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U.S. Army Research, Development and Engineering Command

Microscopic and Spectroscopic Characterization of Gear Tooth Damage from a Loss-of-Lubrication Event

ARL

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  - NASA Rotary Wing
- **Special thanks to …**
  - Space Power Branch (NASA Glenn)
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Background

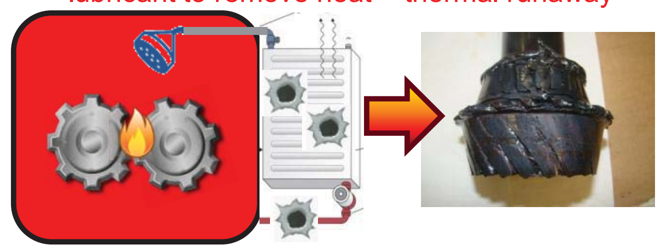
- **Oil starvation**
  - Can occur due to …
    - Loss of lubrication
    - Higher speeds and loads
  - Results in …
    - Film breakdown / Contact
    - High friction
    - Heat generation
    - Wear
    - Failure

NORMAL OPERATION

Flowing lubricant keeps heat generation low and removes excess heat from gearbox

OIL-OUT OPERATION

Gear contacts generate more heat + no flowing lubricant to remove heat = thermal runaway



- **Autorotation to landing not always an option (location, seizure)**
- **U.S. Army rotorcraft qualification requires operation for 30 minutes after loss of primary lubrication system (ADS-50-PRF)**
- **Future challenge**
  - Move beyond auxiliary and emergency lube systems
  - Develop materials and lubricants to meet and extend oil-starved lifetime
  - Understand chemical and physical processes during oil starvation!!!

Outline

- **NASA Spur Gear Test Rig**

- **Post-analysis of gear teeth**
  - Geometry and Morphology (Optical microscope, Profilometry, SEM)
  - Chemical analysis (SEM/EDS, XPS, Raman)
  - Depth profiling (AES, FIB-SEM)

- **Conclusions**

Gear Rig

- **NASA Glenn Contact Fatigue Test Facility**
  - Oswald, F., NASA/TM—2004-212722;
  - Krantz, T. et al., NASA/TM—2005-213956, ARL–TR–3126

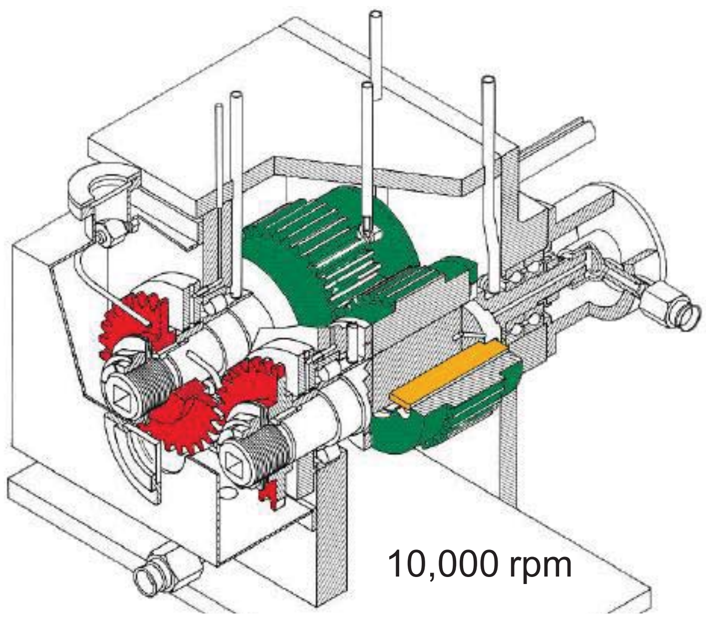
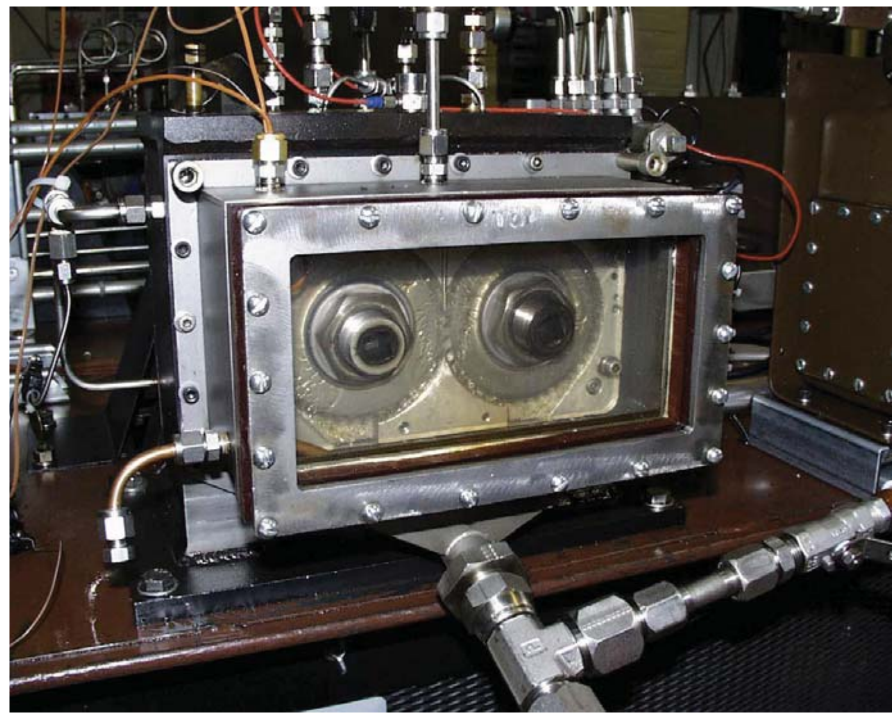


TABLE 1.—BASIC GEAR DESIGN INFORMATION

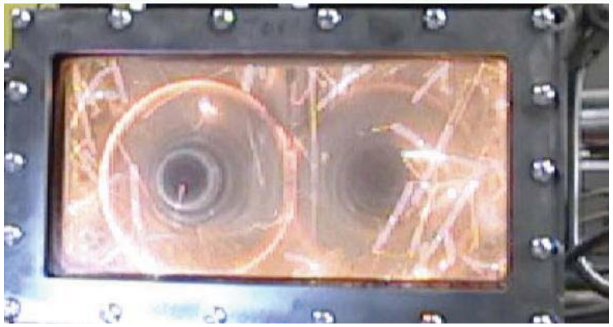
	28 tooth gear	42 tooth gear
Diametral pitch (1/in.)	8	12
Pressure angle (deg.)	20	25
Pitch diameter (in.)	3.5	3.5
Addendum (in.)	0.125	0.083
Whole depth (in.)	0.281	0.196
Chordal tooth thickness (in.)	0.191	0.128
Face width (in.)	0.25	0.25

