2017 STLE Annual Meeting & Exhibition
May 21-25, 2017
Hyatt Regency Hotel
Atlanta, Georgia, USA

An Experimental Study of the Effects of Lubricants on Piston Ring Friction

Category

Authors and Institutions

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Introduction

The purpose of this paper is to investigate the effect that lubricant viscosity and additives can have on this system. The Floating Liner Engine (FLE) is used in both the motored and fired configuration to isolate results from components and provide data for comparative analysis. The FLE is a specialized internal combustion engine in which the cylinder sleeve is essentially "free floating", and connected to the cylinder via two load sensors. This setup allows accurate measurement of friction contributions from the piston assembly while the engine is in operation. This particular FLE was provided by Professor Masaki Takiguchi at Tokyo City University (formerly Musashi Institute of Technology) in 2009 [1].

Effects of Lubricants under Fired Conditions

Effects of Oil Viscosity on Friction

Two different oils were used in order to test the effects of changing oil viscosity on liner friction. One had a High Temperature High Shear (HTHS) rate of 1.4 mPa-s, while the other was 2.9 mPa-s. The HTHS 2.9 is a common production oil under the label of 0W-30. In addition, viscosity for individual oils can be further modified by changing the temperature of the oil: increasing temperature decreases viscosity and vice-versa. Tests were conducted by varying both oil type and temperature and holding all other factors constant. This allowed the isolation of viscosity effects. Results from these tests show that in general, the lower the viscosity of the oil, the lower the friction was in the hydrodynamic regime, due to the reduction in shear stress. However, this gain for lower viscosity came at the cost of allowing boundary friction to occur at higher speeds, at which point FMEP was increased.

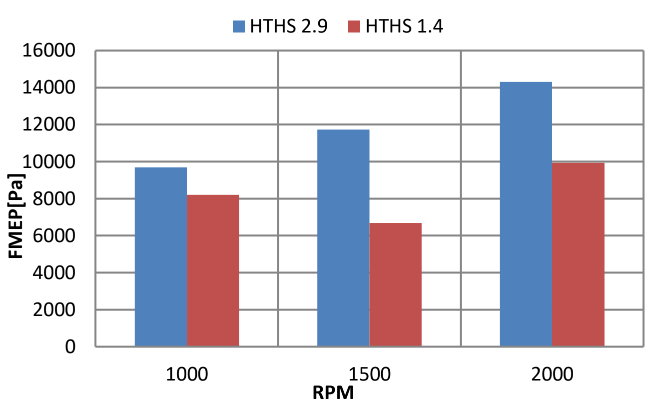

Figure 1: Comparison of FMEP at 2 bar IMEP due to Changing Viscosity with GG22 and 0.23mm 10.5N TLOCR

Figure 2 shows how overall FMEP decreases with increasing temperature. As expected, the change in friction due to changing oil temperature is directly related to the oil viscosity change with temperature. Since viscosity decreases with increasing temperature, the change in FMEP is attributed to the change in viscosity. It is important to note, however, that decreasing viscosity also increases the amount of boundary contact friction on the liner, which can have negative effects such as increased wear which lead to higher maintenance costs in automotive applications.

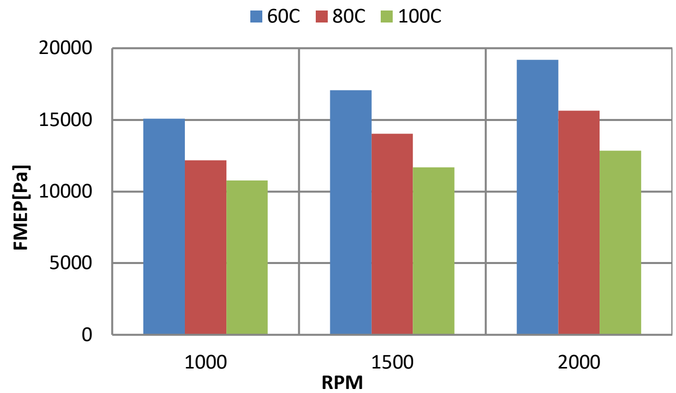

Figure 2: FMEP Effect from Varying Oil Temperature under Fired Conditions with HTHS 2.9 Oil and 0.15mm 19.5N TLOCR at 2 bar IMEP

Effects of Lubricant Additives

Tribofilms are films that form under certain temperatures and pressures from additives in the engine oil. These films form a hard, protective layer to prevent wear. For this study, specifically the zinc dialkyl dithiophosphate (ZDDP) film formed from the presence of zinc and phosphorous was targeted. ZDDP films form under the presence of direct, rubbing, solid contact of solid surfaces and form a film approximately 150 nm thick. While these films are used to prevent wear for many contact surfaces in the engine (such as valve train and crankshaft), they have been shown to have a higher friction coefficient when compared to surfaces without the film [2]. Because of this tradeoff, it was previously theorized that the presence of ZDDP films on the liner surface will increase the friction of the piston assembly.

Test Procedures

The investigation into tribofilms on the liner surface requires unique testing procedure due to the fact that the film buildup is expected to occur in fired conditions. However, the friction differences from the film effects were expected to be very small. For this reason, all comparisons were done using tests in the motored configuration. This configuration lacks the instability of combustion, and therefore has much better repeatability. In order to test the possible effects of the ZDDP film, a washing procedure was used which was proven to remove the film in lab tests [2, 3]. This procedure consisted of soaking the liner and rings in a 0.05M solution of Ethylenediaminetetraacetic acid (EDTA) for five minutes, and then rinsing well with water. The final step was to rinse the parts with acetone and dry them with a clean paper towel. This procedure is referred to as the EDTA wash [4].

The first step of the test sequence was to wash the liner and the rings with the EDTA wash to remove any existing tribofilms. After this, a motored test was conducted to serve as a baseline point for friction comparisons. This test is referred to as the washed test. The next step was to fire the engine for a series of three fired tests, which effectively exposed the liner to the combustion environment for approximately nine hours. After this, a second motored test was conducted (referred to as the post fired test) in order to compare with the initial baseline, and see if any effects could be seen from the formation of tribofilms. The final step was to wash the liner and rings again, and conduct a third motored test, labeled the post fired washed test. The purpose of this test was to serve as a comparison to the initial baseline, to see if any results from the post fired test were permanent or removable by washing. All data presented is from the motored tests in the sequence.

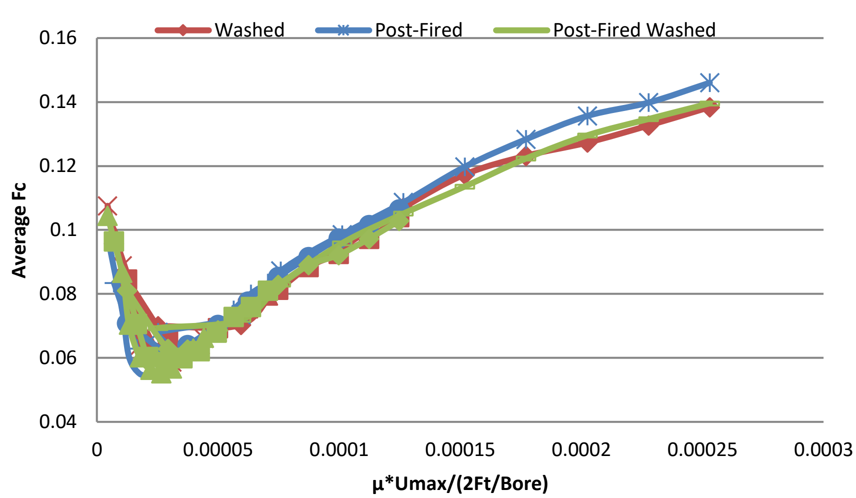

Figure 3: Stribeck Curve Showing Friction Coefficient for HA Oil with Tri-Solvent Wash on GG07 with 0.15mm 19.5N TLOCR

Conclusion

The investigation into lubrication effects on friction yielded some surprising results that definitely warrant future exploration.

1. Decreasing oil viscosity can decrease friction in the hydrodynamic regime, but is also causes boundary contact to occur at higher speeds. This contact can increase overall friction compared to higher viscosity oil at low engine speeds.
2. In regards to the ZDDP anti-wear films stemming from additives in the oil, the expected result of increasing friction in the piston assembly was not observed. In fact, the under the conditions and procedures tested in this study the ZDDP film was found to have a minimal effect.
3. A new effect, dubbed the “firing effect”, was observed. This phenomenon occurs when the liner surface is exposed to the fired conditions in the combustion environment. The result as a change in the performance of the liner surface, which makes it act like a “smoother” surface than before. The effect is non-permanent as washing the liner returned friction levels to pre-fired conditions. The implication is that during engine operation, the liner roughness geometry may experience changes additional to wear and tribo-film buildup. This additional geometrical change can impact the lubrication of the piston-rings and the liner, and thus friction in a non-trivial manner, namely, filling of the valleys. Thus, realistically predicting effect of liner finish on ring friction and oil consumption may need to consider this effect.

