated Engine Showing Radiolabeled Parts and a Gamma Ray Detector

Fuels and Lubricant

The fuel used in this program was 87 ((RON+MON)/2) E10 unleaded gasoline that meets US specifications ASTM D4814 and contains a typical gasoline detergent additive at a concentration typical of a Lowest Allowable Concentration (LAC) fuel.

A leading market representative 5W-30 Group III lubricant meeting API SJ specification was used for the program. Oil samples were taken at the end of every day, ranging from 5 ml to 15 ml. Due to radioactive concerns, only a minimum volume of the oil was sampled. The sump volume

for this engine is 5,600 ml (6 quart); the removal of a small volume of oil for sampling is not expected to have any significant effect on the total oil volume. Eight ounces of oil (236.6 ml) were collected for the fresh and end of test (EOT) samples. The metal concentration in the oil was measured according to ASTM D5185. Oxidation, nitration, kinematic viscosity at 100 °C and 40 °C and dynamic viscosity at 100 °C and 40 °C were also measured for all the samples to keep track of the oil properties over the test duration.

Test Conditions

The engine test was designed to represent the temperature conditions encountered over one full calendar year and therefore include warm and cold starts. The following starting temperatures were used:

Spring: 50 °F; **Summer:** 75 °F; **Fall:** 50 °F and **Winter:** 25 °F

The engine was run for four test cycles each day, for a total of eight hours. The starting temperature conditions were applied only at the beginning of the day.

Wear Profile Measurements

White Light Interferometry (WLI) was used to investigate the differences in wear between the new and worn surfaces.

WLI is a non-contact optical three-dimensional surface measurement technique giving nanometer resolution surface profiles. A Bruker NPFLEX-LA was used in combination with 'Vision64' software to produce 3-D images of the surfaces.

RESULTS AND DISCUSSION

Radioactivity Measurements

Radiation data was collected for three isotopes representing two engine components. The isotopes and their association with wear from a specific engine component are as follows:

Liner: Cobalt 56

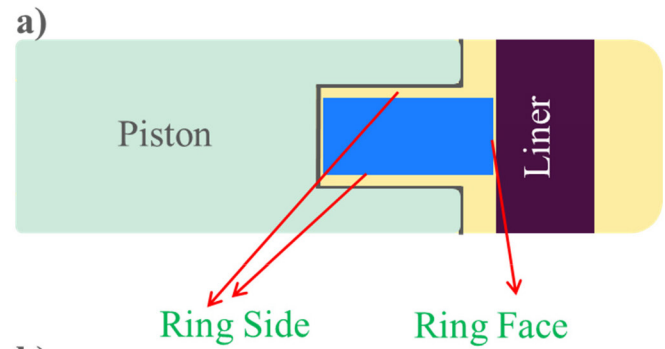
Top Ring Face: Chromium 51

Top Ring Side: Iron 59

The calibration, as discussed in the Experimental Detail - Radioactivity Measurements section, enables the radioactivity data to be converted to μg units. The data was collected for a total of 208 hours. However, measureable liner wear rates were collected only for 32 hours (~1,500 miles) for the liner wear and 136 hours (~6,500 miles) for the top ring side and ring face wear respectively.

Figure 5(a) illustrates how the ring face comes in contact with the liner surface and ring sides come in contact with the piston ring groove surface resulting in ring wear.

The liner wear showed a rapid initial break-in wear over the first two hours before leveling off to a very slow rate, as shown in Figure 5(b).



b)

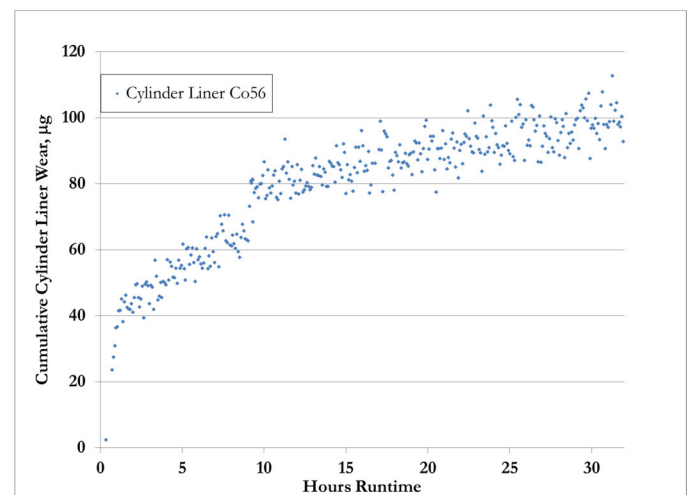


Figure 5. (a): Side Cut Away View of Piston, Liner and Top Piston Ring and 5(b): Cylinder Liner Wear for 32 Hours.

The raw data collected over the duration of the test is shown in the Appendix (Figure A2). After approximately 32 hours (~1,500 miles), as shown in Figure A2, unexpectedly the levels of cumulative liner wear were observed to decrease over time. A decrease in cumulative wear suggests isotopic wear particle removal from the oil system, and/or that not all the wear particles were consistently reaching the germanium detector. A possible explanation is that a certain percentage, albeit small, of wear particles generated over time were trapped in crevices exposed to engine oil and in the lube oil filter. For cylinder wear, 310 μCi total activity was created on a small area of 60 $\times$ 15 mm (six 10 $\times$ 15 mm areas in each cylinder). The specific activity of each liner segment required greater than 15 μg of liner wear per hour to achieve material detection. The operational points beyond 32 hours resulted in liner wear at or below these low μg levels. Wear measurement at this μg range would be significantly affected by the amount of material lost *via* trapping and hence could lead to a decrease in cumulative wear measurement.