Scuffing: From Basic Understanding to Engine Materials Testing*

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Definitions for Scuffing

- Swedish ***skuffa*** – 'to push'

- Webster's Unabridged Dictionary, 3rd ed.: "to walk without lifting the feet; to poke or shuffle a foot in exploration or embarrassment; to become scratched, chipped, or roughened by wear."

- ASTM Terminology standard G40: scuffing – a form of wear occurring in inadequately-lubricated tribosystems that is characterized by macroscopically observable changes in texture, with features related to the direction of motion."

Operational definition: "I'll know it when I see it."

Characteristics of Scuffing

- Scuffing can *roughen* a surface with no net loss of material (not 'wear').
- Can *smooth* an initially rough surface.
- Need not be progressive (one cycle).
- In machinery (engines), scuffing is associated with inadequate or failed lubrication.

- Occurs non-uniformly. Can start at one place on a surface and spread to another after continued operation.
- Can lead to seizure (incipient galling) in tight-tolerance components.
- Scuffing damage is difficult to measure in a quantitative way.

Historical Attempts to Define Critical Scuffing Criteria

- **'Plasticity Index'** (Greenwood and Williamson, *PRS*, 1966).

$$\psi = \left(\frac{E'}{H}\right)\left(\frac{\sigma^*}{R}\right)^{1/2}$$

- **Modified Plasticity Index** (Whitehouse and Archard, *PRS*, 1970).

$$\psi = 0.06\left(\frac{E'}{H}\right)\left(\frac{\sigma^*}{\beta^*}\right)^{1/2}$$

- **'Film thickness ratio'** L (Beerbower, *ASLE Trans*., 1971)

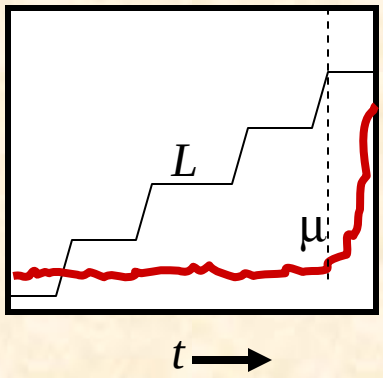
$$\Lambda = \frac{h}{\sigma_c}$$

β^* (autocorrelation function) is measure of surface randomness, $\beta^* = 0$ when surface heights are random; $\beta^* = 1$ for a flat, smooth surface)

Some Problems with Critical Scuffing Criteria based solely on Mechanics

- Surface roughness rarely remains constant once relative motion begins (break-in, wear-in). Plasticity indices cannot easily accommodate the consequences of time-dependent changes in roughness and texture during continued contact.
- Plasticity models ignore the important effects of the lubricant chemistry (Park and Ludema, *Wear*, 1994)
- Testing approaches to oil additive formulation are based on lubricant properties. Tests keeps the material combination and surface conditions constant.

Current Scuffing Tests Popularly Use Stepped Loading to Determine Critical Loads



- Stepped loading does not simulate actual component conditions.
- Dwell times at each load allow subsurface damage to accumulate and may not produce the same result as if load were held constant for the same time but at the level that induced scuffing.
- Stepped loading tests do not address the issue of localized initiation and propagation of scuffing damage.
- Stepped tests often use unidirectional sliding but many key engine components reciprocate (e.g., pistons, fuel injectors, actuators, valve guides)