The revelation of the firing effect identifies the need for much more investigation in the future. To start with, repeating the investigation with a smooth liner to see if the same pattern exists may be helpful. In addition, timeline constraints prevented a full analysis of the FLE liners to verify the chemical composition of the residues on the liners. In the future a full physical and chemical analysis would be beneficial. Furthermore, future collaboration with manufacturers on this topic may lead to alternative lubricant formulations with which to isolate specific factors in the results.

Acknowledgements

This work has been sponsored by the MIT consortium on Lubrication in Internal Combustion Engines. The authors would like to thank all current members: Argonne National Laboratory, Daimler AG, Mahle GmbH, MTU Friedrichshafen GmbH, PSA Peugeot Citroën, Renault S.A., Royal Dutch Shell, Toyota, Volkswagen AG, Volvo Cars and Volvo Trucks. The authors would like to thank Mahle, Shell, and Daimler for providing all the necessary testing parts and lubricants.

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Nomenclature

CA	crank angle
CAD	crank angle degree
RPM	revolutions per minute
TDC	top dead center
BDC	bottom dead center
FMEP	friction mean effective pressure
IMEP	indicated mean effective pressure
FLE	floating liner engine
TLOCR	twin land oil control ring
TPOCR	three piece oil control ring
OD	outer diameter
HTHS	high temperature high shear

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Abstract

The Floating Liner Engine is a specialized internal combustion engine that allows detailed measurement of friction from components in the piston power system. The unique testing capabilities of this engine were used to explore the effects lubricants can play in the friction of the piston assembly. This study started by detailing the outcome on friction of changing lubricant viscosity through both temperature and formulation. Next, lubricants with and without anti-wear additives were tested. Formation of a tribo-layer and its effect on boundary lubrication could not be implicated from the friction measurement results. However, testing efforts led to new observations about the changing nature of the liner surface during firing conditions, and it is not clear if/what material is filling the valleys of the liner surface and influencing friction.

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Contents

- Motivation
- Test Methods
  - Motored and fired
- Lubrication Theory in the Piston Assembly
- Effects of Lubricants under Fired Conditions
  - Viscosity
  - Lubricant additives
- Liner examination results
- Summary/Conclusions

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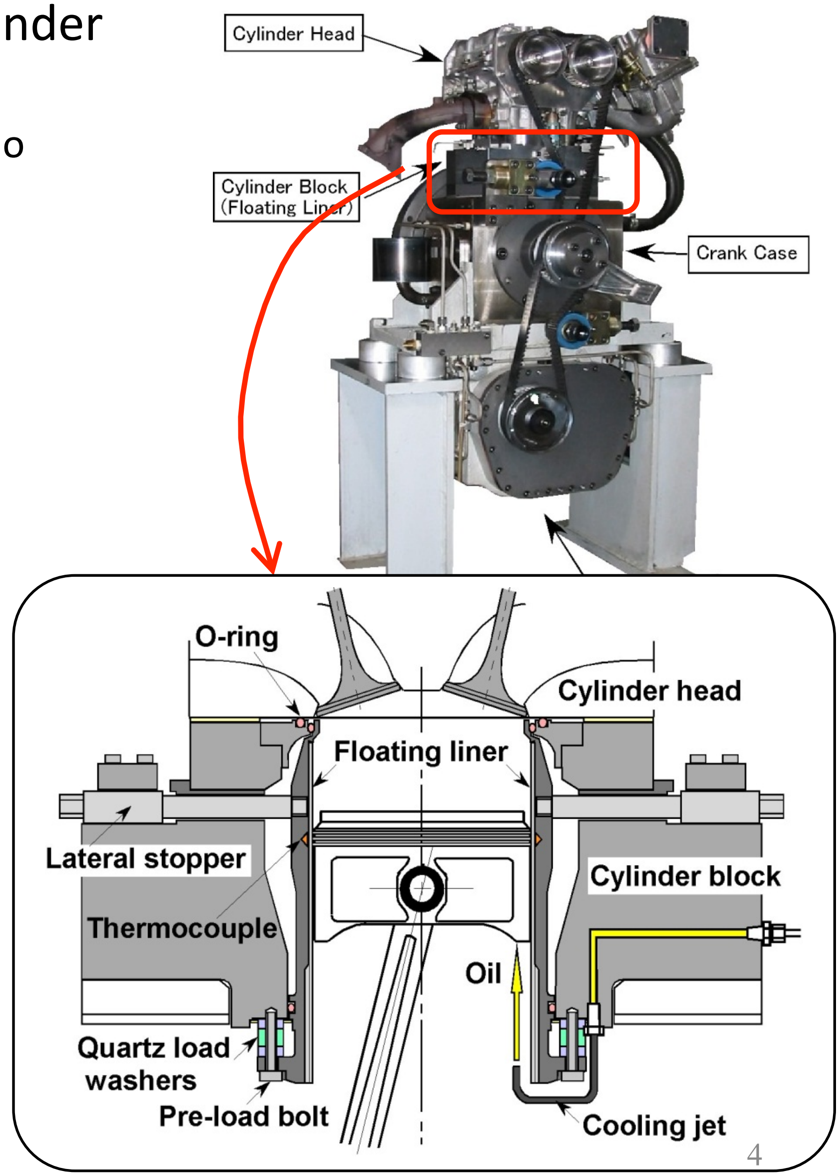
Overview of Floating Liner Engine

Allows for measuring of piston friction force under fired and motored conditions

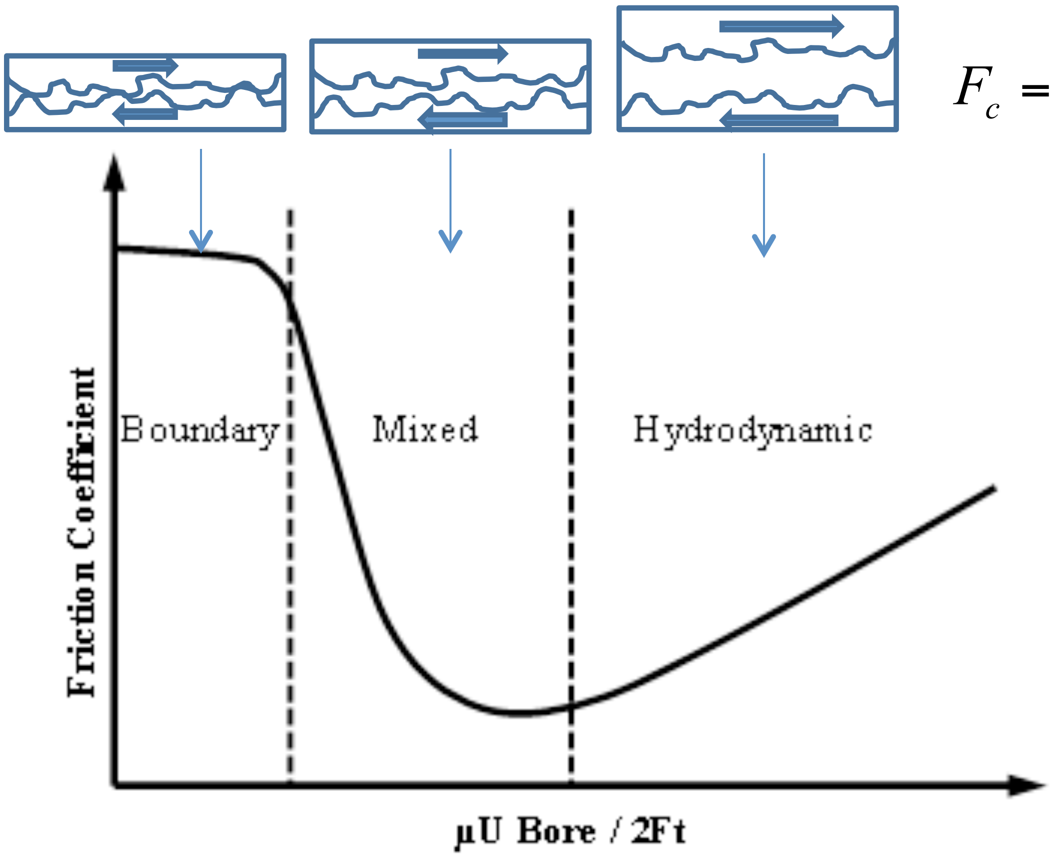
- Motored – Crank case open, head removed, dyno drives motor
- Fired – Normal fired conditions, 2bar and 4 bar cylinder pressure

Specification of engine

Engine Type	Single-Cylinder Four-Stroke Gasoline Engine
Displacement [L]	0.496
Bore × Stroke [mm]	82.5× 92.8
Compression Ratio	10
Maximum BMEP [MPa]	0.7
Maximum Engine Speed [rpm]	3000
Balance Shaft	Primary and Secondary
Piston Cooling	Oil Jet
Cyl.Temp [deg C]	30-120
Oil Temp [deg C]	30-100



