Keronite

The ATLAS project – Thermal swing coatings for improved engine efficiency

Ankit Khurana, Keronite Ltd
Dr Robin Francis, Keronite Ltd
Professor Alasdair Cairns, University of Nottingham

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Thermal swing coatings are believed to improve the efficiency of engines via reduction of heat transfer to the piston and enhanced burn characteristics

- Thermal swing coatings on the top surfaces of pistons have been indicated to lead to improved fuel efficiency
- In particular, Toyota's "Sirpa" coating, a reinforced porous anodised coating, has been claimed to increase fuel efficiency by ~1-2%
- The mode of action of the coating is still the subject of intensive study, but seems to result from a combination of:
    - Reduced heat transfer to the piston
    - Increase in piston work
    - More stable burn
    - Enhanced evaporation and mixing during the intake and compression strokes

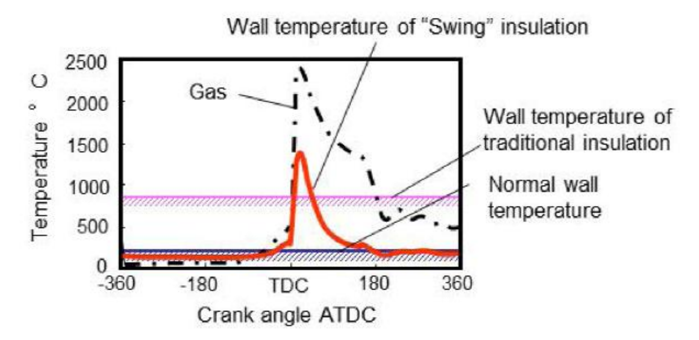
Ref: Kawaguchi, A., et al., *Thermo-Swing Wall Insulation Technology; - A Novel Heat Loss Reduction Approach on Engine Combustion Chamber*. 2016, SAE International.

The basic idea – low thermal conductivity & heat capacity coatings that limit thermal transfer and "follow" temperatures inside the piston

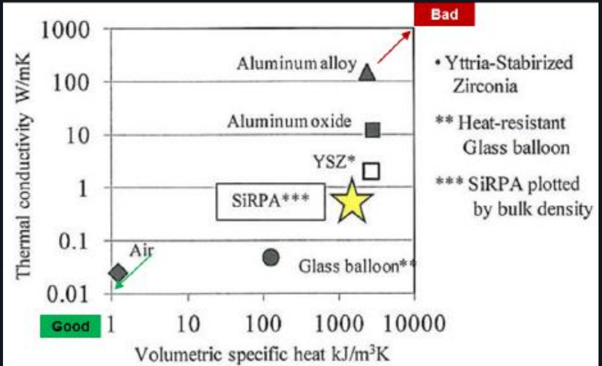
- A good thermal swing coating combines low thermal conductivity and low volumetric heat capacity
- Low thermal conductivity reduces heat transfer to the piston during the combustion stroke
- Low Cv reduces heat uptake and allows release back during the exhaust, intake and compression strokes

Target is:

- **Conductivity<~0.5W/m.K**
- **Heat capacity <1,000 kJ/m^3.K**



Ref: Kawaguchi et.al. Toyota – Thermo Swing Wall Insulation Technology. 2015, 24th Aachen Colloquium



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Plasma electrolytic oxidation (PEO) converts the surface of light metals to a thick oxide layer whose properties are attractive for thermal swing coatings

- PEO technology combines oxidation of the surface and co-deposition from the electrolyte
- Millions of short-lived plasma discharges transform the surface layer into oxide phases such as corundum on Al
- Higher potentials employed (up to 800V) - plasma modifies and enhances the structure of the oxide layer
- Coating has attractive properties for thermal swing application

Thermal resistance

- Coatings stable to over 900°C
- 'Low' to 'Moderate' thermal conductivities (k~0.1-10Wm-1K-1) compared to 18Wm-1K-1 for industrial alumina.