Some ASTM Standards Used to Quantify Scuffing-Related Performance of Oils

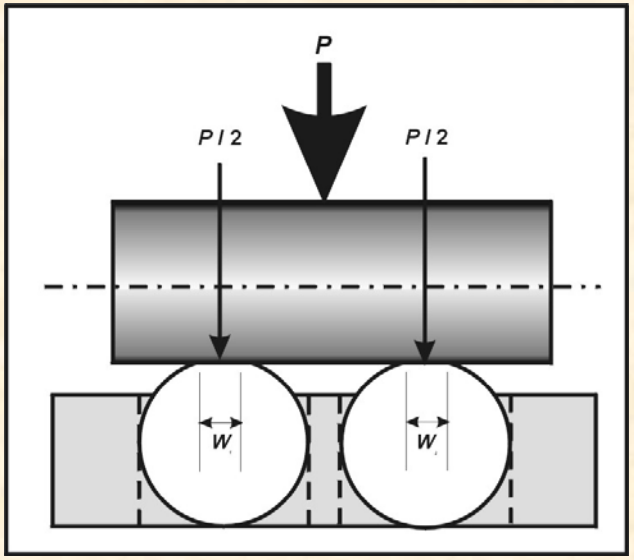
- **ASTM D5182**: "Standard test method for the scuffing load capacity of oils (FZG visual method)" (*Example of step loading*)
  - Motor-driven gear set uses twelve 15-minute test stages with examinations after each one.
  - Document shows sample images of *polishing*, *scuffing*, and *scoring* to estimate the extent of damage
  - "Failure" occurs when total width of scuffing or scoring damage for all 16 teeth on the test gear ≥ the width of one tooth (20 mm). Metric: the 'failure load' stage.
- **ASTM D6078 Ball-on-Cylinder Lubricant Evaluation** (**BOCLE**)
- **ASTM D6425 Optimal SRV Test** – high-speed linear oscillation

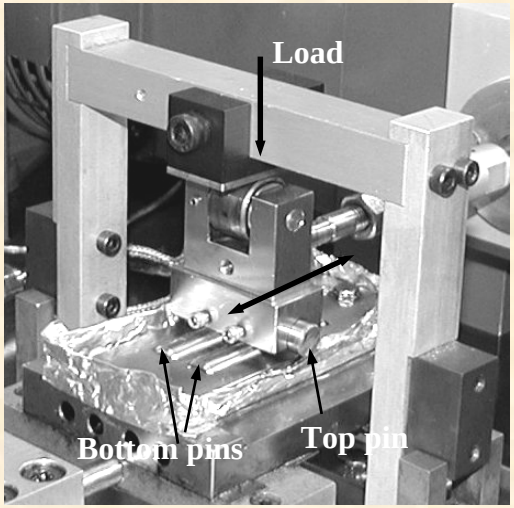
ORNL's Approach to Scuffing Measurement
Case Study I: Fuel Injector Plungers

- **Develop a convenient bench-scale laboratory test** that does not rely on stepped loading, but characterizes the time-dependent progression of damage on a contact surface.
- Flexibility to use either **experimental test coupons** or **production parts**.
- **Minimize the time per test**.
- Enable studies of the effect of **surface finishes**, **coatings**, and other **surface engineering** approaches.
- Develop **scuffing maps** / models useful in material selection.

Development of the 'Pin-on-Twin' Test

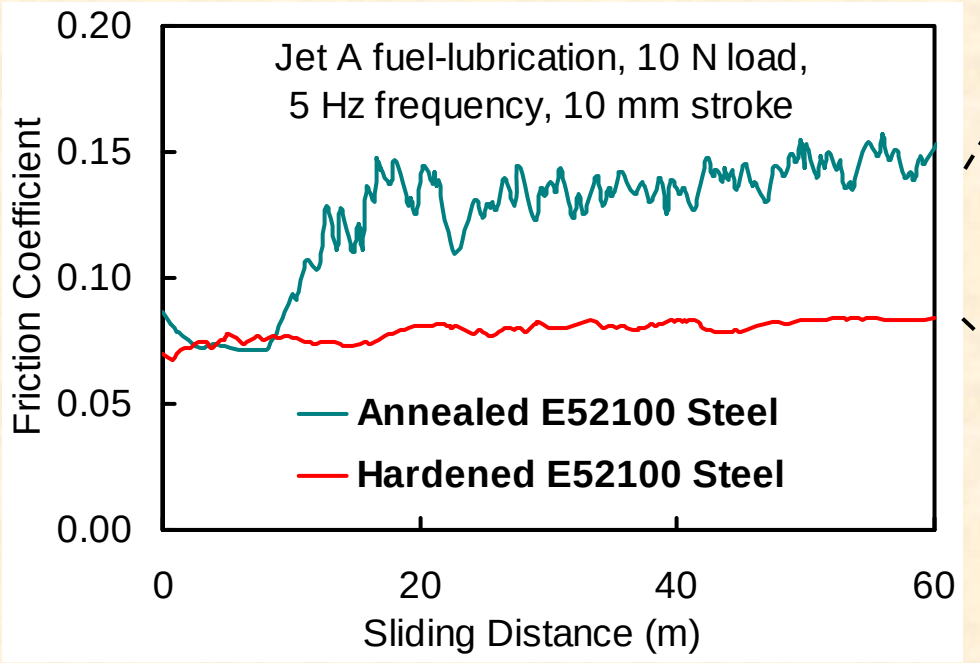
- Geometry allows testing both simple cylinders and actual fuel injector plungers.