Lubrication Theory



$$F_c = \frac{W_{f\,rictioncycle}}{(2\pi F_t)(4\times stroke)} = \frac{FMEP}{32F_t / B^2}$$

µ: oil dynamic viscosity

U: piston linear speed

Bore: diameter of cylinder

Ft: piston ring tension

Ring Lubrication

- Same liner/ring, higher oil viscosity, higher piston velocity, lower ring tension will move the ring towards hydrodynamic lubrication

Liner Roughness Effects

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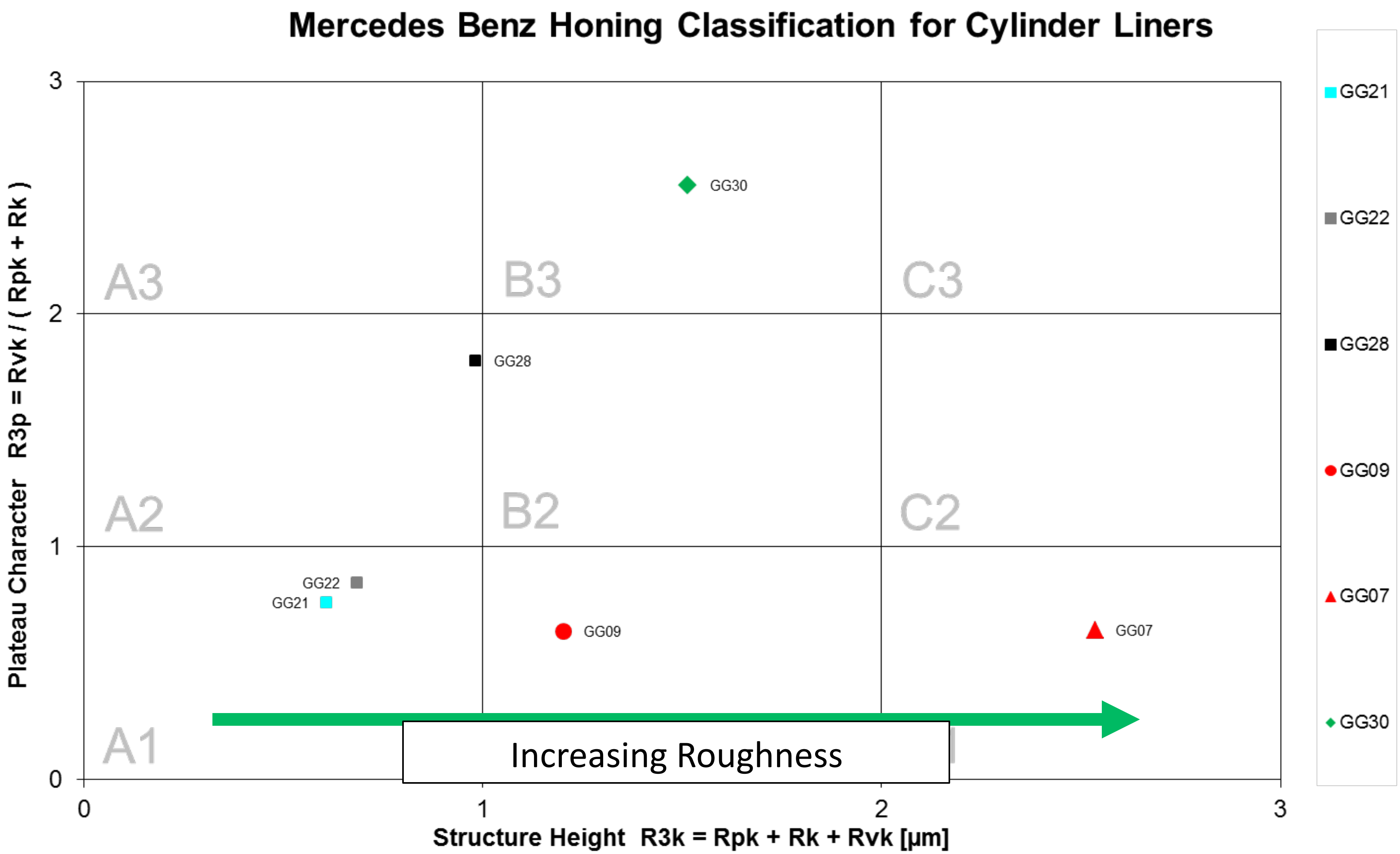
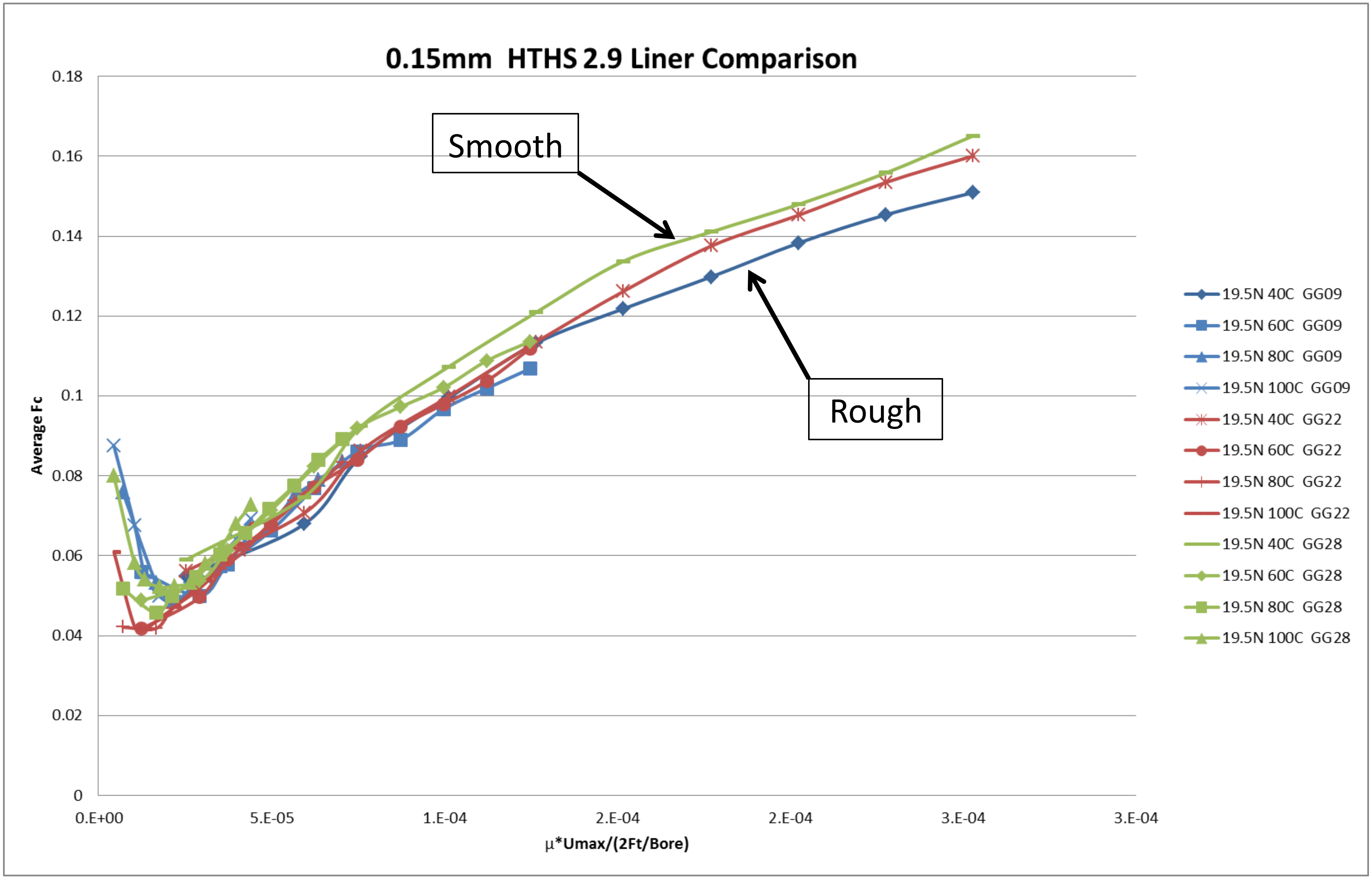
Defining Liner Roughness



