Development of a test procedure, system and process for high throughput tribological testing of used oil samples as part of a condition monitoring protocol

George Plint
Phoenix Tribology Ltd

info@phoenix-tribology.com

Target Requirements

- Cost per data point for tribolgical test must be comparable with cost of analytical data point
- Must use minimal quantities of fluid samples
- Must be able to achieve throughput of 200 samples per day
- Must have potential for process automation

Test Specimens and Test Geometry

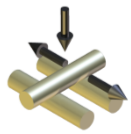
Sliding hertzian point contact ruled out:

- Provides poor models for real contacts
- Relatively insensitive to variations in additive performance.
- Measurement of ball wear scar fraught with difficulty and uncertainty
- High costs of plate specimens

Line contact (cylinder on flat) ruled out:

- Time required to generate measurable wear
- High costs of plate specimens

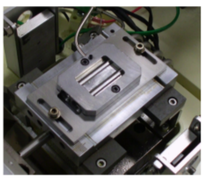
Test Specimens and Test Geometry

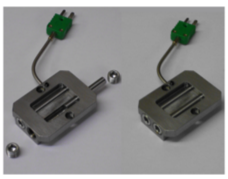


- low cost roller specimens
- self-locating
- can produce crisp wear scars
- generates two wear scars per test

The development of a "pin on twin" scuffing test to evaluate materials for heavy-duty diesel fuel injectors
J J Truhan, J Qu, P J Blau
Tribology Transactions Volume 50 Number 1 January - March 2007

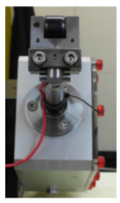
Fixed Specimen Tooling





- 6 mm diameter x 40 mm long rod samples
- 5 ml fluid sample sufficient to cover rods

Moving Specimen Tooling



- 6 mm diameter x 20 mm long pin
- self-clamping and self-aligning tool

Exploratory Tests

Three types of test pin/rod:

- Nitrided steel dowel pin (hard)
- 52100 bearing roller (hard)
- Silver steel rod (soft)

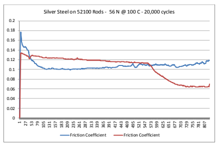
Typical Test Conditions:

- Contact Pressure: 2 GPa
- Stroke: 5 mm
- Frequency: 10 Hz
- Temperature: 100 C
- Duration: 10,000 or 20,000 cycles

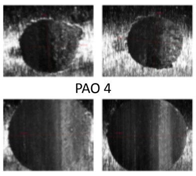
Test Sequence:

- Apply test load
- Heat sample (conditional step)
- Ramp speed to test frequency (in 1 minute)
- Run until required number of cycles completed
- Terminate test

Soft Pin on Hard Twin



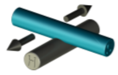
Blue – PAO 4 / Red – Mobil 1



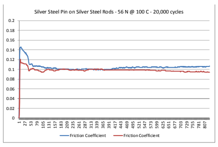
PAO 4

Mobil 1

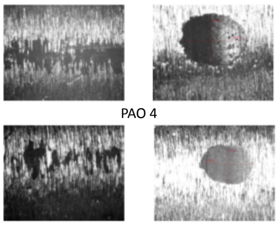
- Very different friction traces
- Pin specimen gives readily identifiable wear scars
- But, wear with fully formulated oil much higher than with base fluid!



Soft Pin on Soft Twin



Blue – PAO 4 / Red – Mobil 1

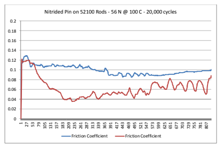


PAO 4

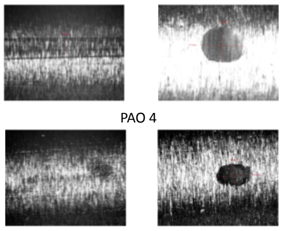
Mobil 1

- Base fluid produces more pin wear than fully formulated oil
- Twin wear unmeasurable
- Little difference in friction, except during initial running-in

Hard Pin on Hard Twin



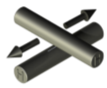
Blue – PAO 4 / Red – Mobil 1



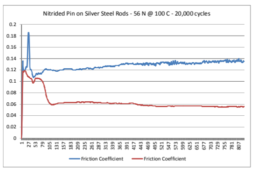
PAO 4

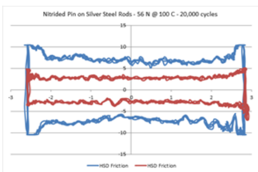
Mobil 1

- Base fluid produces more wear than fully formulated oil
- Significant difference in frictional response