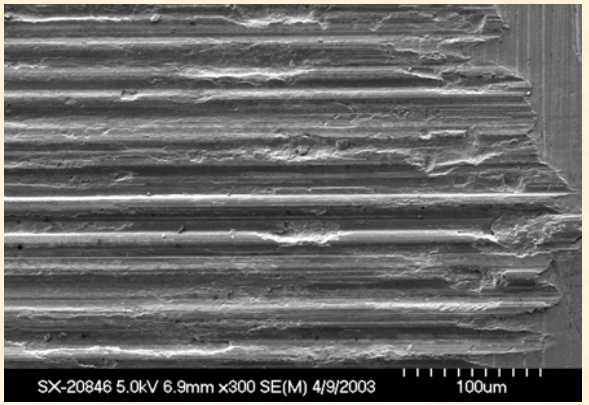


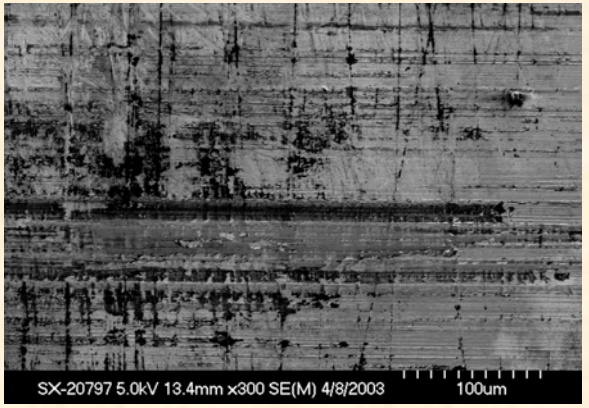


- High-speed data acquisition captures friction for various locations on the stroke as a function of time or numbers of cycles.

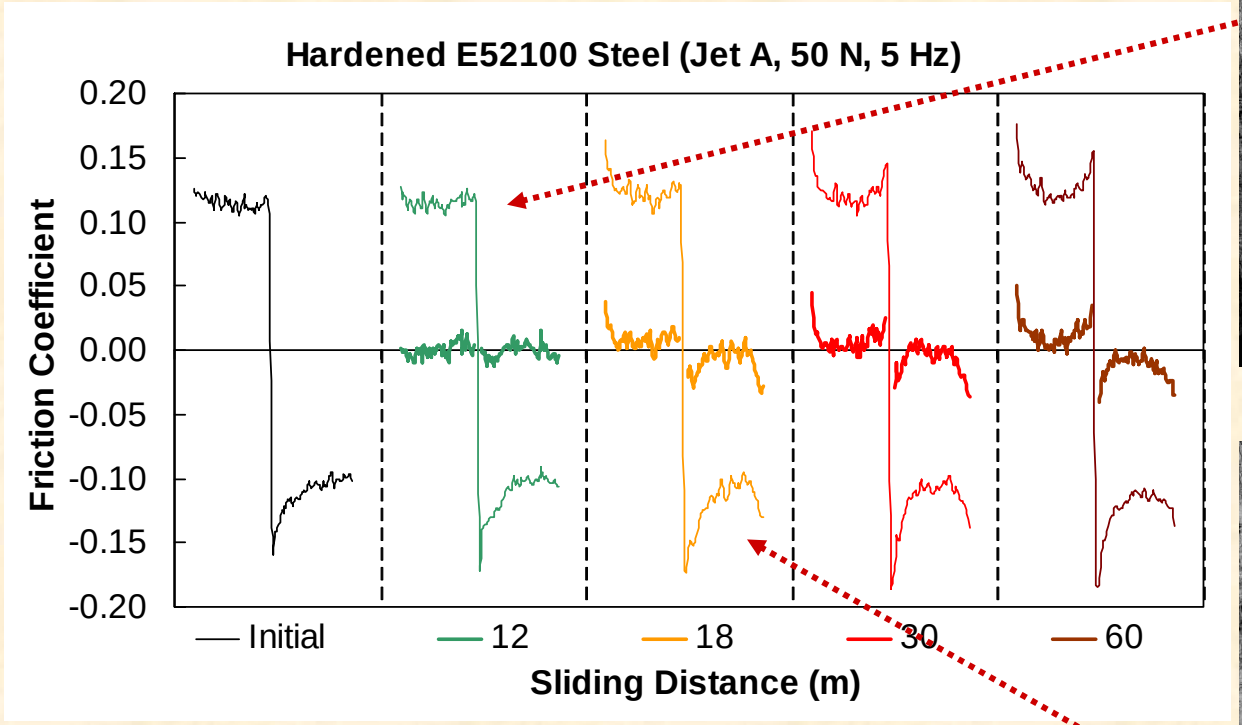
First experiments evaluated 52100 steel in #2 Diesel fuel and a low sulfur fuel ('Jet A')