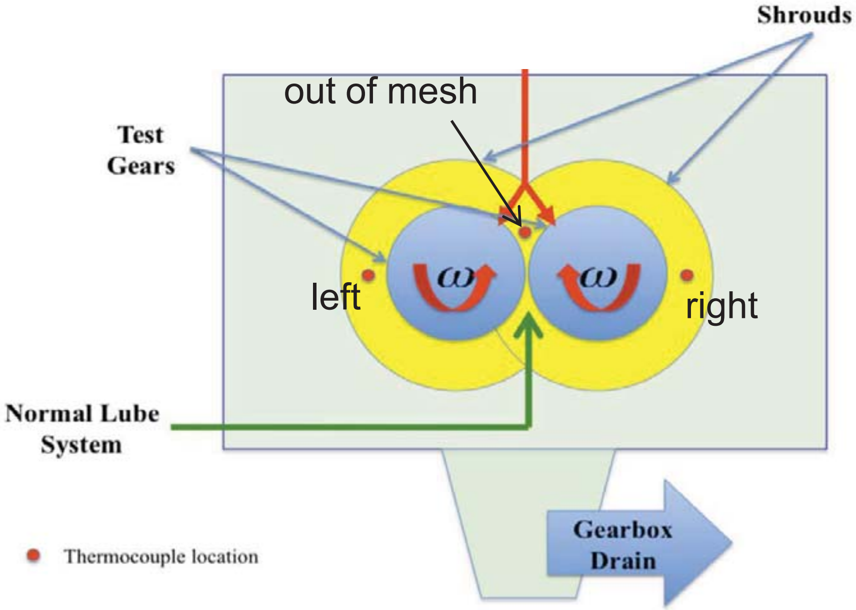


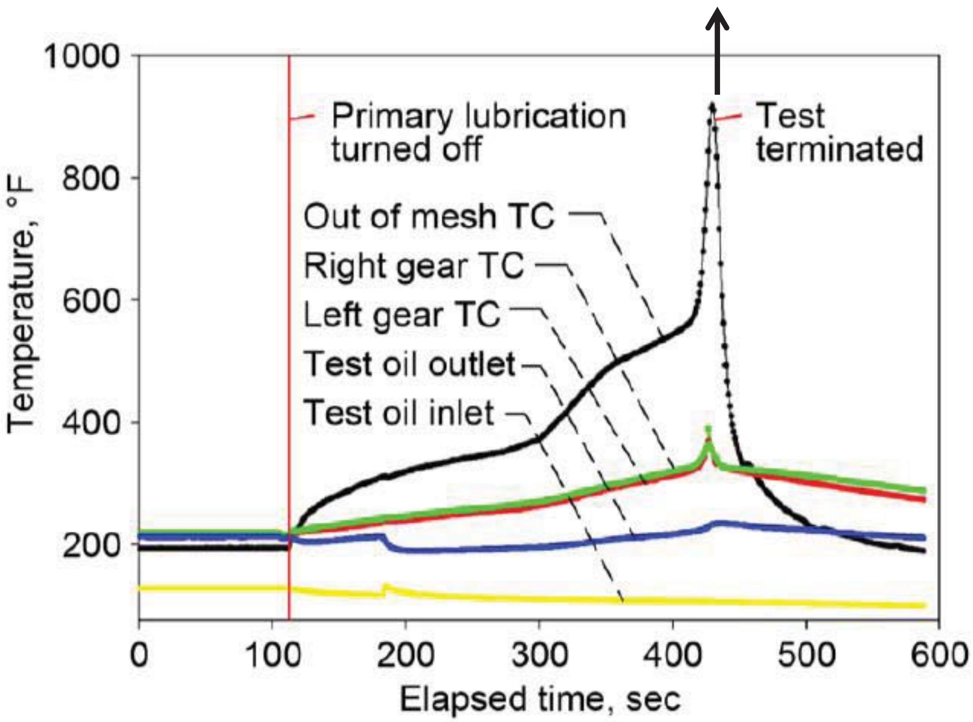
Handschuh et al., NASA/TM—2011-217106

Loss of lubrication experimental methodology

- Typical run
  - Break-in at lower load
  - Run at full load to steady state (about two hours)
  - Turn off oil supply







Handschuh et al., NASA/TM—2011-217106

Outline

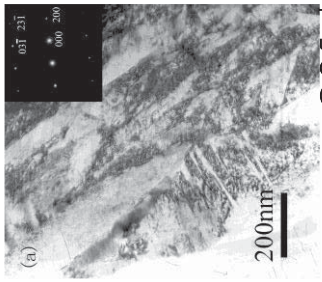
- NASA Spur Gear Test Rig

- Post-analysis of gear teeth
  - Geometry and Morphology (Optical microscope, Profilometry, SEM)
  - Chemical analysis (SEM/EDS, XPS, Raman)
  - Depth profiling (AES, FIB-SEM)

- Conclusions

Materials and Experiment

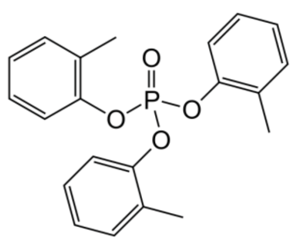
- **M50 steel gears (typical bearing steel)**



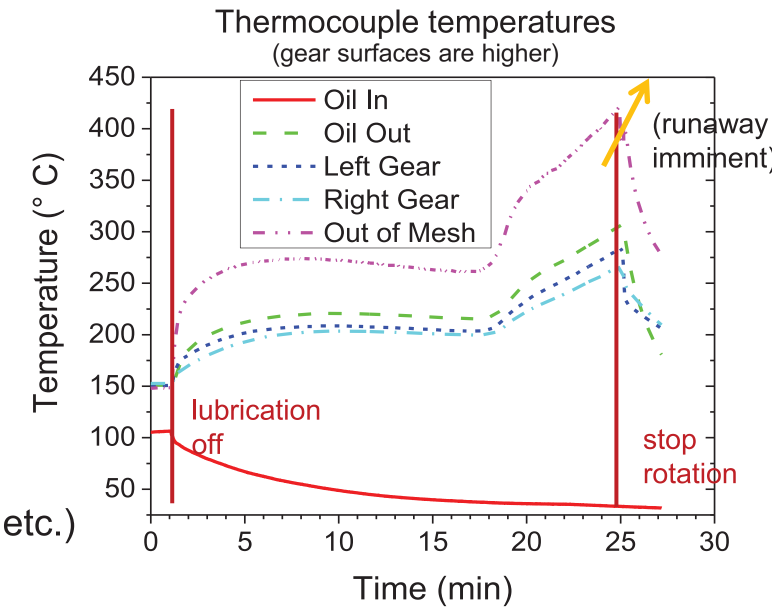
TEM micrograph of untreated M50 steel G. Tang, NIM B 288 (2012)

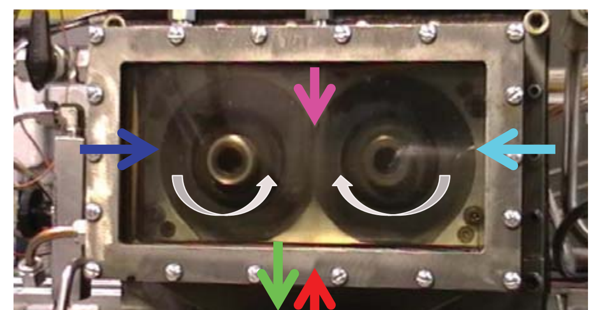
Fe	C	Cr	Mo	V	Si
balance	0.8%	4%	4%	1%	0.2%

- **5 cSt turbine oil (DOD-L-85734)**
  - Typically polyol ester base
  - Chemical additives (amines, chloralkyl phosphonate, etc.)
    - Antiwear
    - Detergent
    - Corrosion inhibitors
    - Antifoaming
    - Extreme pressure



- **Stop experiment before destruction**
  - Typically will reach >550 °C
  - Stopped here at estimated 500 °C gear surface average temperature

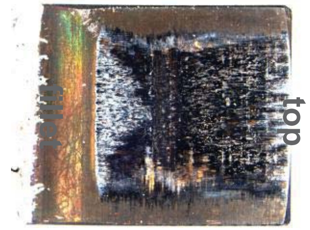




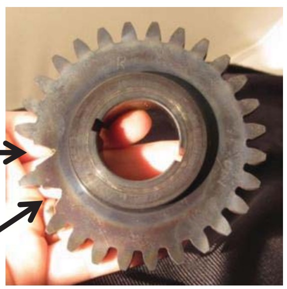
Thermocouple positions and rotation

Teeth for analysis

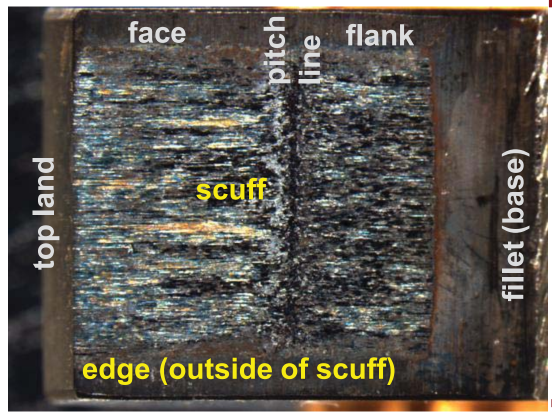
- **Two teeth from different gear positions**
  - Crowned
  - Representative of all teeth
- **Loss of 5 – 10 µm along center line**



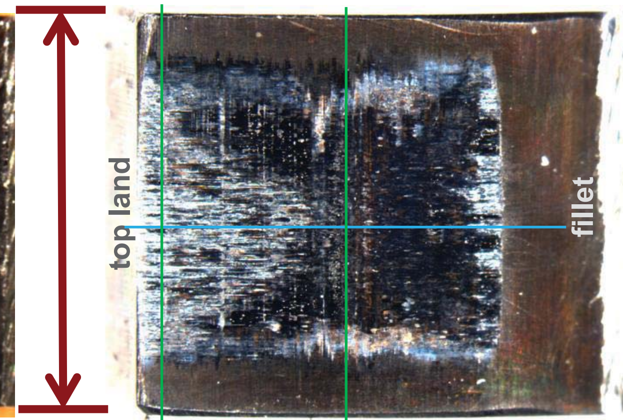
Tooth from opposite gear facing #2 (not to proportion)