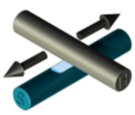


Hard Pin on Soft Twin

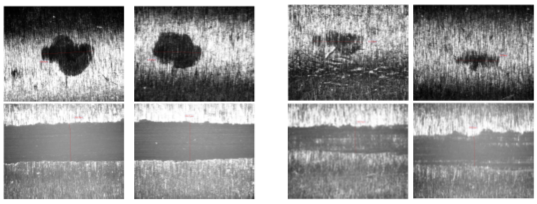




Blue – PAO 4 / Red – Mobil 1



Hard Pin on Soft Twin



PAO 4 — 499 microns, 505 microns

Mobil 1 — 348 microns, 391 microns

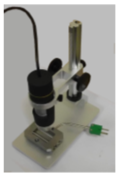
- Different frictional response with fully formulated oil producing much lower friction than base fluid
- Wear scars on softer twin samples readily identifiable
- Fully formulated oil produces much smaller wear scar than base fluid
- Wear scars on pin samples not readily measurable

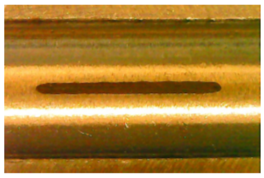
Summary – Exploratory Test Results

	Friction	Pin Wear	Twin Wear	Additive Response
Soft on Hard	Significant difference	Well Defined	Witness mark	Negative
Soft on Soft	No difference	Defined	Witness mark	Questionable
Hard on Hard	Significant difference	Defined	Witness mark	Positive
Hard on Soft	Significant difference	Witness mark	Well defined	Positive

- Relative hardness of specimens has significant influence on friction and wear response
- Hard on soft configuration:
  - preserves entrainment geometry as twin samples wear
  - produces twin wear scars with potential for automated measurement

Automated Measurement - ImageJ





- Wear scar over 5 mm long and finite width can be viewed with a simple macroscope
- USB devices readily available for as little as $40

Automated Measurement - ImageJ

Captured image

Process with ImageJ using following steps:

- Band pass filter to remove vertical lines
- Auto threshold
- Wear scar auto-selected
- Area calculated automatically

Friction and Wear Test
Proof of Concept – Oxidation Samples

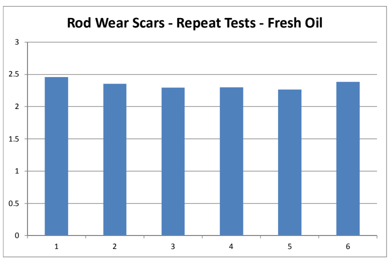
Hard pin on soft twin

- 52100 (hard) pin on (annealed) silver steel twin

Fully formulated lubricant:

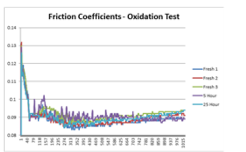
- fresh
- after 5 hours pre-oxidation
- after 25 hours pre-oxidation

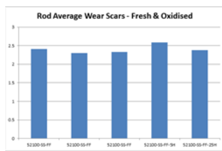
Proof of Concept – Oxidation Samples

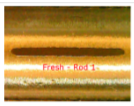


Average: 2.342   Standard Deviation: 0.0651   Coefficient of Variance: 0.0278

Proof of Concept – Oxidation Samples







- Friction traces for fresh oil and oxidised samples showed little difference, although 5 hour oxidation sample produced a less smooth trace
- Wear scars showed higher wear for 5 hour oxidation sample compared with others
- Lower wear and smoother friction produced by 25 hour oxidation sample as result of polymerisation of oil (?)

Friction and Wear Test Conditioning Monitoring Samples

Samples and condition monitoring data provided by Oelcheck GmbH

Assumption:

- that only substantial changes in a condition monitored parameter could (potentially) give rise to, or be associated with, changes in wear, friction and contact resistance

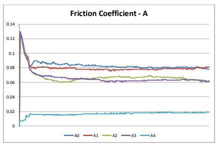
Method:

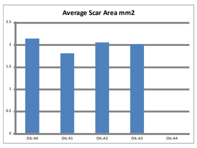
- calculate standard deviation for each measured parameter and select those with largest variance to compare with tribological test data