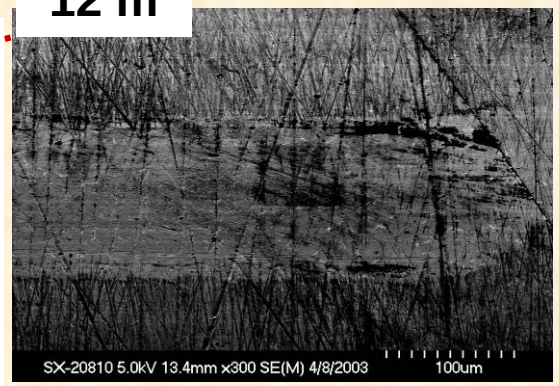


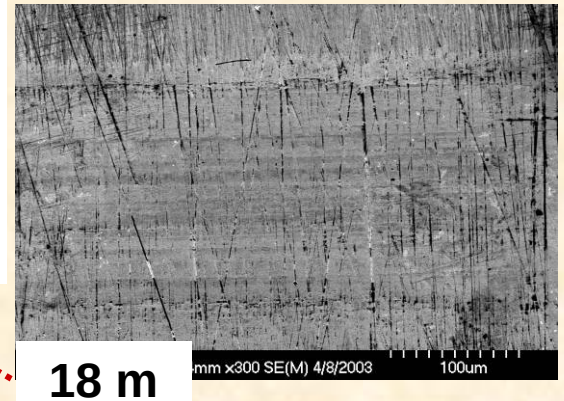


Friction Trace Comparison Method Enables Initiation to be Detected



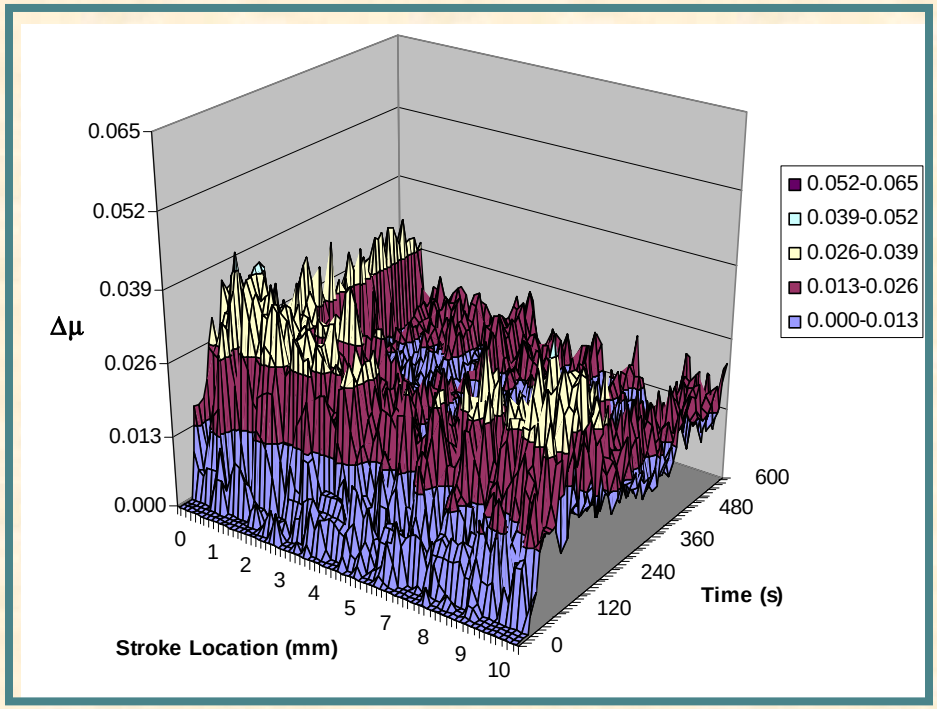
12 m