GG09, GG22, & GG28 Liner Average Fc Comparison



GG09, GG22, & GG28 Liner Average Fc Comparison

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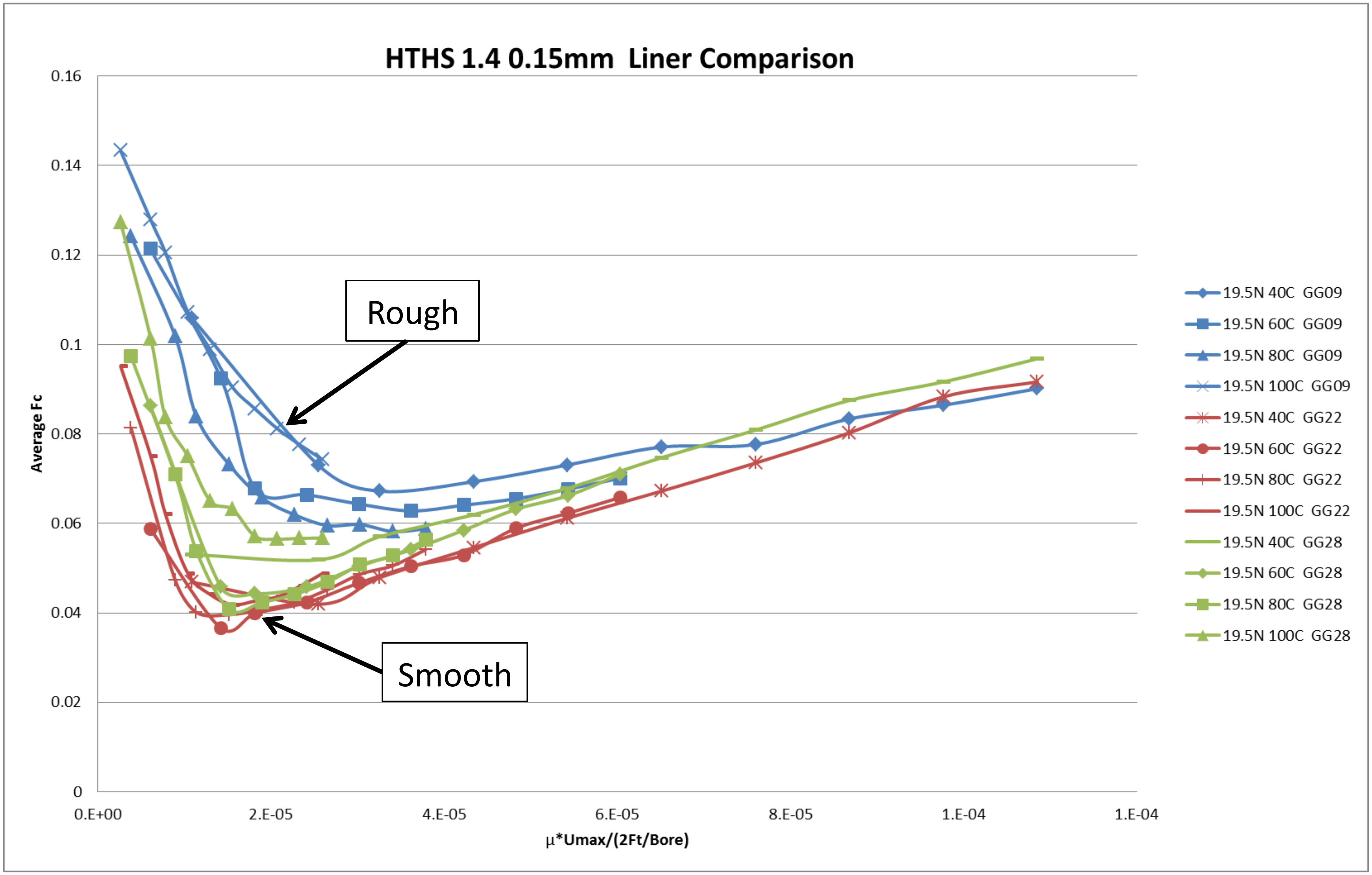

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Comparison of FMEP between liner finishes

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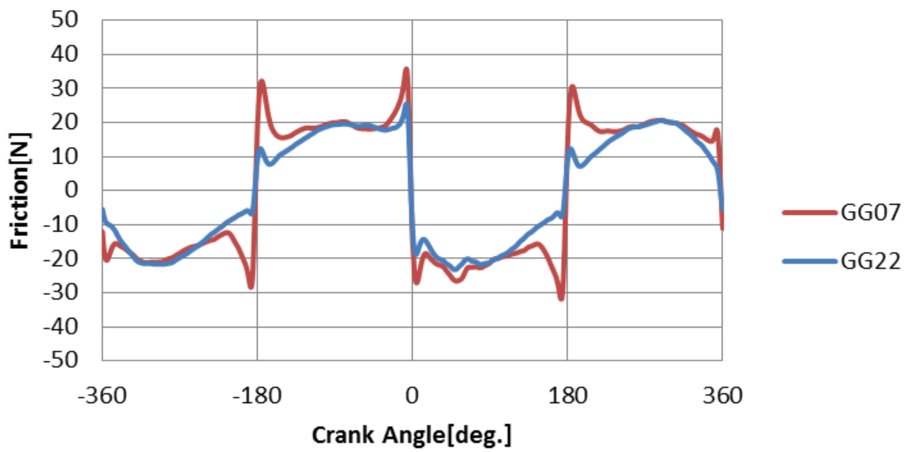
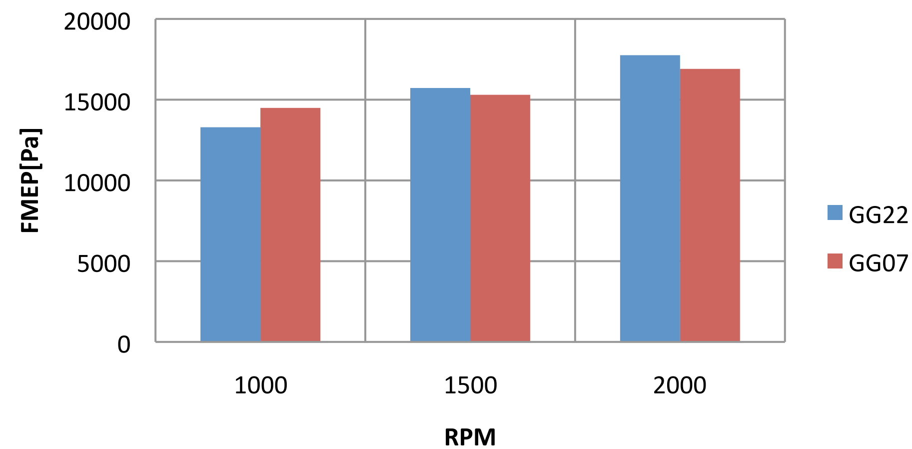
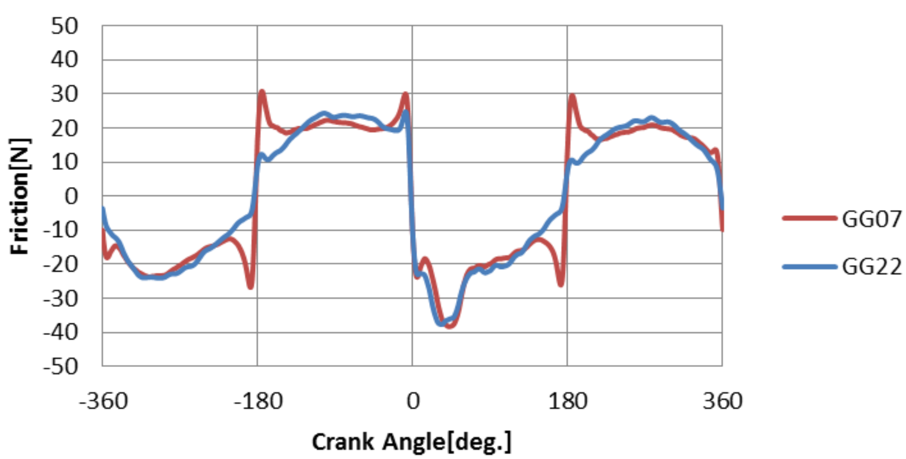