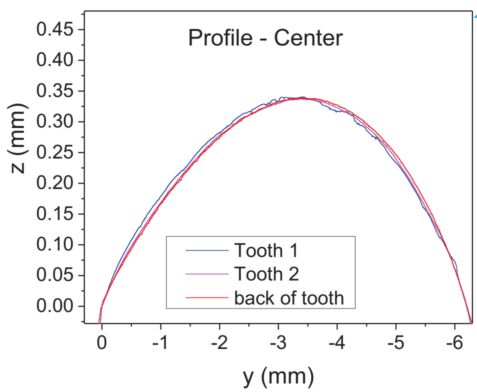
Handschuh et al., NASA/TM—2011-217106

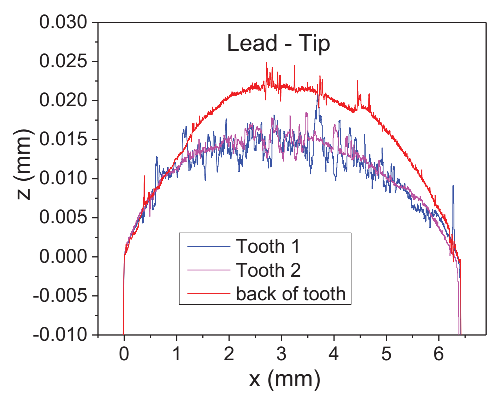


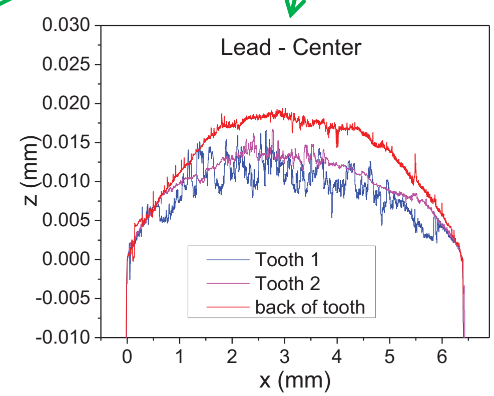
Tooth #1



Tooth #2

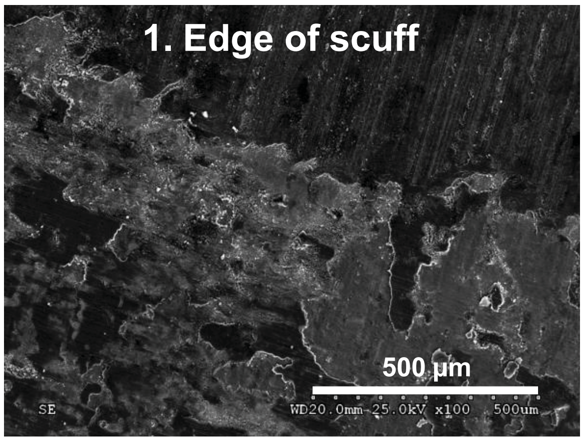


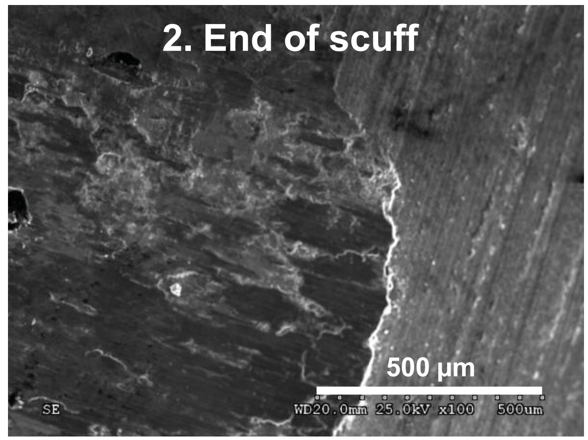


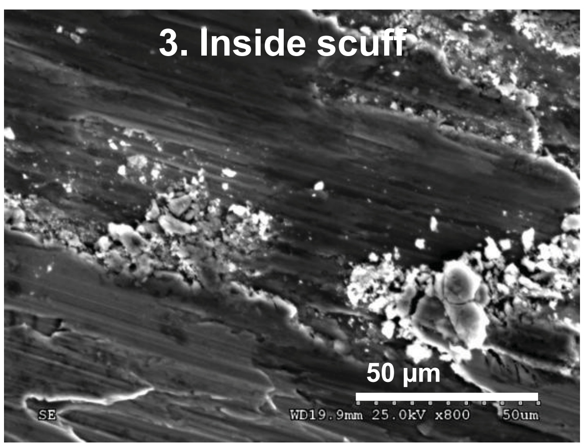


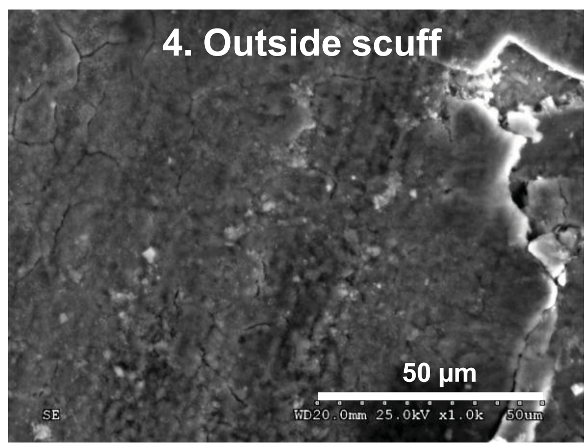
What does it look like?

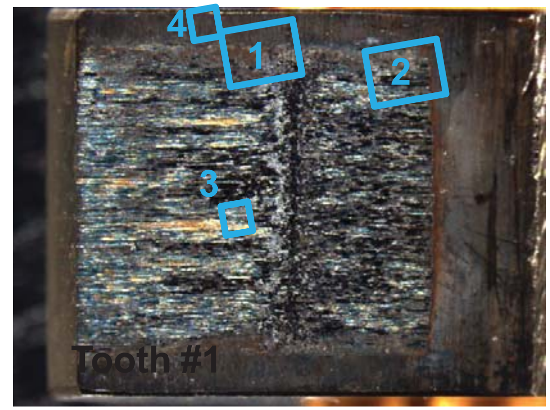
- Scanning Electron Microscopy
- Tooth # 1





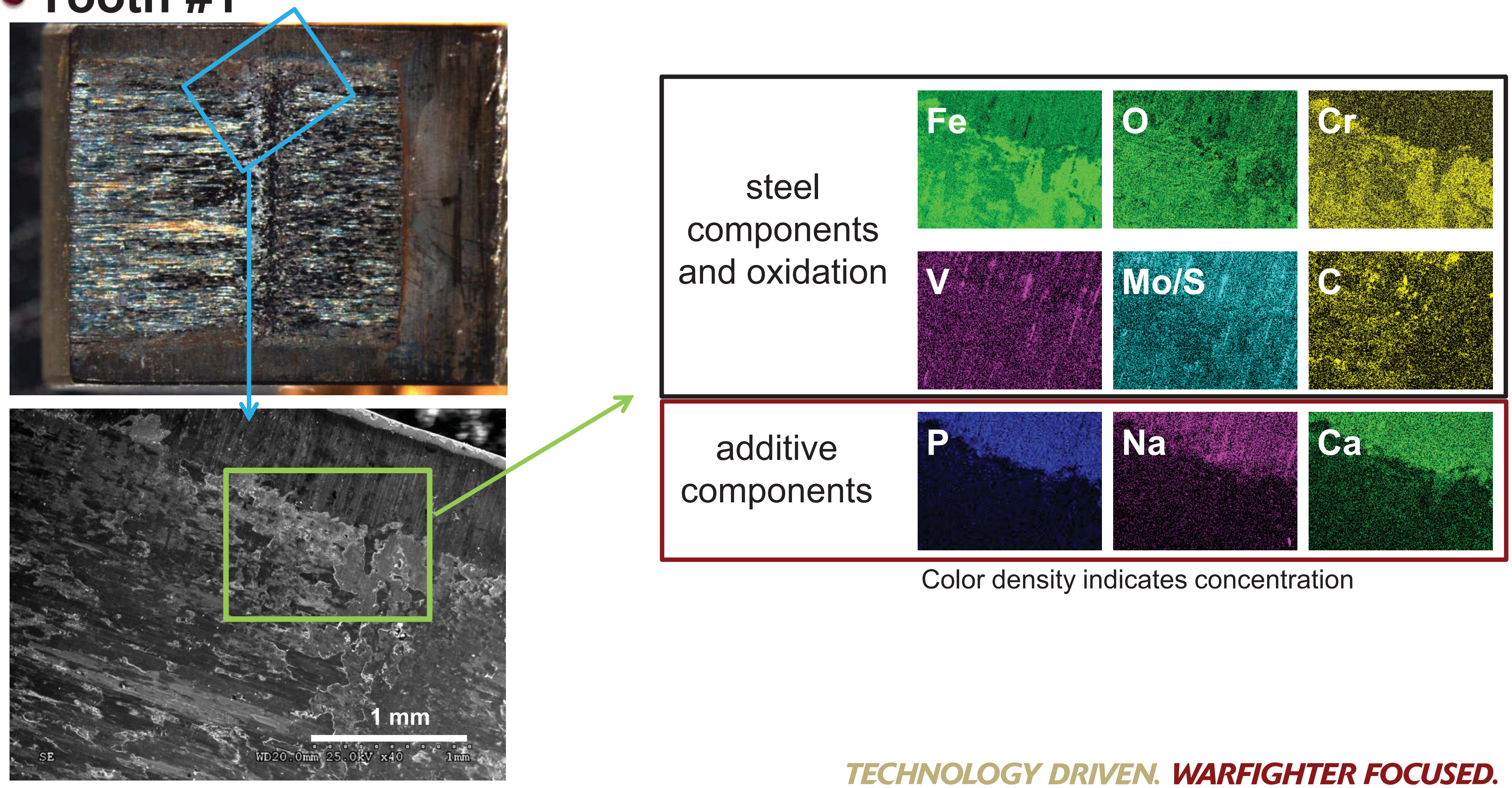






What's on the surface?