Adhesion & durability

- Extreme adhesion due to conversion of the substrate results in no interfacial attack/corrosion creep and coating delamination

Porosity

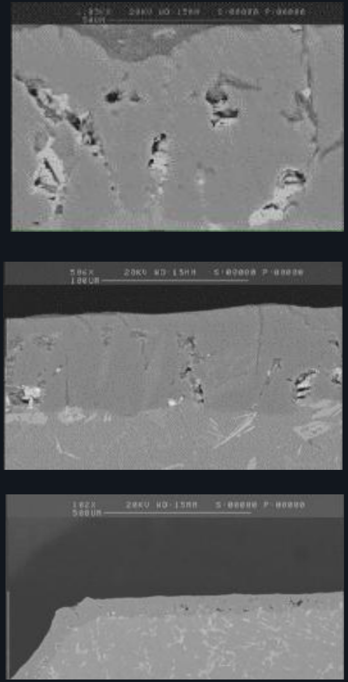
- Uniformly distributed pore architecture in both microscale and nano-scale sizes – good for low conductivity and heat capacity

Hardness & wear resistance

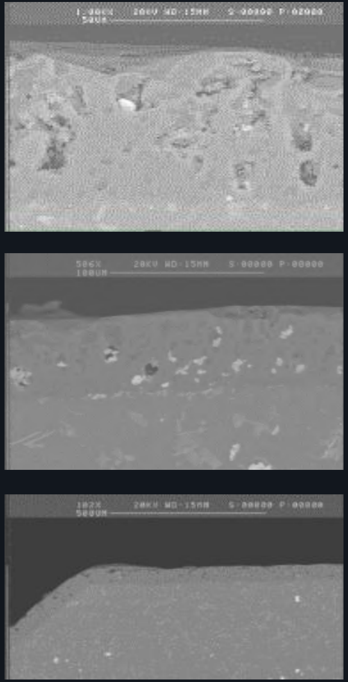
- 1200-1800HV hardness, significant in excess of anodised coatings
- Coating significantly harder than steel, sand, glass, common wear counterparts

Keronite is more conformal, uniform and has higher porosity than hard anodised coatings

Hard anodised



Keronite PEO



- Cross sectional examinations confirm both HA and PEO coatings have good edge retention, though Keronite appears to be more conformal and uniform
- Keronite coating displays a greater porosity that hard anodised coatings
- Hard anodised sample shows Si particle entrapment within the coating
- The sealer forms a thin (typically 5-10μm) blanket layer on top of the Keronite with good adhesion and smoothening the surface roughness
- These properties are all favourable for piston thermal swing coatings

The ATLAS project – “Active Thermal Layers in Automotive Systems”

- ATLAS project – Innovate UK supported project comprising a consortium of Keronite, Tata Technologies, Jaguar Land Rover, TWI, and UoN
- 1 year project which concluded in 2018
- Primary aim was to perform single cylinder engine tests of Keronite PEO coated pistons and compare them with uncoated and anodised pistons

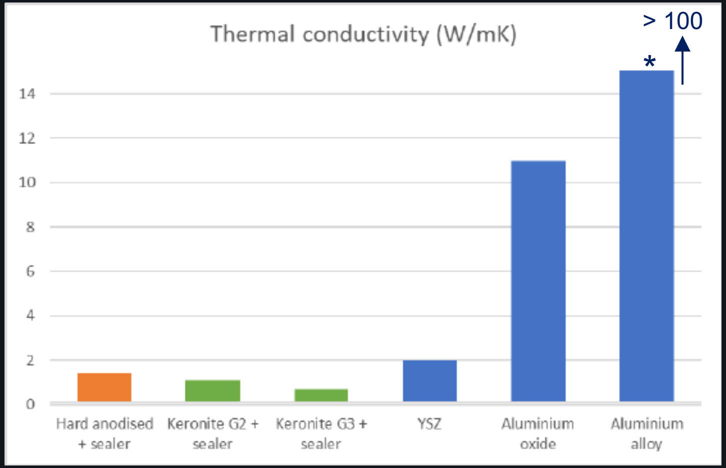
ATLAS – Keronite coatings applied to both full crown and bowl only coated pistons