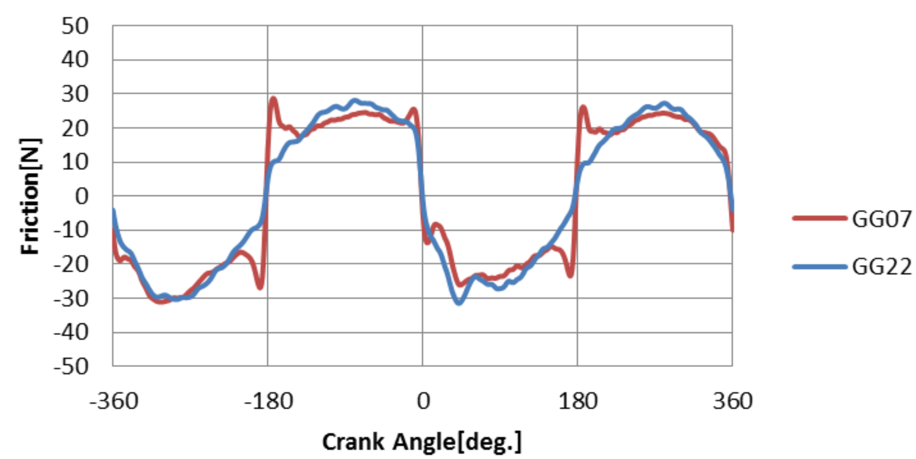
OCR 0.15mm 28.5N-2bar



OCR 0.15mm 28.5N 1500RPM-2bar



OCR 0.15mm 28.5N 2000RPM-2bar



- Increasing ring tension – similar results

Firing Effect

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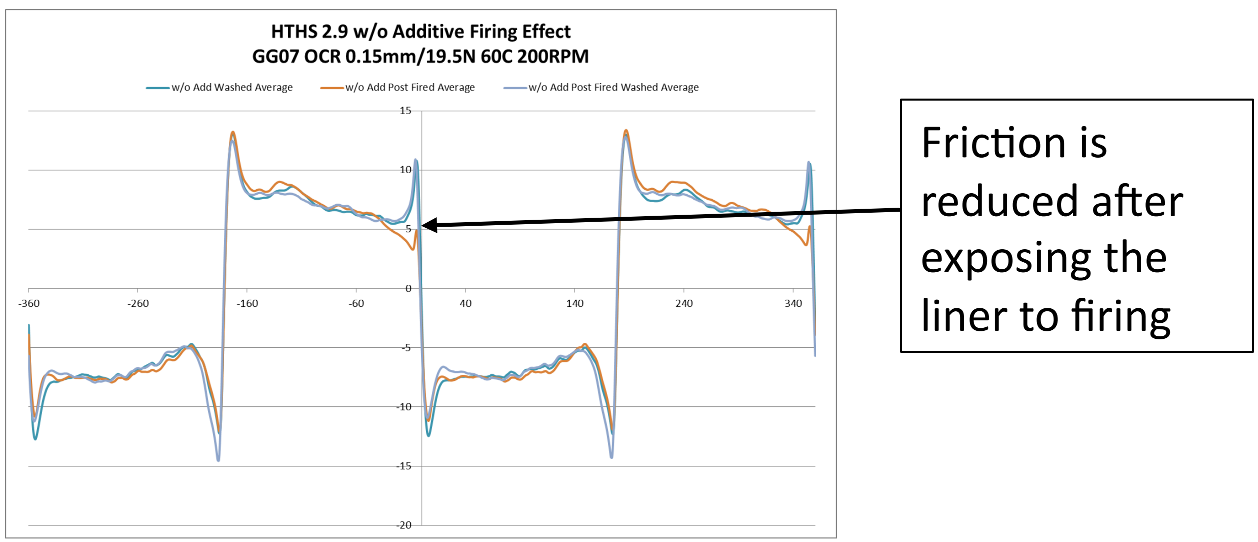
Firing Effect – What is it?

- Discovered while using motored tests to investigate possible effects of tribofilm on piston/liner interface
- Unique pattern of friction being reduced in mixed regions and increased in hydrodynamic regions after exposing the liner to fired conditions – similar effect to liner "smoothing"



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Tribofilm Introduction

- What is it?
  - ZDDP Anti-wear film
    - Additives – Zn and P
  - Forms a thin film (approx. 150 nm) when metal-on-metal contact (boundary) occurs.
  - Used to prevent wear on many components in the engine (ie. Valve train, crankshaft, etc.)
- How it forms
  - ZDDP reaction films are only generated when direct, rubbing, solid contact occurs (*Topolovec-Miklozic et al.*)
  - Formation time – mean film thickness stabilizes at around 30 min of contact
- Why it matters:
  - ZDDP films have a higher friction coefficient
- Oils
  - XSA7424HA (HTHS 2.9)
  - XSA7424HK (HTHS 2.9 w/o Additive)
    - (from Shell) Formulation is identical in all respects except without the anti-wear additive. A small amount of base fluid was used to replace the anti-wear additive.
    - Ca concentration in XSA7424HK is therefore identical with XSA7424HA, but there is no Zn or P.
  - XSA7424HL (HTHS 2.9 w/ alternative viscosity modifiers)

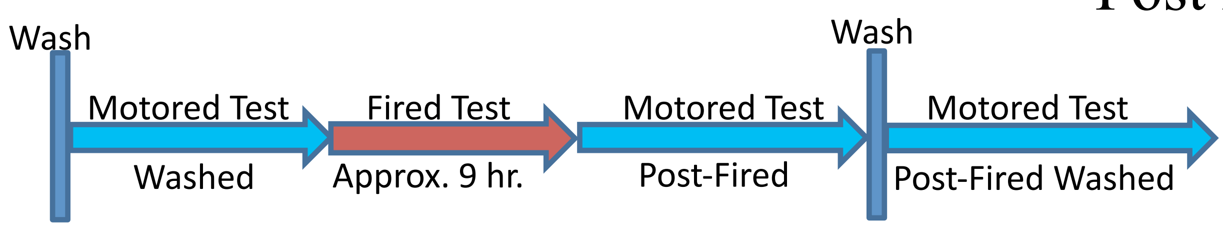
Test Procedure

Set Up

- Sequential Tests – eliminates wear effect
- Average of 5 data sets (“runs”) collected
  - Each data set = average of 30 cycles for motored, 90 cycles for fired

Test Sequence:

	Test Label
1. Liner wash	
2. Motored test →	Washed
3. 3 Fired tests (Approx. 9 hrs)	
4. Motored test →	Post Fired
5. Liner wash	
6. Motored test →	Post Fired Washed



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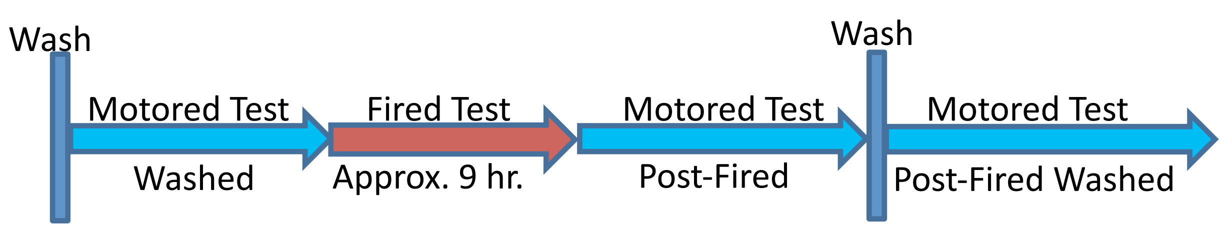
Test Procedure

Test Sequence:	Test Label
1. Liner wash	
2. Motored test →	Washed
3. 3 Fired tests (Approx. 9 hrs)	
4. Motored test →	Post Fired
5. Liner wash	
6. Motored test →	Post Fired Washed



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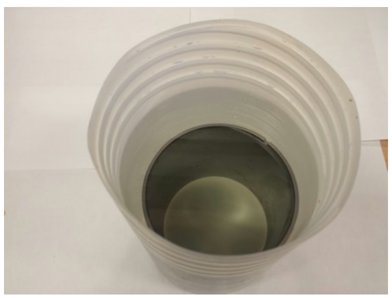
Removing the Film (washing)