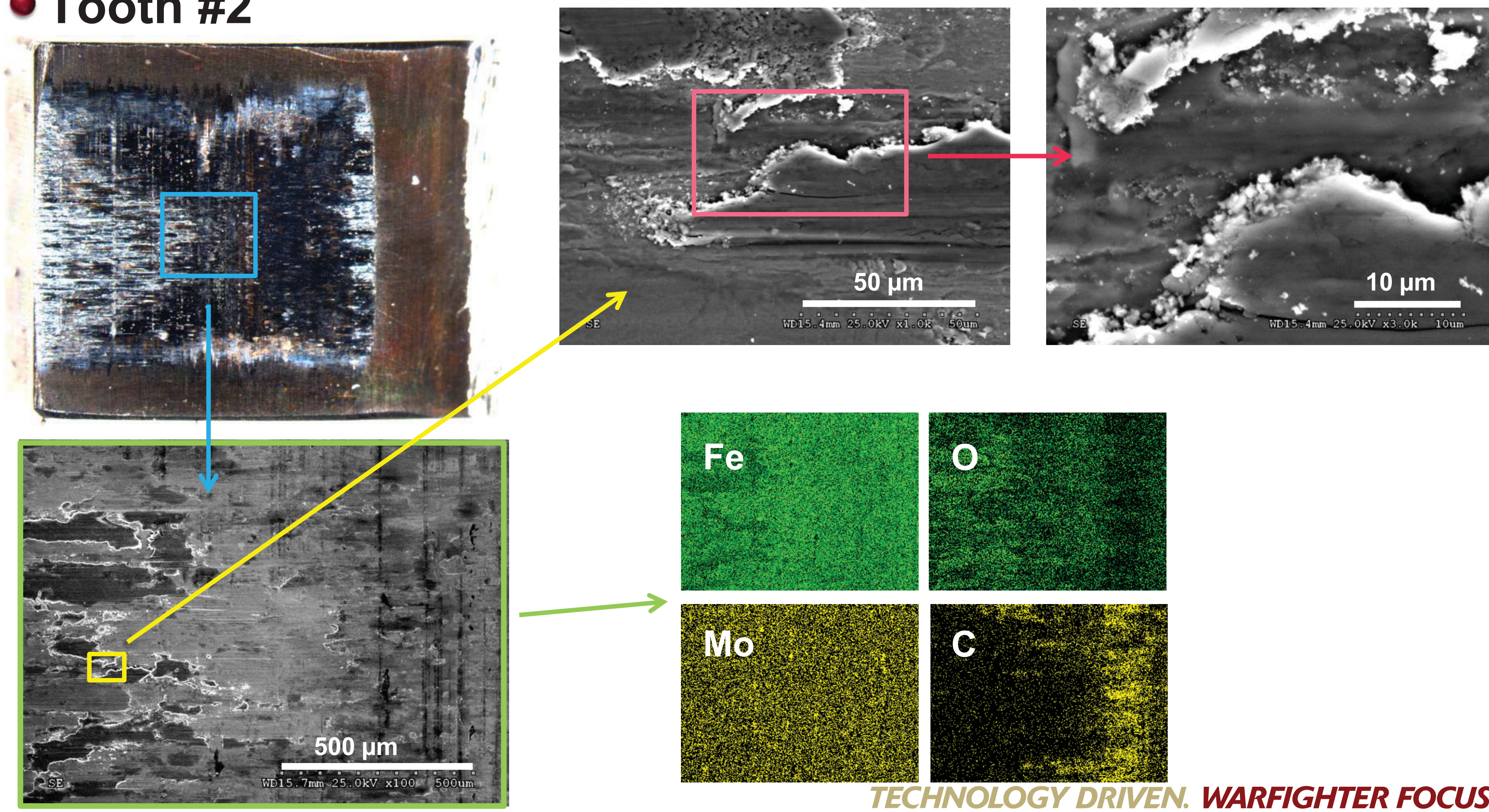
- **SEM with Energy Dispersive Spectroscopy**
  - Depth resolution/sensitivity ~3 μm
- **Tooth #1**



Color density indicates concentration

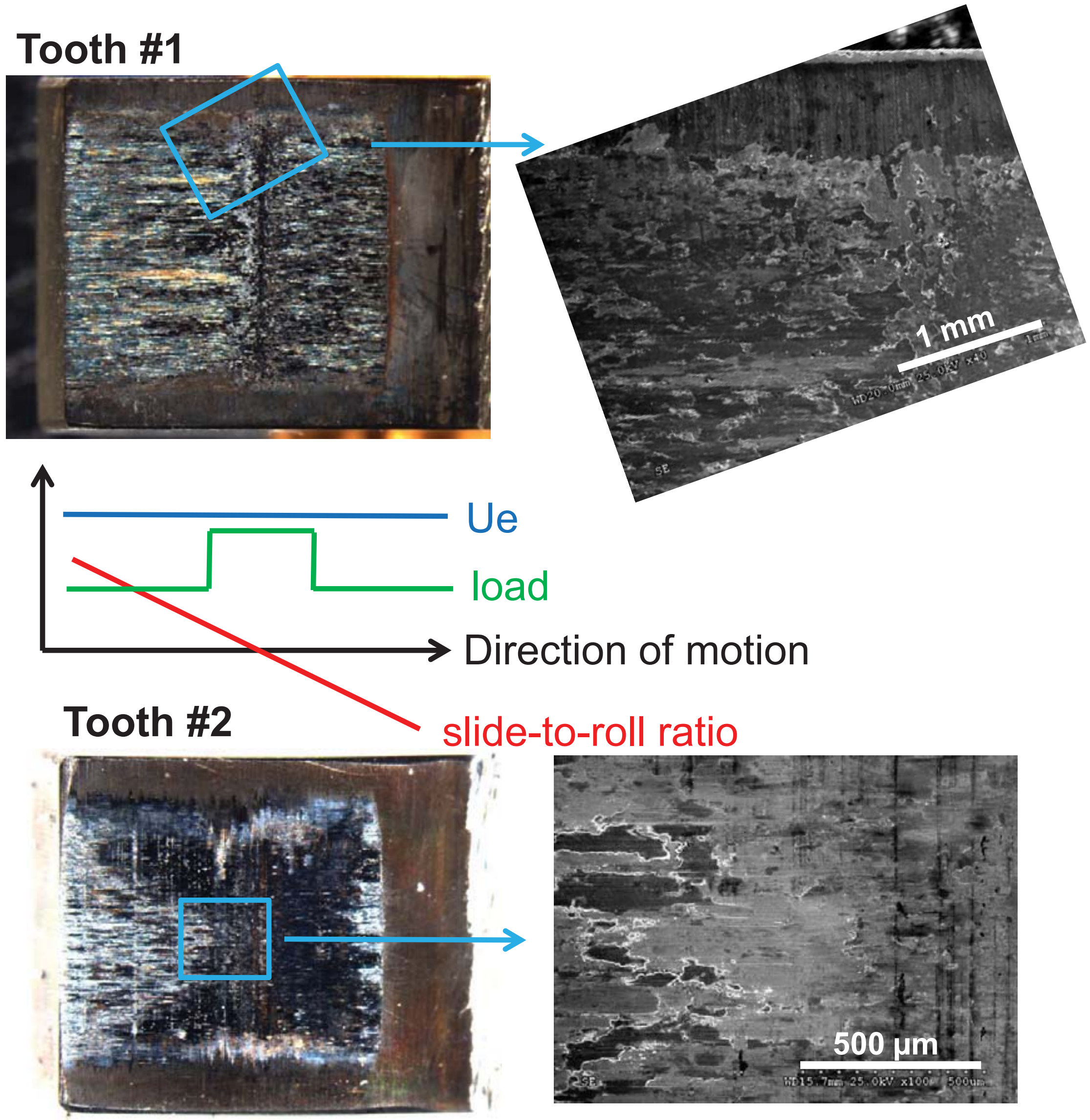
What's on the surface?