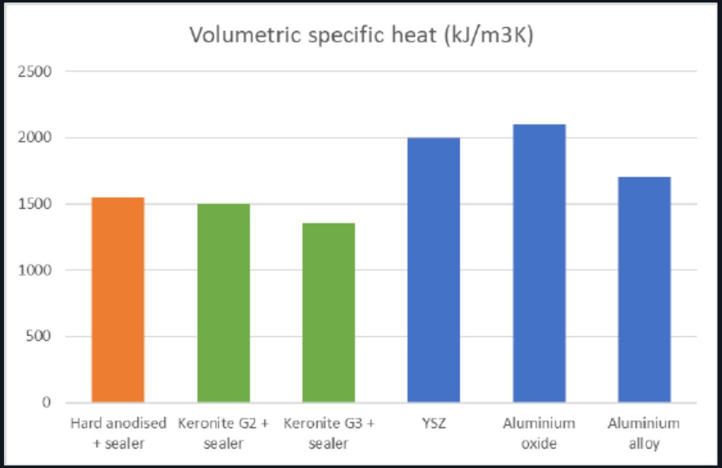
- Keronite has developed techniques to form uniform coatings on both the complete top surface of pistons and crown area only

Full coverage

Bowl masked

Thermal measurements using laser flash show that the best PEO coatings display lower conductivities than the benchmark hard anodised coatings



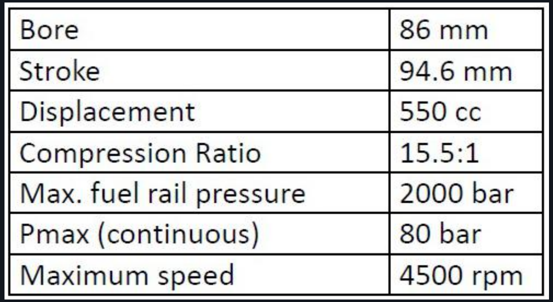


Note:

- Values for hard anodised and Keronite samples are averages of measurements performed by Keronite and partner companies
- Values for other materials are approximate values obtained from the literature. Actual values depend on the precise composition and form of the materials

- Keronite G3 + sealer has both low ‘λ’ and ‘Cv’ - *lower than hard anodised benchmark*

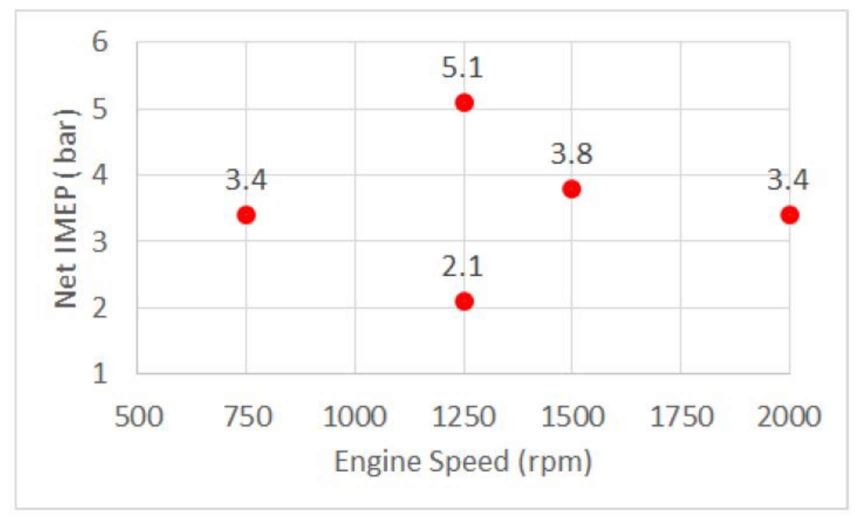
ATLAS – Single cylinder testing

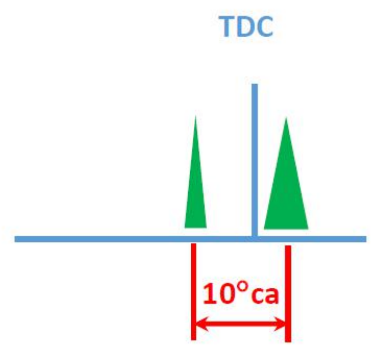


Bore	86 mm
Stroke	94.6 mm
Displacement	550 cc
Compression Ratio	15.5:1
Max. fuel rail pressure	2000 bar
Pmax (continuous)	80 bar
Maximum speed	4500 rpm