- Process to remove ZDDP film recommended by Shell



Soak the liner in a 0.05M aqueous EDTA solution for ~5 minutes

Rinse well with water

Rinse with acetone

Dry liner well

- More from shell later

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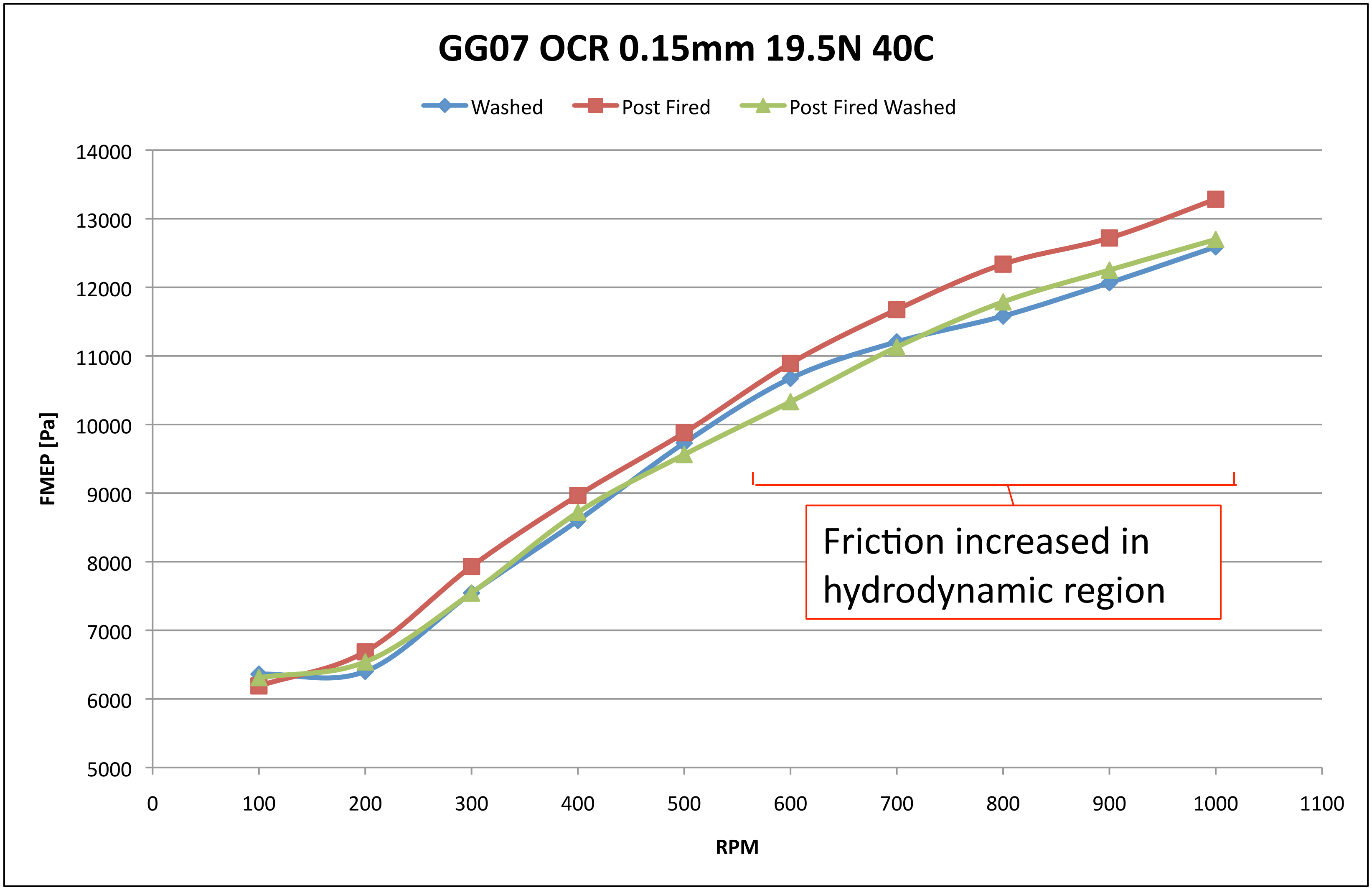
Tri-Solvent Wash Procedure

- Does not remove tribofilm, only other “filler” materials
- Soak the liner in a solution of 33/33/33 equal volume blend of toluene, heptane and acetone for ~5 minutes
- Dab dry with clean paper towel

Firing Effect – HTHS 2.9HK

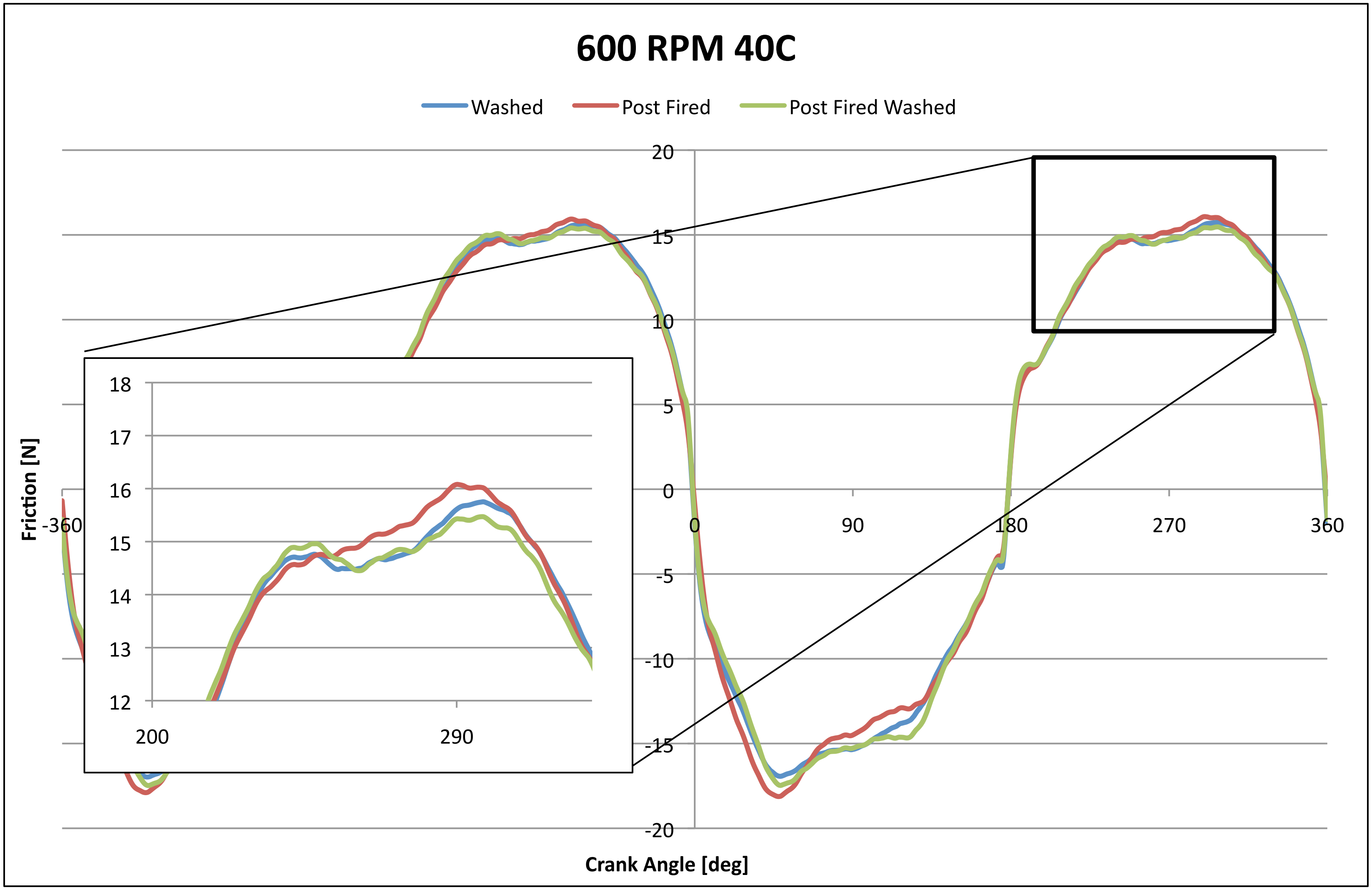
- Fully formulated minus anti-wear additives

FMEP 40C



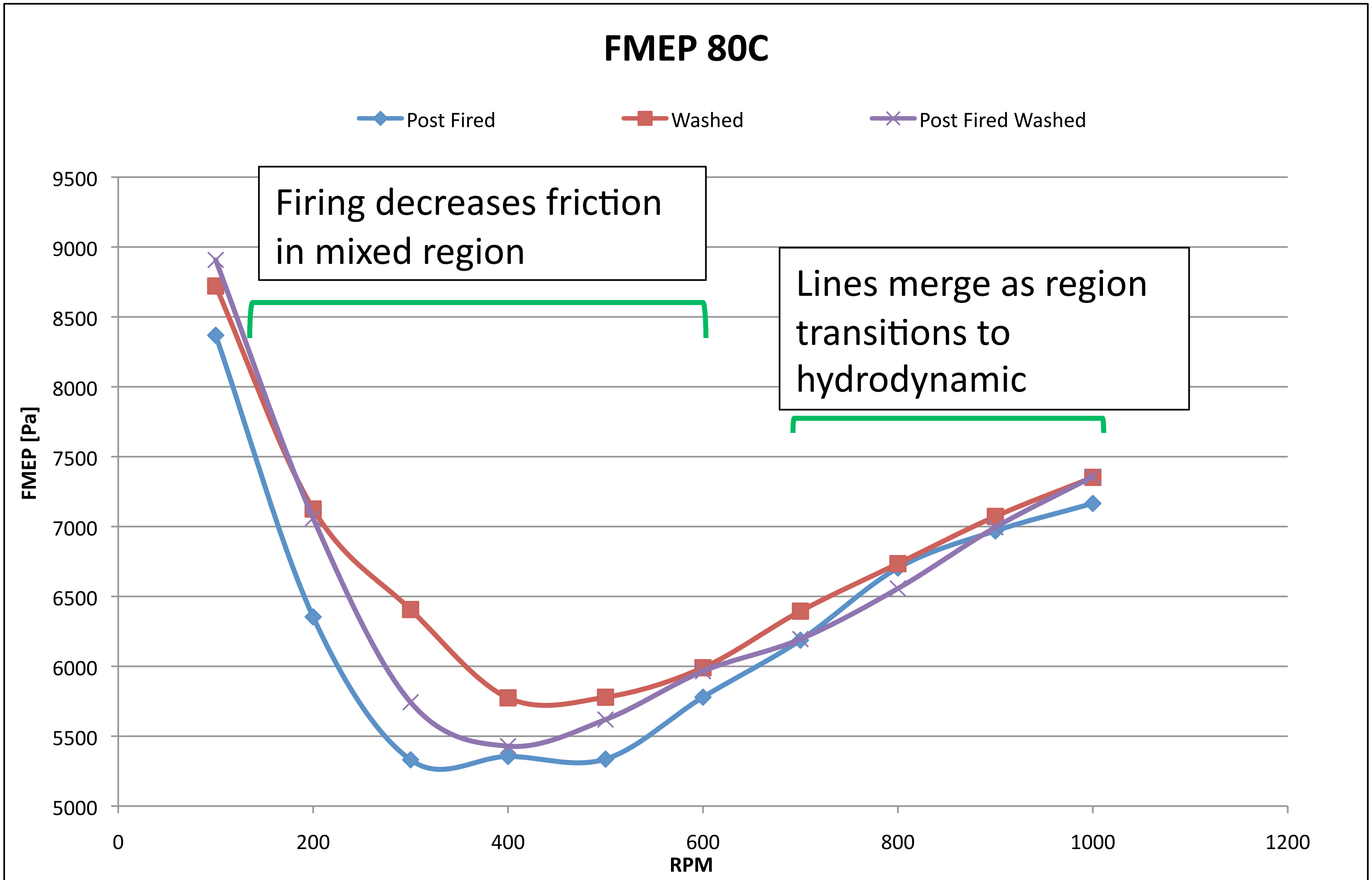
- 40C shows increase in friction in hydrodynamic region
- Post fired friction is higher, just like smoother liner