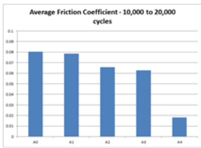
Conditioning Monitoring – Sample A

	A0	A1	A2	A3	A4		SD
LAB. Nr	3683505	3645184	3627862	50056012	50056013		
Operating hrs	fresh oil	22732	31167	> 50.000	> 50.000		
Wear							
Iron Fe mg/kg	0	2	29	26	3		12.73
Copper Cu mg/kg	0	0	1	3	96		38.02
Contamination							
Silicium Si mg/kg	34	16	0	1	0		13.36
Water K. F. ppm	80	75	69	76	82		4.50
Oil Condition							
Viscosity 40°C mm²/s	345.49	325.04	324.25	325.89	321.93		8.59
Viscosity 100°C mm²/s	40.03	36.76	36.36	35.13	35.46		1.74
Viscosity-Index	168	161	160	153	156		5.08
Oxidation A/cm	-	-	99.84	99.73	99.74		0.05
Additives							
Zinc Zn mg/kg	6	10	5	17	16		4.96
Phosphorous P mg/kg	489	437	298	244	243		101.96
Sulfur S mg/kg	4156	3550	3404	5311	3323		741.08
Machine tests							
Average friction coefficient	0.08	0.078	0.065	0.062	0.018		0.02
Average scar area mm²	2.1	1.75	2.05	2	0		0.13
Average contact potential	32	35	29	47	49		8.09

Conditioning Monitoring - Sample A

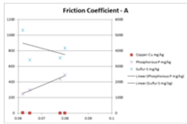


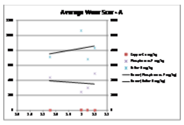




Sample A4 is significant outlier: high copper content - high contact resistance - very low friction - no measurable wear

Conditioning Monitoring - Sample A





Very tentative conclusions:

The higher the sulphur content and the lower the phosphorous content:

- the lower the friction coefficient
- the higher the wear
- and the higher the contact resistance

Suggesting that:

- surfaces are getting smoother as wear takes place
- sulphur provides low frictional response at expense of blocking anti-wear properties of phosphorus

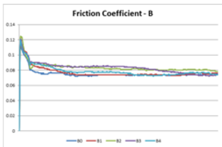
Presence of copper in Sample A4 may provide reason for low friction and wear and high contact potential, but:

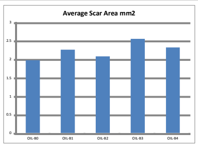
- has copper has been intentionally added to lubricant?
- Or, has been generated by some unwanted wear process elsewhere in system?

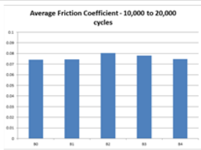
Conditioning Monitoring – Sample B

	B0	B1	B2	B3	B4		SD
LAB. Nr	3156050 3776576	3789114	3635321	3730999			
Operating hrs	fresh oil	1016	unknown	60672	98816		40247.35
Wear							
Iron Fe mg/kg	0	2	35	120	48		43.65
Copper Cu mg/kg	0	0	0	0	5		2.00
Contamination							
Silicium Si mg/kg	4	0	1	6	2		2.15
Water K. F. ppm	55	150	97	77	91		31.51
Oil Condition							
Viscosity 40°C mm²/s	315	314.1	319.39	321.62	310.26		4.02
Viscosity 100°C mm²/s	23.77	23.68	24	24.14	23.6		0.20
Viscosity-Index	95	95	95	96	96		0.49
Oxidation A/cm	-	99.95	99.83	99.47	99.76		0.18
Additives							
Zinc Zn mg/kg	7	22	142	28	87		50.38
Phosphorous P mg/kg	201	221	215	210	127		34.53
Sulfur S mg/kg	10.007	11.6	11.861	11.046	14.84		1.62
Machine tests							
Average friction coefficient	0.074	0.075	0.08	0.078	0.075		0.00
Average scar area mm²	1.95	2.3	2.1	2.6	2.3		0.22
Average contact potential	5	15.1	32	5	5.1		10.53

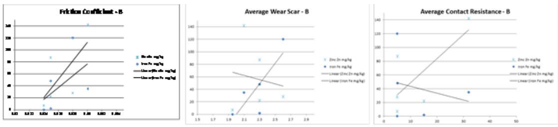
Conditioning Monitoring – Sample B





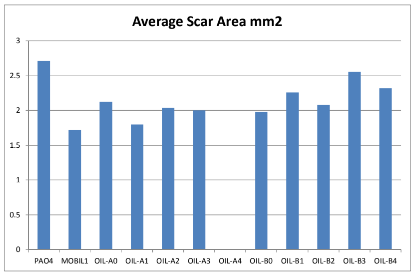


Conditioning Monitoring – Sample B



- **Very** tentative conclusions:
  - the higher the zinc and iron content, the higher the friction coefficient
  - the higher the zinc content, the higher the contact resistance and the lower the wear
  - the higher the iron content, the lower the contact resistance and the higher the wear
- Presumably:
  - zinc is meant to be in lubricant as an anti-wear additive
  - iron is not meant to be in lubricant, but has been generated by some unwanted wear process elsewhere in the system

Summary – Friction and Wear Tests



Samples A: PAO synthetic oil based Mobilgear SHC XMP 320
Samples B: Mineral oil based Mobilgear XMP 320

How do we make any sense of this?