- Testing performed at the Powertrain Research Group facility at the University of Nottingham
- Ricardo Hydra with Ford Puma internals (piezo DI, EGR, air heating, external boost rig)
- Restricted to part load operation
  - Hydra bottom end limited to Pmax of 80 bar
  - Current set-up not designed for continuous high speed/load

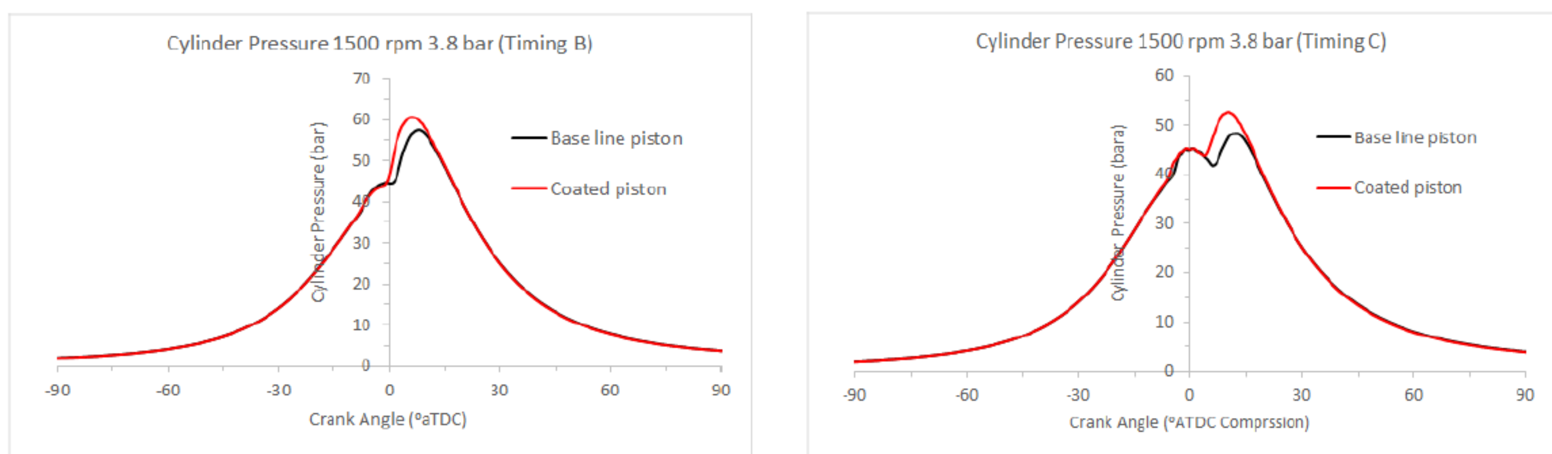
ATLAS – Test plan





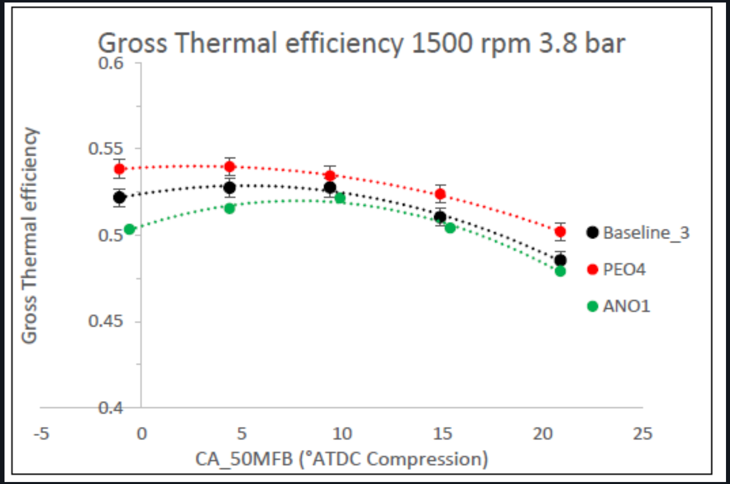
- All indicated sites were subjected to fuel timing sweeps (pilot and main)
- 1600rpm/3.8 bar is key site with additional sweeps
  - Fixed fuel mass, EGR (PCCI)