- **SEM with Energy Dispersive Spectroscopy**
  - Depth resolution/sensitivity ~3 µm
- **Tooth #2**



Four General Features

- **Two areas, four general features**
  - Edge outside scuff
    - Additive-modified surface
      - Only on edges and fillet
  - Inside scuff
    - Fresh steel
      - Elongated in direction of motion
    - Oxide scales
      - Especially at tip, but spread inwards
    - Carbon
      - Especially at pitch line, but also elsewhere

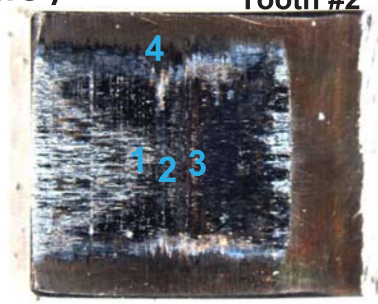


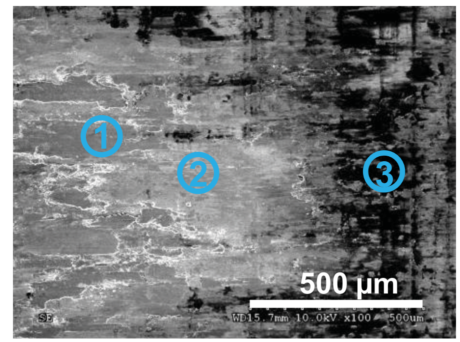
What is really on the surface? (a closer look)

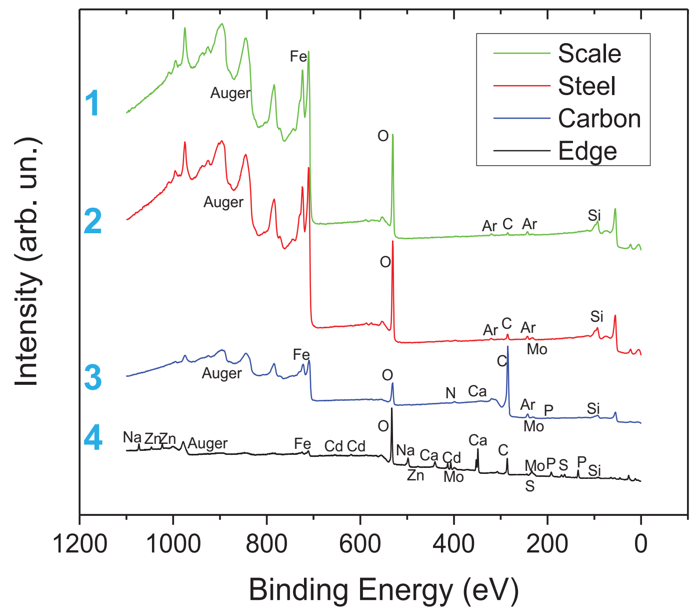
- **X-ray Photoemission Spectroscopy**
  - First few nm of material
  - 0.1 at. % sensitivity, ~1 % accuracy
- **Tooth #2**

Atomic %	Oxide scale (1)	Fresh steel (2)	Carbon (3)	Edge outside scuff (4)
Fe	38.4	35.4	6.7	2.1
O	59.2	56.8	11.5	43.0
C	2.4	7.2	80.3	29.8
Mo		0.3	0.1	0.8
Cr		0.3		
N			1.2	
P			0.2	7.1
Ca				7.6
Na				3.1
S				4.0
Zn, Mg, Cd				<1.0

Tooth #2

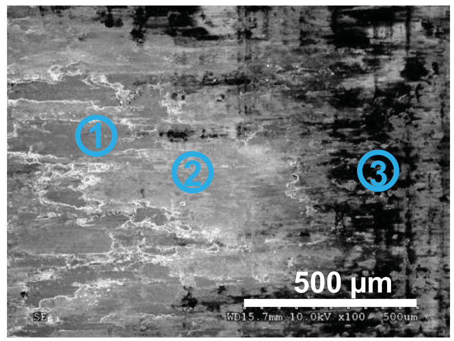


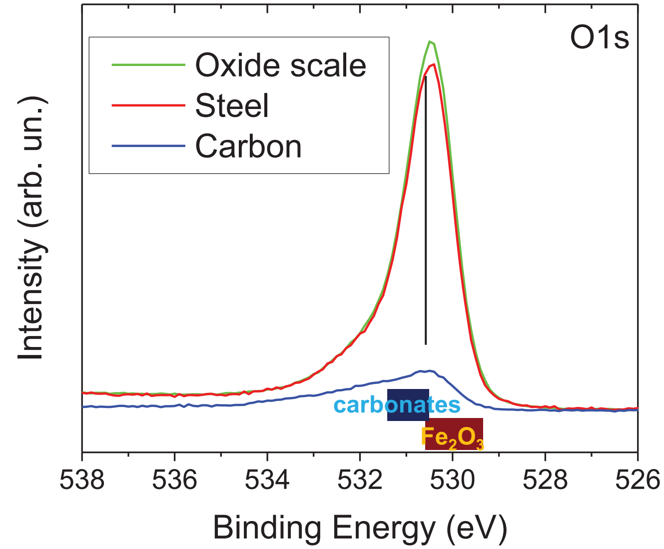


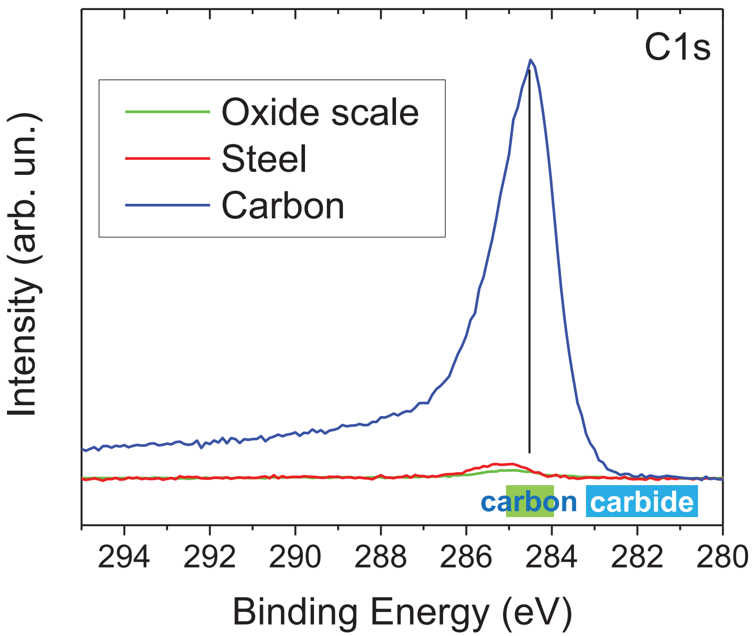


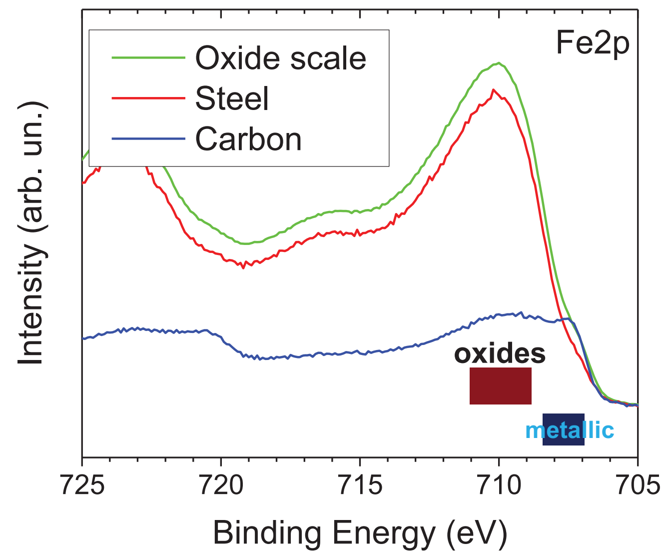
What is really on the surface? (a closer look)