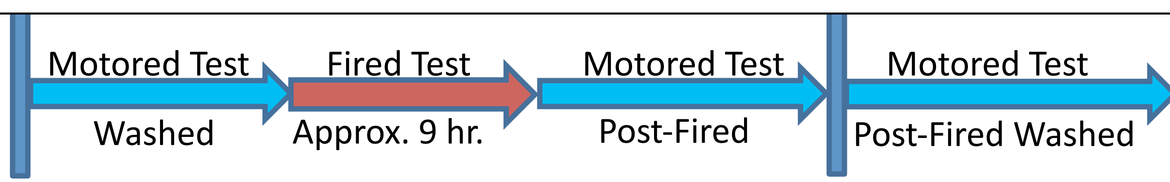
Instantaneous Friction - Hydrodynamic



- Firing increases friction in hydrodynamic regions

Firing Effect FMEP 80C





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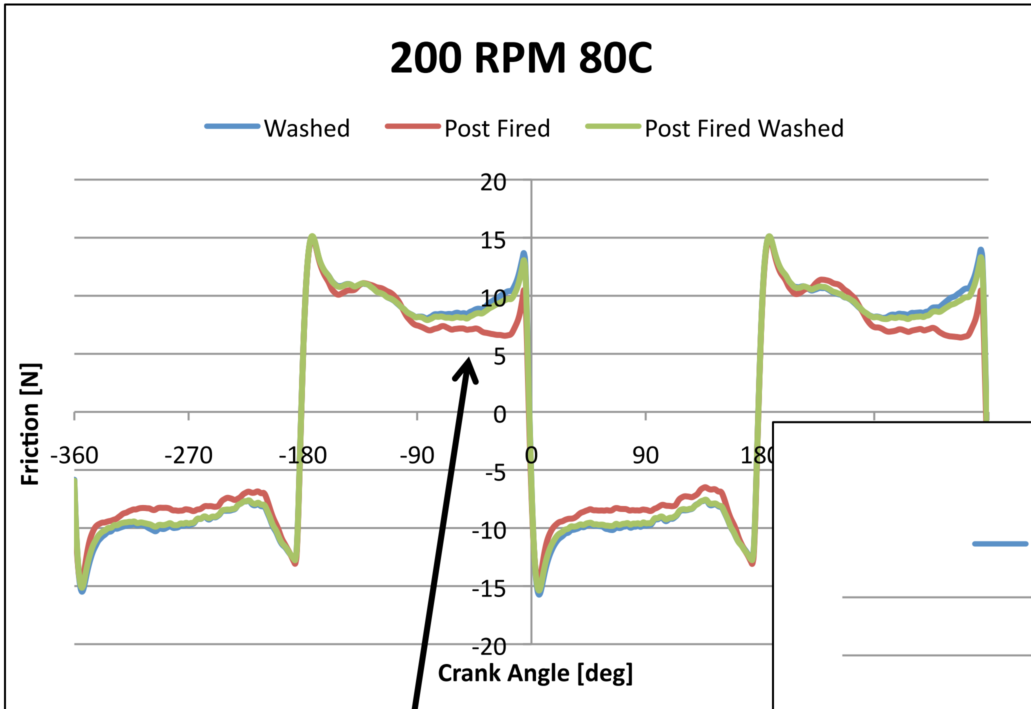
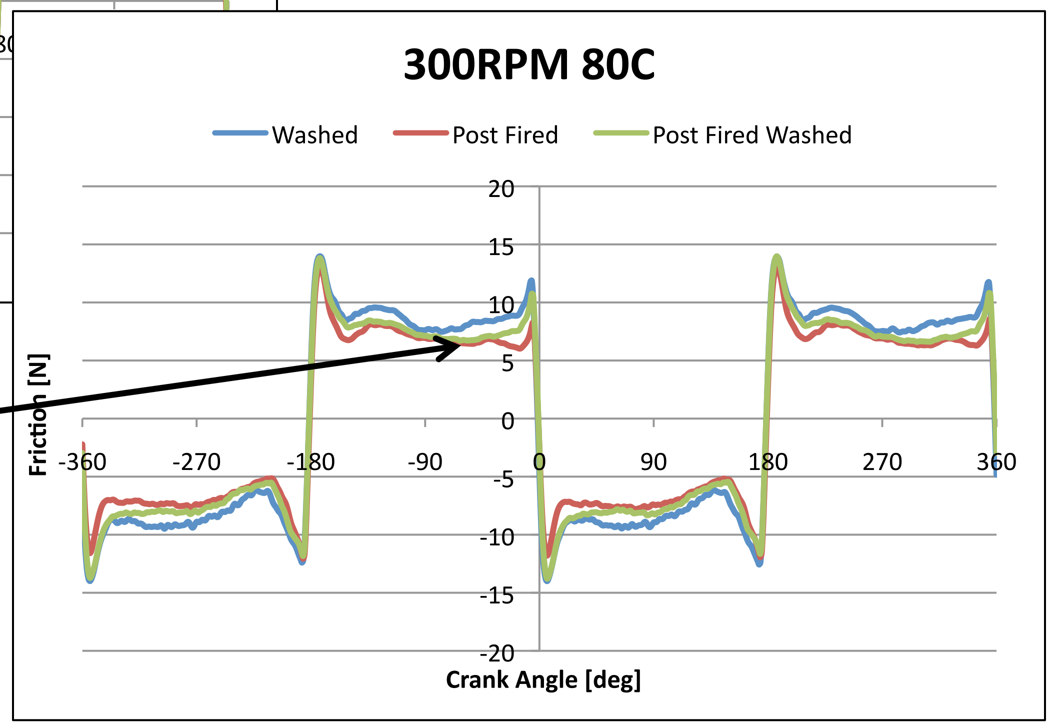
Firing Effect 80C