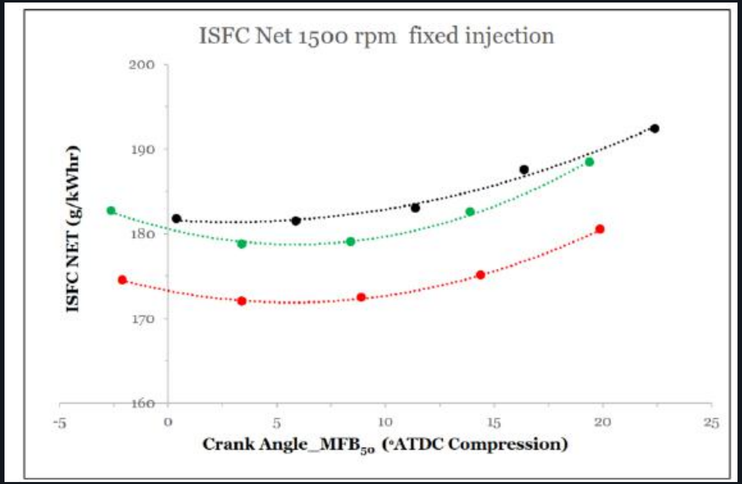
ATLAS – Technical observations



- Average pressure data over 300 cycles (note CoV IMEP <1%)
- Combustion advances for fixed injection timings
  - Timing B: Pilot injection @-20 aTDC and main injection @-10 aTDC
  - Timing C: Pilot injection @-15 aTDC and main injection @-5 aTDC
- Differences more profound with retarded combustion timings
- Agrees with reduced heat losses during combustion