- **X-ray Photoemission Spectroscopy**
- **Tooth #2**
  - No carbide



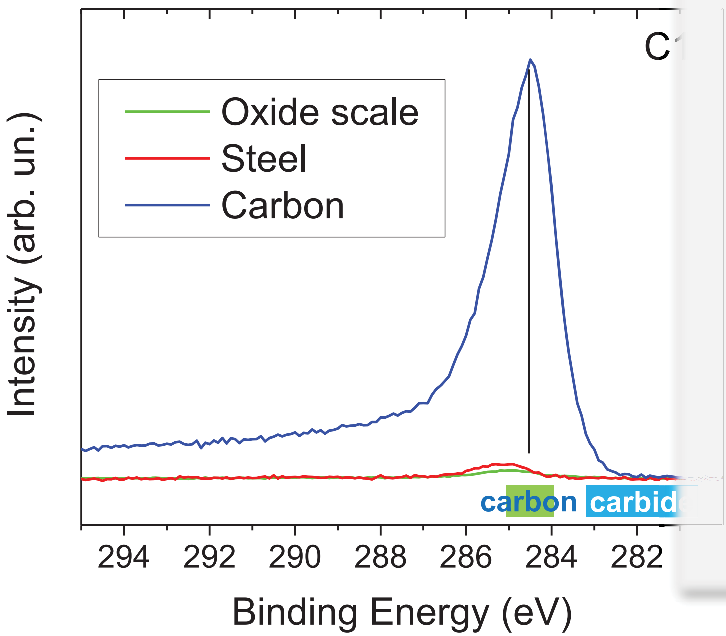


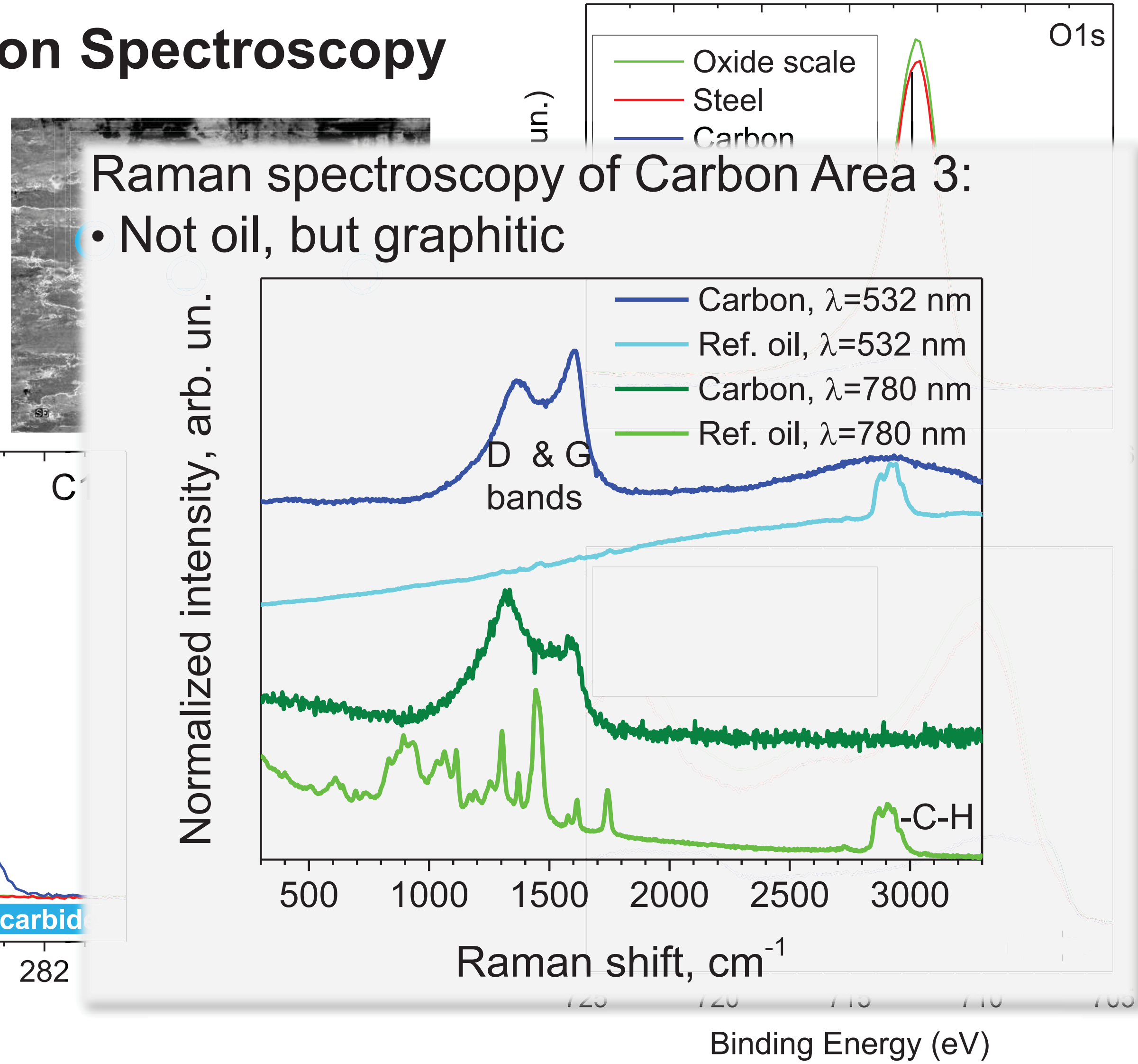




What is really on the surface? (a closer look)

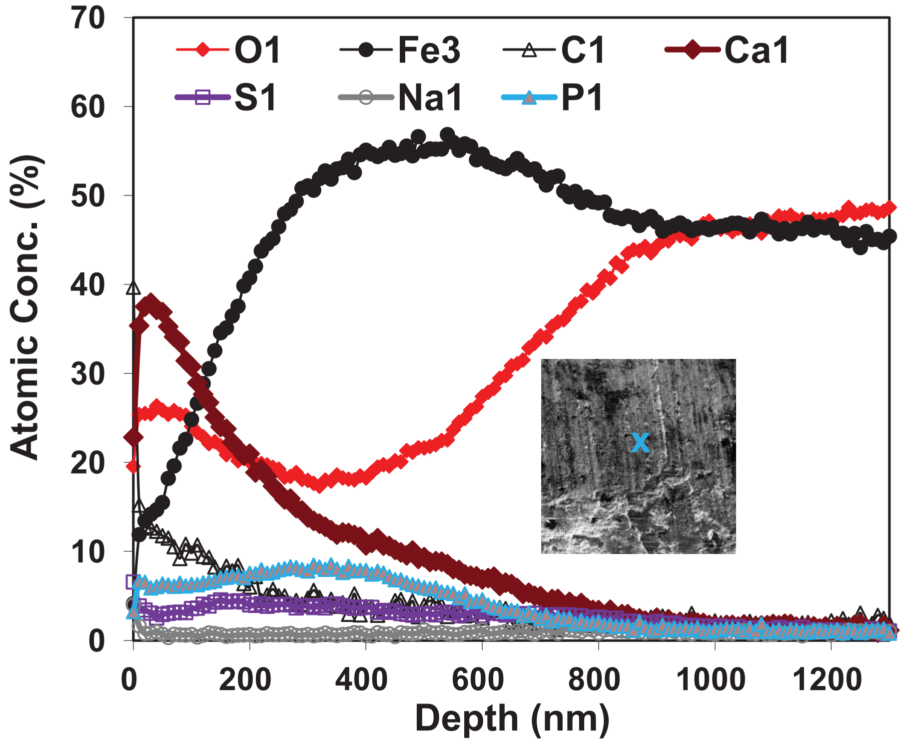
- **X-ray Photoemission Spectroscopy**
- **Tooth #2**
  - No carbide

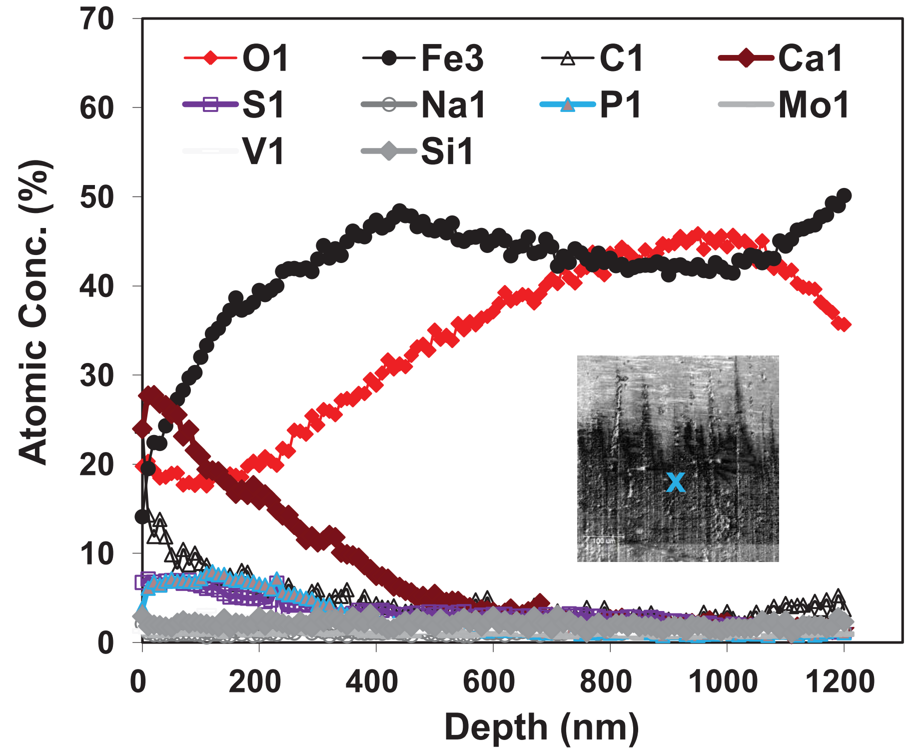


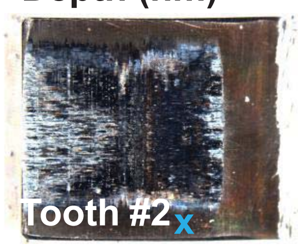


How deep does it go?