TDC and BDC areas show why friction is lower in the mixed region

Washing increases boundary friction

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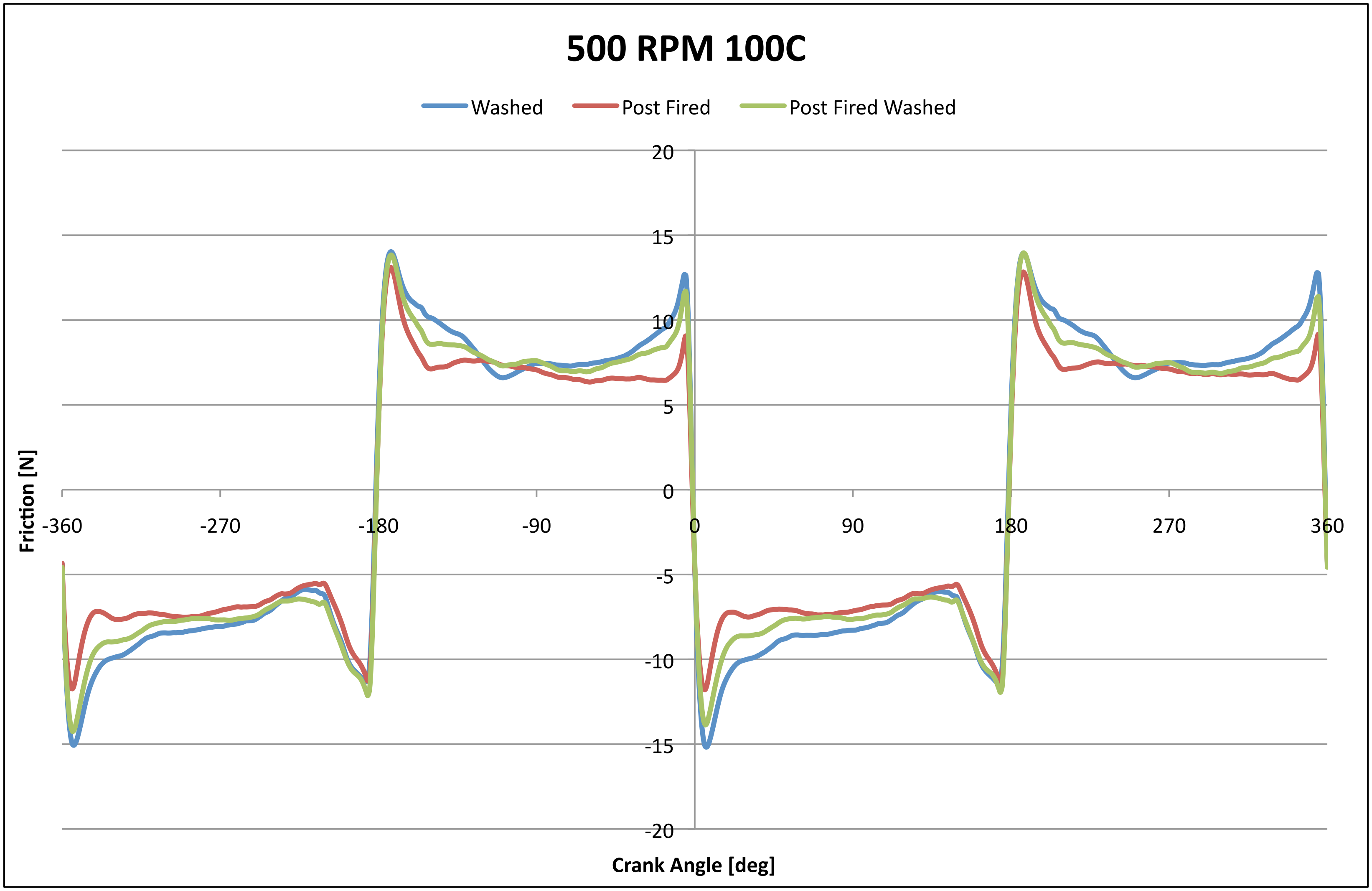
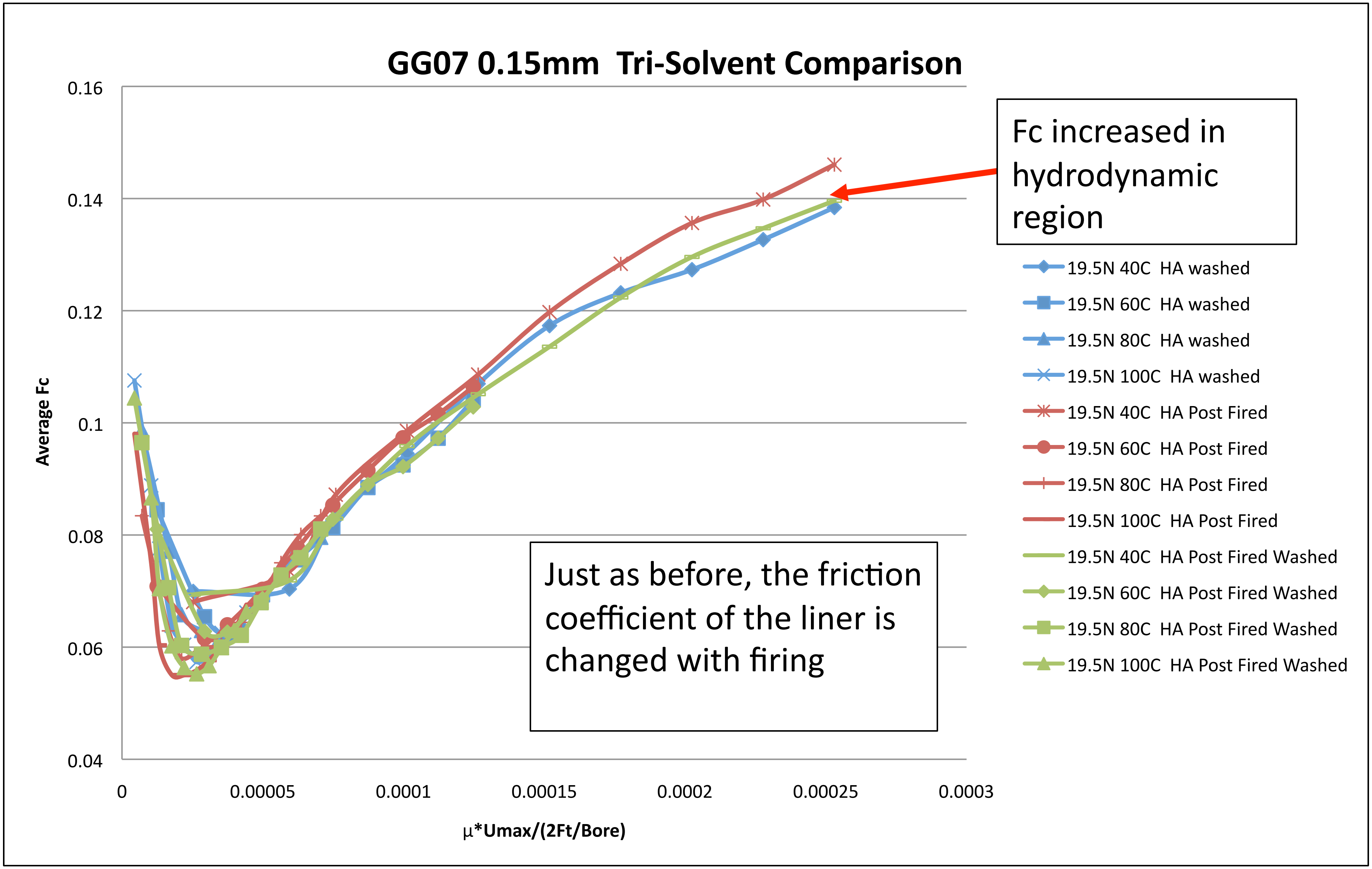
Firing Effect – HTHS 2.9HK

Same effect is seen with HK oil – this oil does not contain the anti-wear additives Zn and P



Fc Comparison – HK Oil



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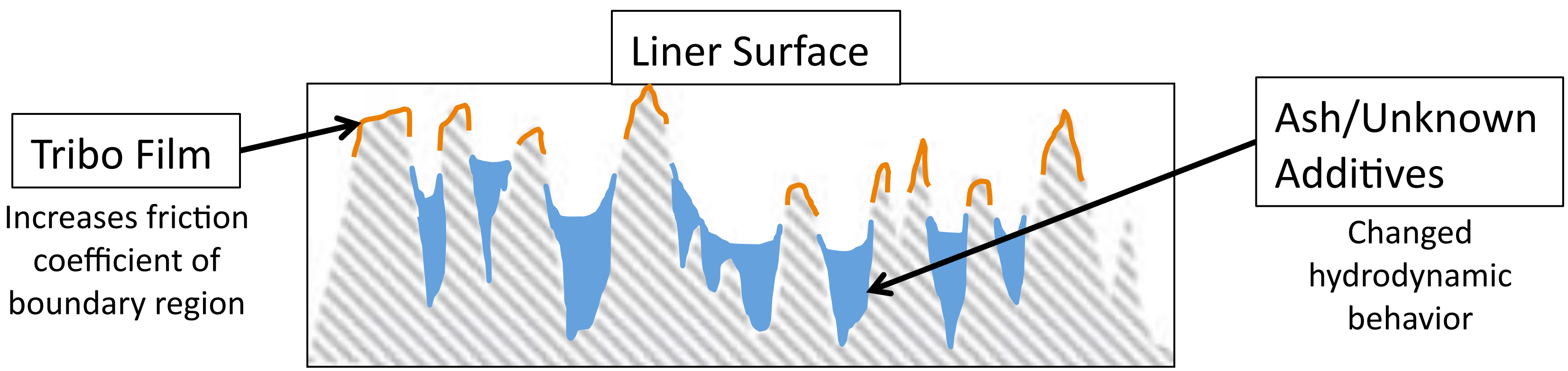
Firing Effect Key Findings

- Three Oils tested
  - HA – Fully Formulated
  - HK – Fully Formulated minus anti-wear additives (Zn and P)
- All oils tested, HA and HK, show the same pattern when subjected to the firing test sequence
- No evidence had shown that the tribofilm is the dominant effect on liner friction
  - Verified by alternate wash
- Other effects, such as "filing effect", are taking place, making the liner act like a smoother liner
- Same pattern was observed regardless of oil/wash
  - **Conclusion:** the effect is not due to only the tribofilm, and exposing the liner to fired conditions has the effect of smoothing the surface, a process which can be reversed by washing off the effects of firing

Possible Explanations

- Ash/Unknown Additives Theory
  - One possible explanation for this phenomenon is ash or other byproducts from the combustion cycle accumulates at the top of the liner, filling in voids and “smoothing” the liner.
- Combination effect
  - The smoothing of the liner is contradicted by the increased Fc due to tribo layer effects
    - “smoothing” has a greater effect



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