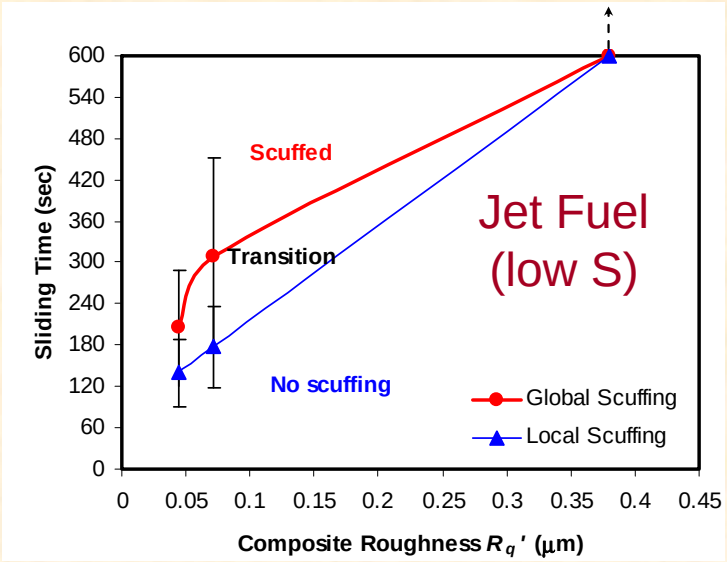
18 m

Scuffing Map Portrays Initiation and Spread of Surface Damage on Cylindrical Plungers



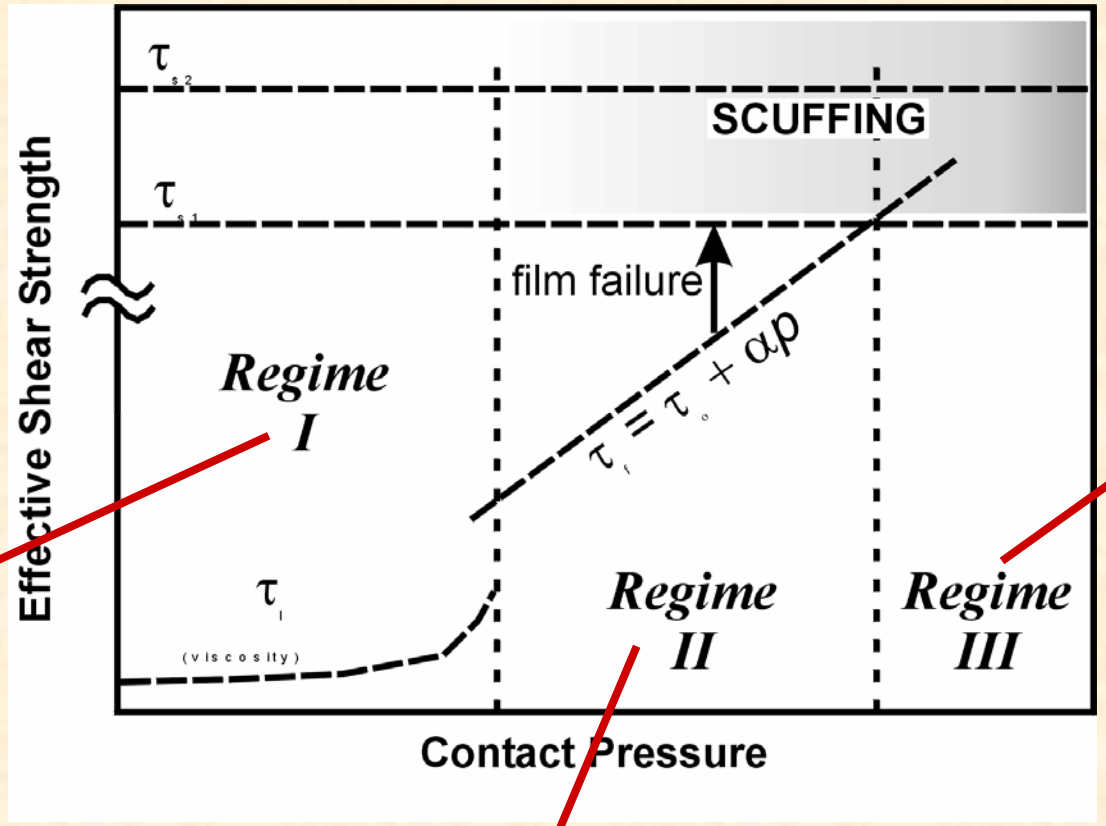
Sequence of friction traces on a simulated fuel injector plunger