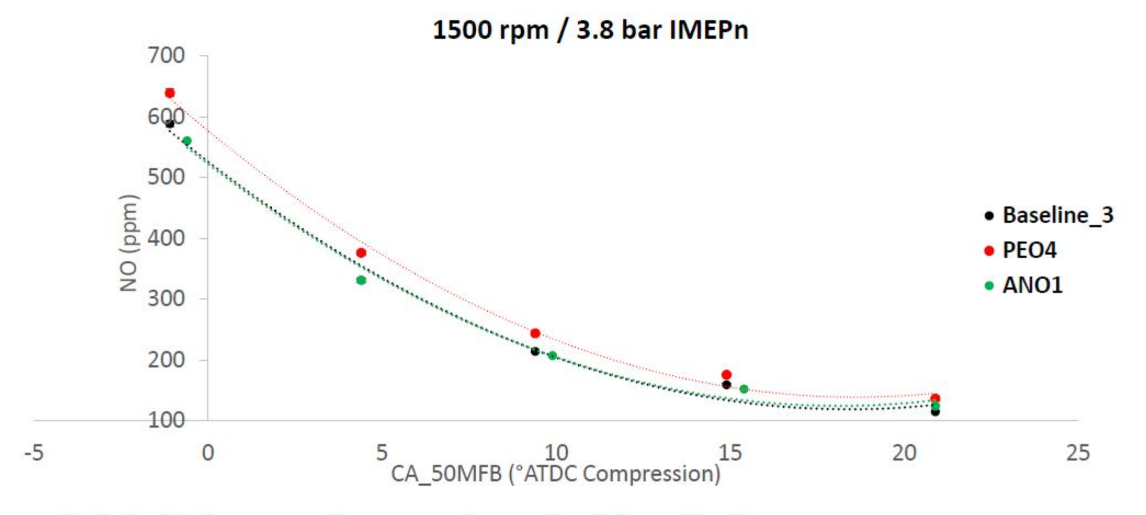
ATLAS – Fuel consumption data





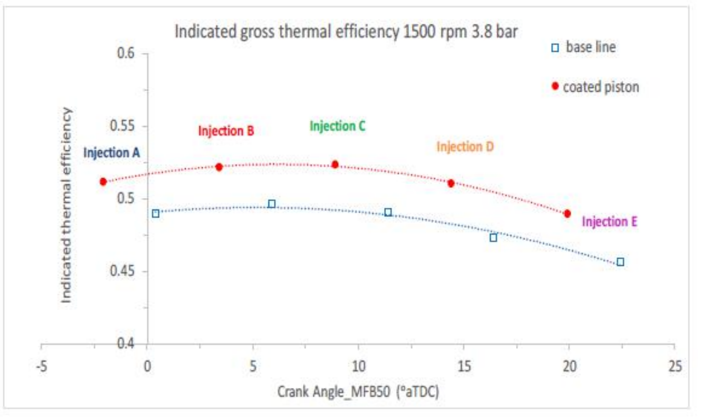
- Approximately 3-5% efficiency improvement seen in 0% EGR conditions
- Anodised piston marginally worse on same basis

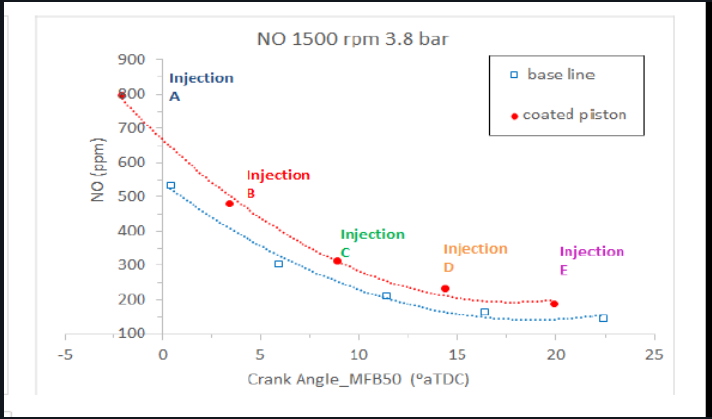
ATLAS – Engine out NO

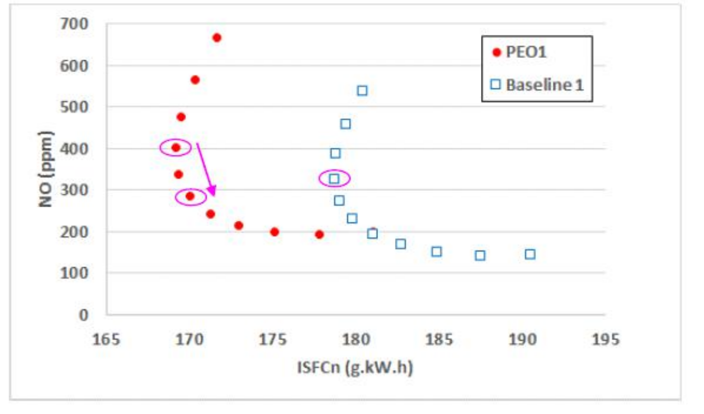


- Slightly higher NOx for PEO (~+13%)
- Anodised comparable to baseline

ATLAS – Fuel consumption gain beats NOx trade-off







- 100% ISFC for 23% increase in NOx

OR

- >90% of ISFC benefit for matched NOx

In summary, ATLAS results suggest that a significant efficiency benefit is possible using TS coatings

- Thermal swing coatings on pistons are believed to improve the efficiency of engines. A good thermal swing coating combines low thermal conductivity and low volumetric heat capacity
- Plasma electrolytic oxidation (PEO) converts the surface of engineering metals to a thick oxide layer which has high porosity, thermal resistance, adhesion and durability
- This combination is highly attractive from the perspective of developing TS coatings, and thermal measurements do indeed show that the best PEO coatings display very low conductivities and heat capacities
- Results from ATLAS suggest a potential fuel reduction potential of 3-5% under part load conditions (no EGR). For comparable emissions, fuel reduction potential is 2-3%
- These are only early results and only a limited range of conditions has been tested to date. Similar performance improvements may not be seen under all conditions and in all engines therefore. Furthermore the results need to be fully validated by repeat testing
- **Nevertheless, the data gives confidence that the good thermal properties of the coatings do translate into improved engine thermodynamics**