There are two potential types of connection: "causal" and "indicative":

- An example of an "indicative" connection would be the case of the high iron content generated in the application, correlating with the high wear in the bench test; something unidentified results in both, but the high iron content in itself does not result in high wear in the bench test; something else causes both. In other words, we are using the term as an alternative to non-causal correlation.
- An example of a "causal" connection would be the reduction in friction associated with an increase in sulphur content in the lubricant sample.

The results for Sample A4 are instructive and demonstrate that we cannot simply rely on a decrease in wear and/or friction as an indication that the sample is satisfactory. The copper has an apparently very beneficial effect on friction and wear, but where did the copper come from? Does its presence indicate something bad going on elsewhere? We get exactly the same sort of response with heavily soot ladened oils from diesel engines; low friction and wear but, in this case, an increased risk of seizure, caused by oil starvation.

Friction and Wear Test

- If there is **no significant change** in the friction and wear response between the fresh oil and the used sample, the used sample will **probably continue to function satisfactorily** in the real application
- If the wear and/or friction produced by the used sample is **higher** than the fresh oil, we could **anticipate reduced performance** in the real application
- If the wear and/or friction produced by the used sample is **significantly lower** than with the fresh oil, this may **indicate problems elsewhere in the system**

To summarise:

- **any increase or decrease in wear and/or friction should be taken as a sign of degraded performance**

Scuffing Test

Wear and Friction Tests:

- aim to generate wear under steady state conditions, avoiding unwanted wear transitions

Scuffing Test:

- aim to precipitate wear transitions

Established scuffing tests achieve this by:

- running repeat tests with progressively higher loads
- running single tests with load increased in steps
- running single tests with temperature ramped

Scuffing Test - Challenges

Repeat tests with higher loads

- Not compatible with requirements for condition monitoring scuffing test because of cost, time and total volume of lubricant required

Single test with stepped loads

- Each load step initiates new running-in process, accompanied by an initial increase in mean friction and temporary increase in wear rate
- Wear transition tends to be from severe, at the beginning of load step, to more benign wear, once the surfaces have re-run-in; for scuffing, we ideally need to precipitate a transition the other way

Single test with ramped temperature

- Oelcheck reported difficulty in explaining to non-tribologist clients that this was a meaningful thing to do, especially if temperatures required significantly exceeded normal operating bulk temperature of their systems

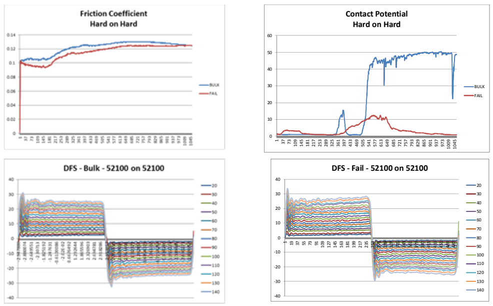
Proof of Concept - Scuffing Tests

Single test with ramped load and temperature:

Typical Sequence:

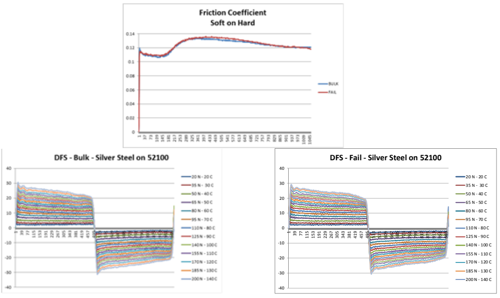
- Run-in for 600s at 20 N load and 20 C
- Ramp load to 200 N and temperature to 200 C in 960s
- Take high speed data at 10 N/10 C increments

Proof of Concept - Scuffing Tests



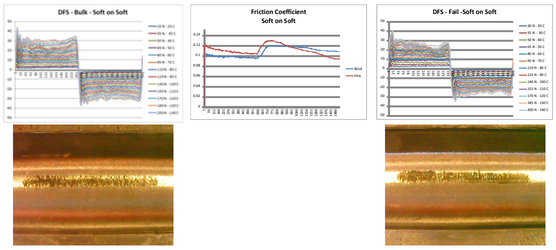
Hard on Hard – No real difference except contact resistance

Proof of Concept - Scuffing Tests



Soft on Hard – No real difference

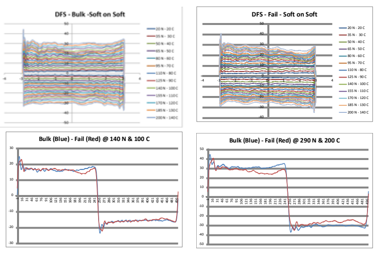
Proof of Concept - Scuffing Tests



Soft on Soft – Difference in instantaneous friction

Dip in FAIL friction at stroke end coincides with polished patches?