- **Scanning Auger Electron Spectroscopy Depth Profiling**
  - Edge outside of scuff

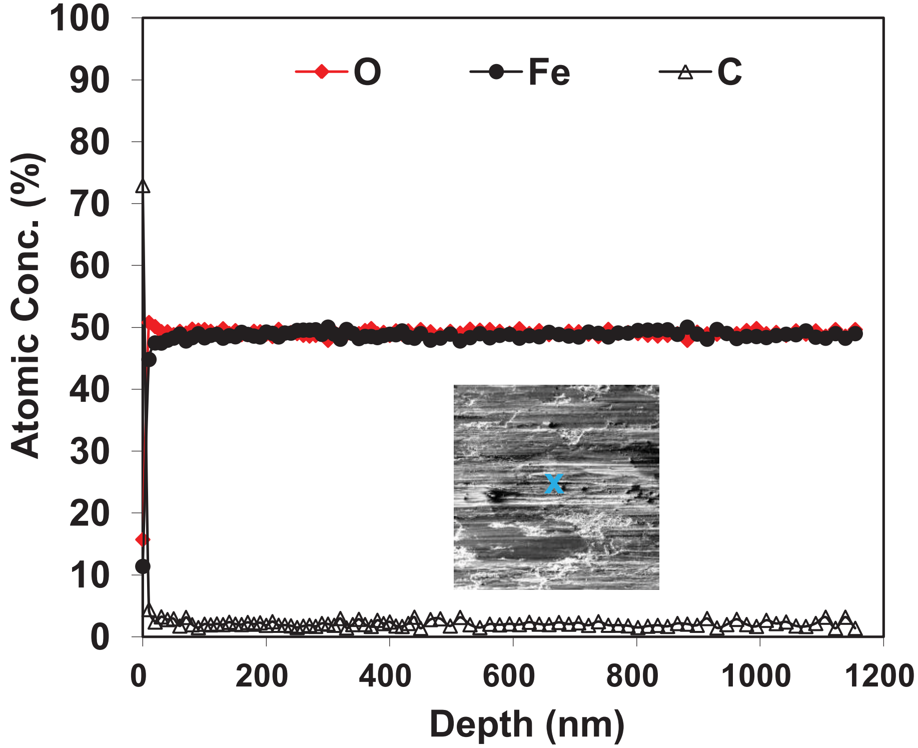


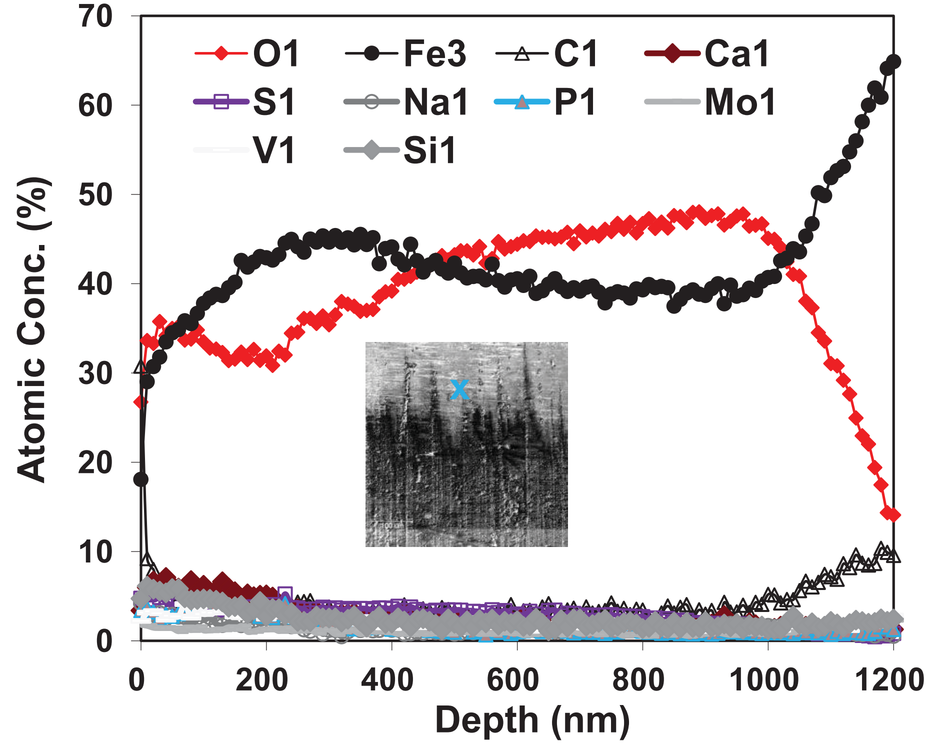




How deep does it go?

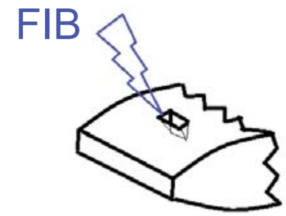
- Scanning Auger Electron Spectroscopy Depth Profiling
  - Central scuff



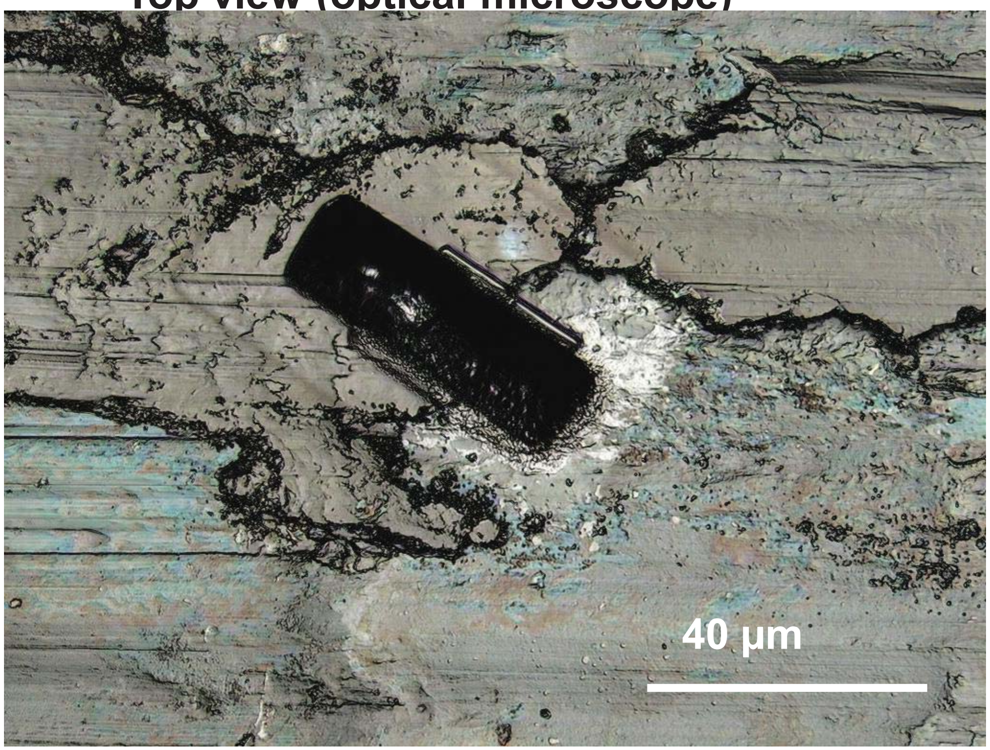


How much deeper?

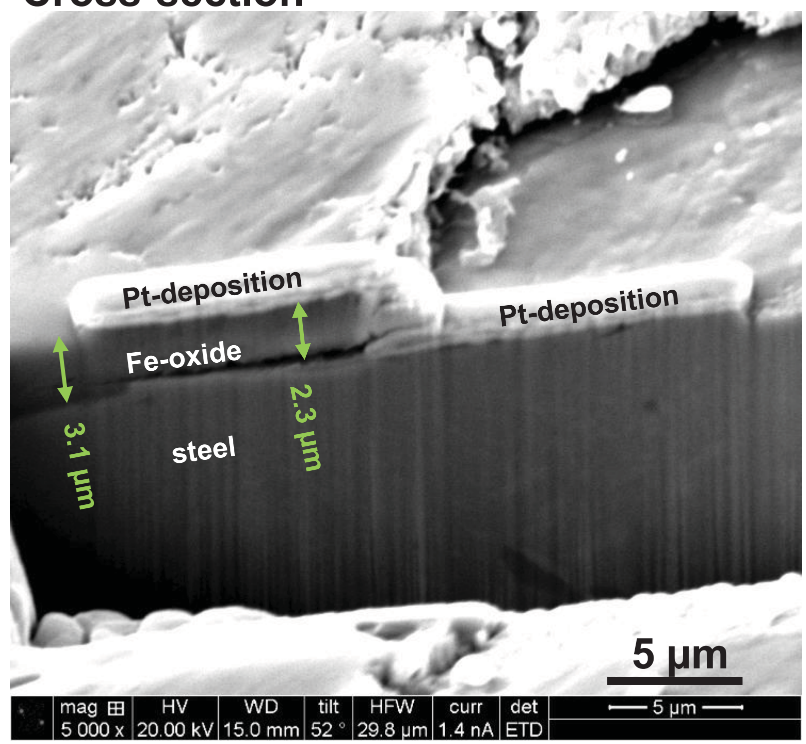
- Focused Ion Beam sectioning with SEM
- Tooth #2
- Oxide scale in scuff



Top view (optical microscope)



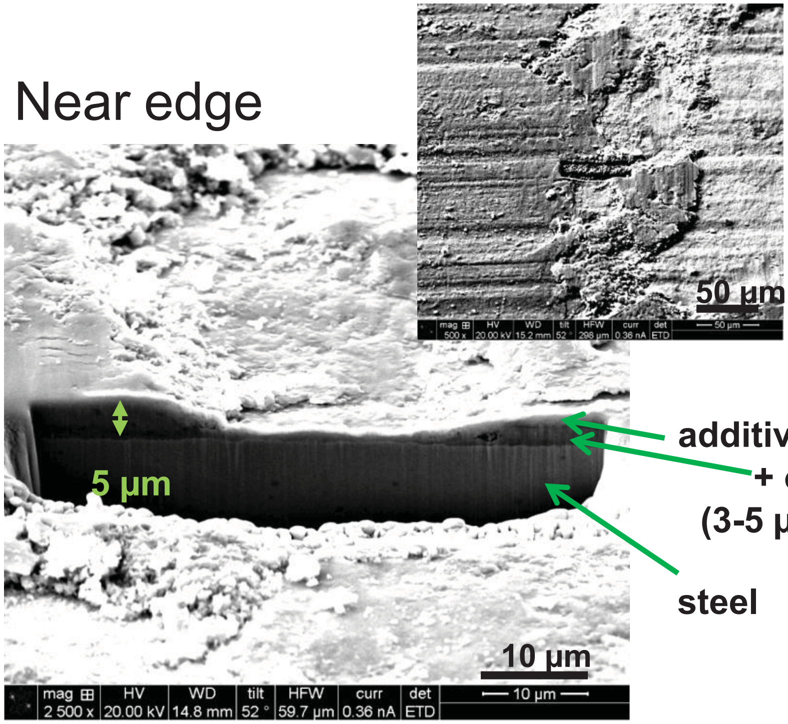
Cross-section



How much deeper?