Initial surface roughness affects the time to initiate scuffing and the time to transition to a fully scuffed surface



Zirconia on Steel

New Multi-Stage Scuffing Model Includes both Lubricant and Materials Effects

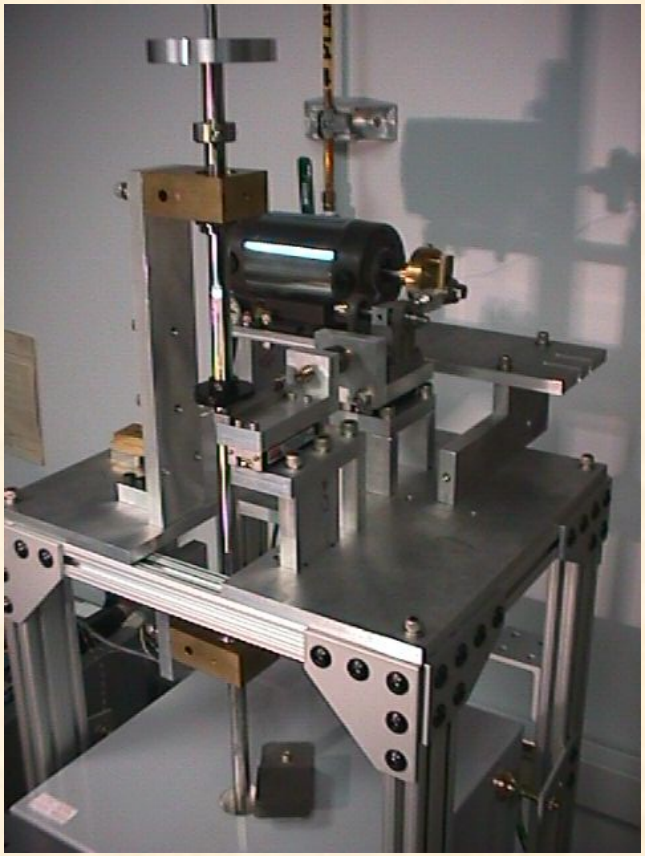


Lubricant flow and viscosity

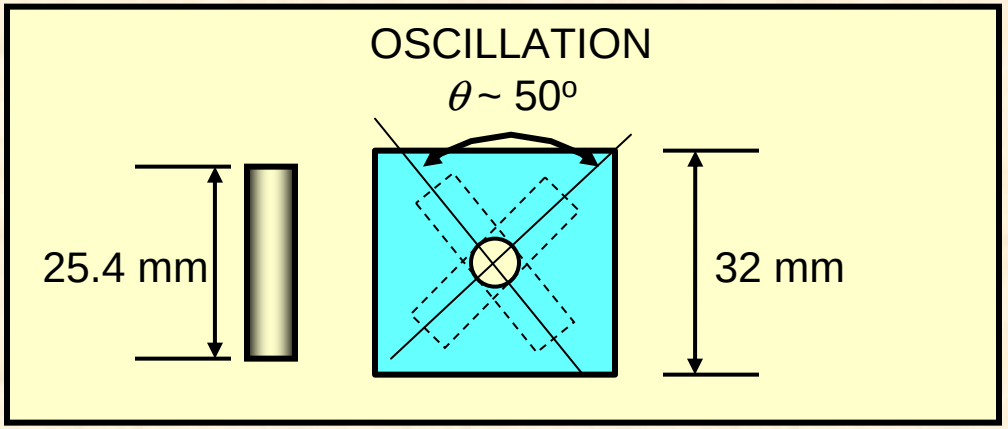
Material properties

Boundary film properties

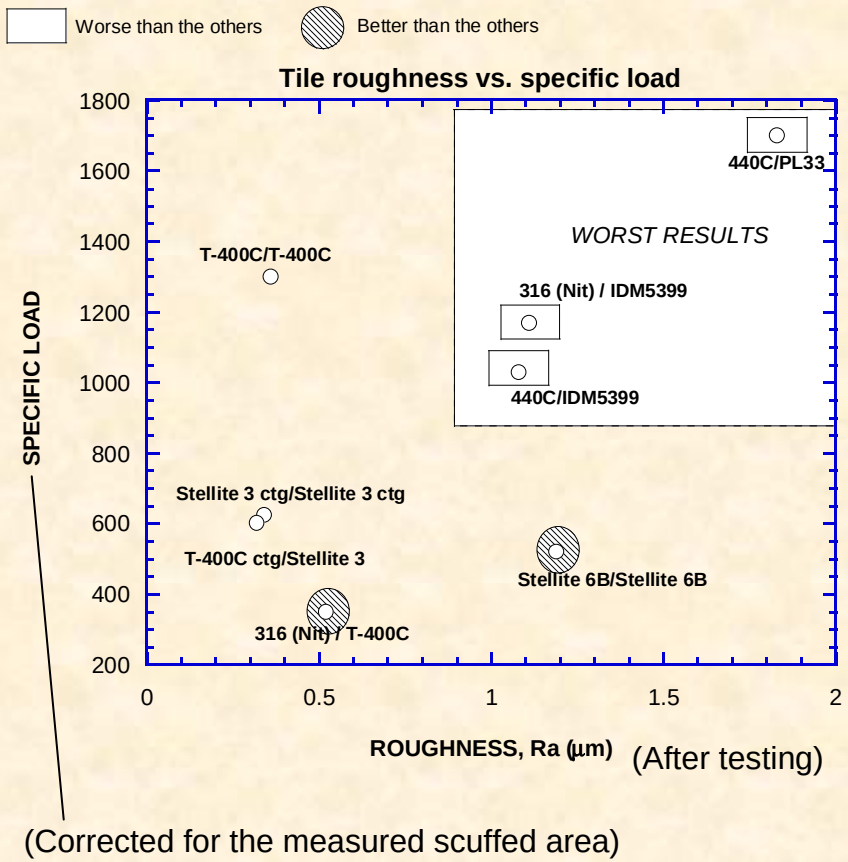
Case Study II: High-Temperature Scuffing of Wastegate Bushing Materials for EGR Systems



- Developed a “bow-tie test” for cylinder on flat geometry up to 650^{o} C
- Measures changes in torque due to surface damage and debris accumulation



Multiple Criteria were used to create Scuffing Severity Maps



(After testing)

(Corrected for the measured scuffed area)

1) Torque as a function of time

2) Changes in surface roughness

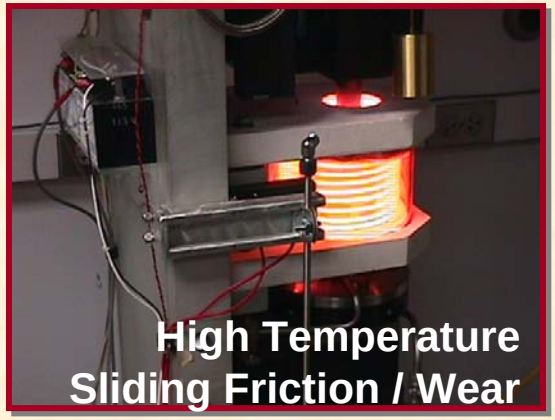
3) Examination of test specimens

J. Wu and M. Yao, Deloro-Stellite

Biodiesel Additive Issues: ***How much BD can improve lubricity? Fundamentally, what effect does BD have on scuffing initiation and propagation?***