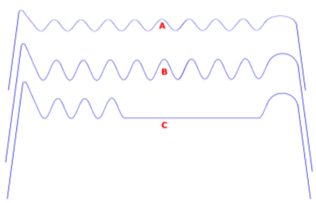
Scuffing Test – Bulk/Fail



FAIL traces:

- magnitude of initial friction spike reduces but position of peak is delayed
- friction decreases sliding towards smoother surface at end of stroke
- friction spikes when moving from rest across smoother surface
- instantaneous friction clearly dependent on local topography and motion

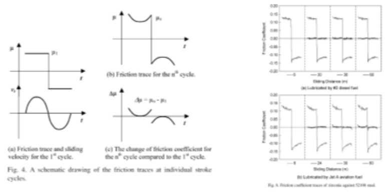
How to Evaluate High Speed Friction



Friction Noise Signal

Works for transition A to B but not A to C

How to Evaluate High Speed Friction

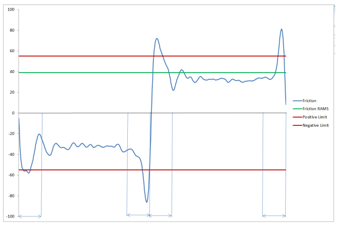


Investigation of the scuffing characteristics of candidate materials for heavy duty diesel fuel injectors
Jun Qu, JJ Truhan, PJ Blau
Tribology International 38 (2005) 381-390

ORNL Oakridge Scuffing Detect Method

Not clear what happens if initial stroke produces rougher friction than subsequent strokes

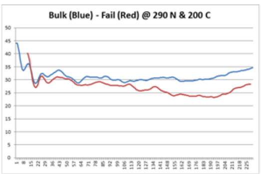
How to Evaluate High Speed Friction

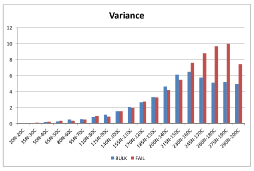


Kamps Scuffing Algorithm

Requires user to set arbitrary limits

High Speed Friction – Variance Method





- High speed friction data sampled between peak value at beginning of stroke and peak value at end of stroke
- Variance (squared deviation from mean) of each data point between peaks calculated and plotted
- Significant difference in variance between BULK and FAIL tests

Summary – Scuffing Tests

Requirements for a scuffing test using pin on twin test configuration are:

- Soft pin running on soft twin (as used by Blau et al)
- Careful running-in process under conditions of mild adhesive wear
- Continuous load and temperature ramp to allow results to be generated from a single test sample
- Choice of load and temperature ramp rates sufficient to precipitate transition back to adhesive wear
- Test terminated at or near point of maximum adhesive wear; there is no point continuing to run until specimens have worn to the point where adhesive wear effectively ceases
- Logically, for evaluating fresh and degraded oil samples, latter should be tested first, with the test terminated as soon as a transition becomes evident
- Because of uncertainty over use of term “scuffing”, it may be more appropriate to re-classify this test as a “wear transition” test

Conclusion

During this project we have:

- Adopted a test geometry and selected specimen materials that meet the cost and performance objectives
- Devised a low cost, quick and low skill method of measuring a flat wear scar
- Devised a new method for analysing the “smoothness” or otherwise of instantaneous friction signals
- Proposed a means of selecting parameters from condition monitoring data on which to focus, the method chosen being to calculate standard deviation for each measured parameter and then select those with largest variance
- Identified the importance of the difference between “causal” and “indicative” correlation when reviewing such data
- Developed two test procedures:
  - A friction and wear test with hard pin on soft twin at constant load and temperature, that can be completed in less than 30 minutes
  - A wear transition (scuffing?) test with soft pin on soft twin, with simultaneously ramped load and temperature, that can be completed in less than 30 minutes
- Proposed a simple rules-based system for determining whether a fluid sample should continue in service:
  - For friction and wear test:
    - an **increase or a decrease** in wear and/or mean steady state friction, for whatever reason, should be taken as signs of degraded performance
  - For wear transition test:
    - an **increase** in variance of high speed friction signal, for whatever reason, should be taken as signs of degraded performance
- And, perhaps most importantly, demonstrated that relative hardness of specimens and resulting contact morphology has a significant influence on friction and wear response