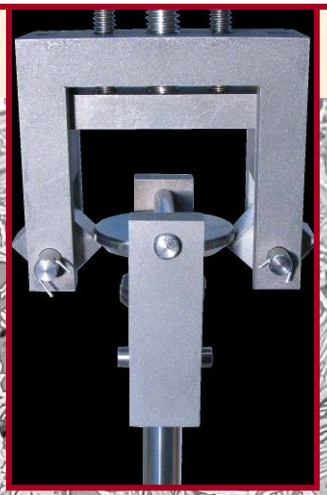
- The National Biodiesel Board – www.biodiesel.org – reports lubricity benefits when adding > 1% to #2 Diesel fuel (BOCLE). Soybean oil-based additives claimed to **meet or exceed lubricity of current diesel fuels**.
- Degree to which BD additives improve lubricity of low-S fuels depends on **which test method is used** (e.g., BOCLE, SRV, etc. -- report by L. Schumacher, U Idaho)
- **Materials-based research** is needed to understand these discrepancies and to identify BD effects on the initiation and propagation of scuffing damage in different materials.

DOE's HTML User Program (Tribology Research User Center) Provides Access to Specialized Test Methods



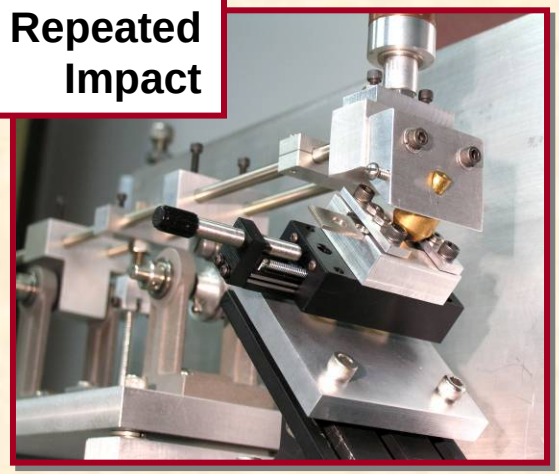
Ring and Liner

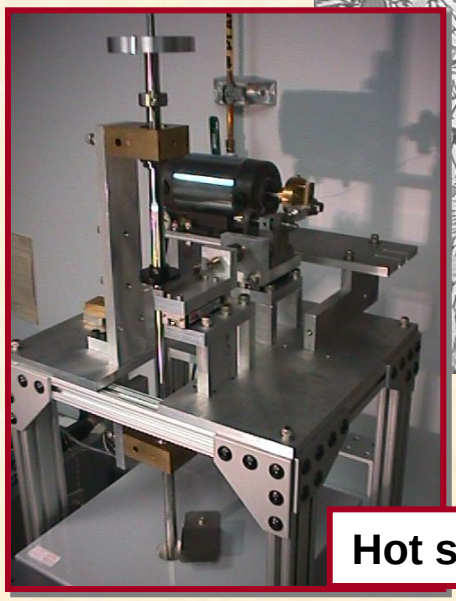
High-temperature valve tests



Advanced materials

Repeated Impact





Hot scuff testing

Summary

- **Scuffing is context-dependent**. Tribosystems should be individually analyzed in order to define 'failure of function'.
- **Scuffing damage can occur quickly or over time:** depends on operating conditions, materials, and lubrication.
- **Approaches**: redesign, alter operating conditions, alternative materials or surface treatments, surface finish optimization, or change lubricant type and means of supply.
- **Simulative experiments and analytical models** should be applied to investigate effects of biodiesel fuels on the scuffing mechanisms in materials/coatings.
- Methods described here are available to U.S. industry and universities in the **HTML Tribology Research User Center**.

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