- Focused Ion Beam sectioning with SEM
- Tooth #1

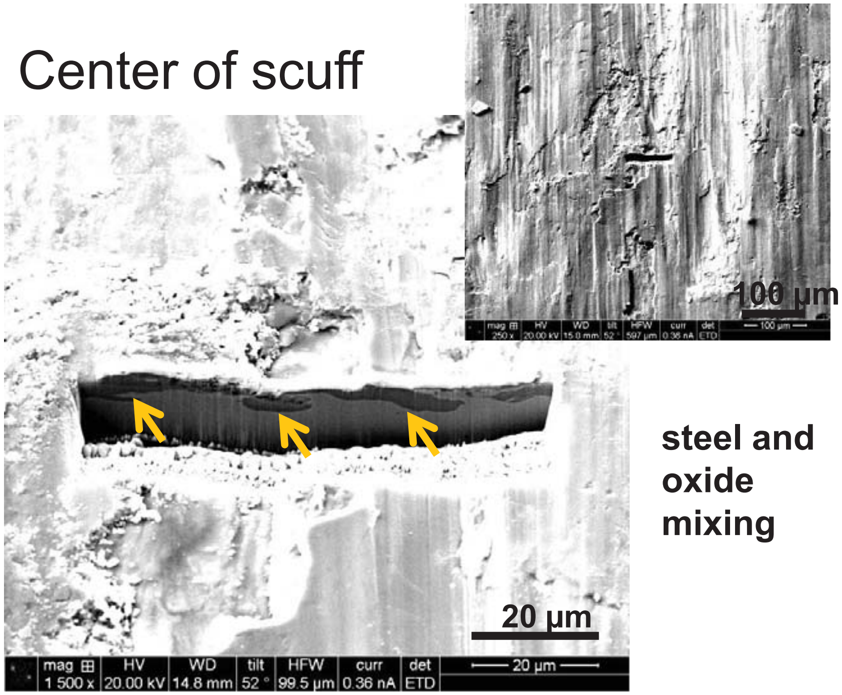
Near edge



additive species
+ oxide
(3-5 µm thick)

steel

Center of scuff



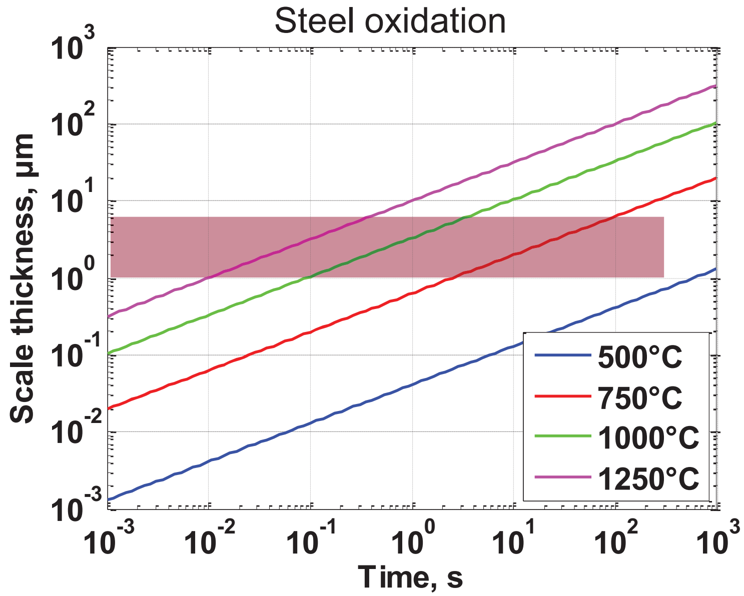
steel and
oxide
mixing

Outline

- NASA Spur Gear Test Rig
- Post-analysis of gear teeth
  - Geometry and Morphology (Optical microscope, Profilometry, SEM)
  - Chemical analysis (SEM/EDS, XPS, Raman)
  - Depth profiling (AES, FIB-SEM)
- **Conclusions**

What have we learned?

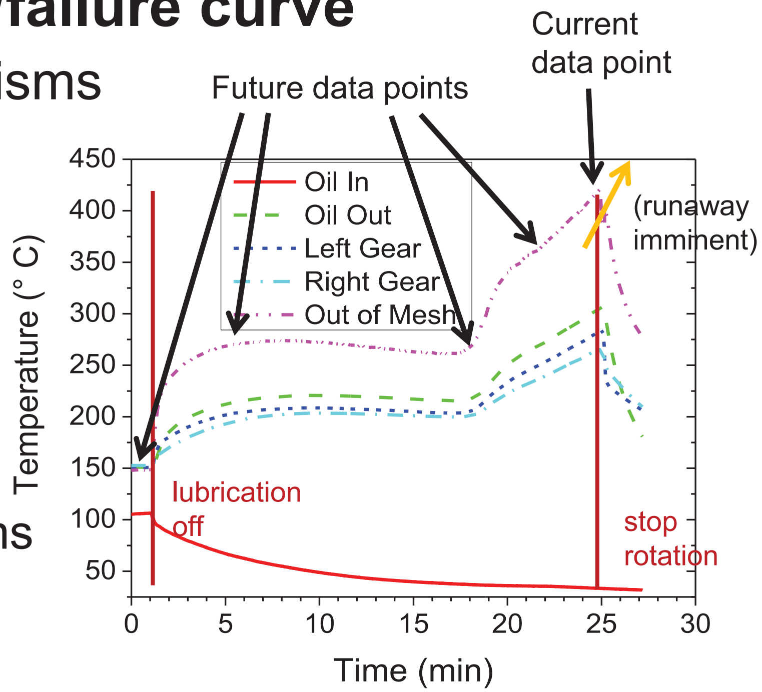
- **At this point during gear failure …**
  - Additive species diffuse into unscuffed surface
    - Not much Fe at surface
    - No oil left
    - Ca, (O, C), P, S, Na, up to 0.5 μm
    - Something in additives slows oxidation at elevated temperatures
    - Removed by scuffing
  - Oxide scales form within scuff
    - About 1 – 5 μm thick
    - Preferentially under high sliding
    - Some spall off
    - Some mix with the steel (plastic displacement)
    - Abrasion?



- **Oxidation and additive chemistry are actively affecting surface of steel during run away stage of gear failure**

Where do we go from here?

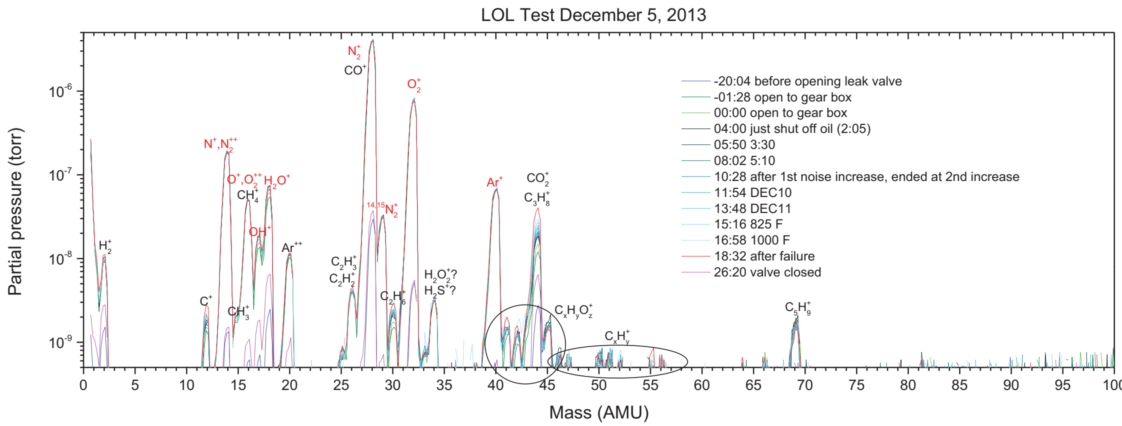
- **More points along the temperature/failure curve**
  - Fuller understanding of failure mechanisms
  - Identify first failure modes
  - Identify continuing failure modes
- **Start considering solutions**
  - Oxidation inhibitors
  - Additives
    - As main component in emergency systems
    - Subsurface reservoirs
  - What else?
- **Feed information into controlled tribological simulations**

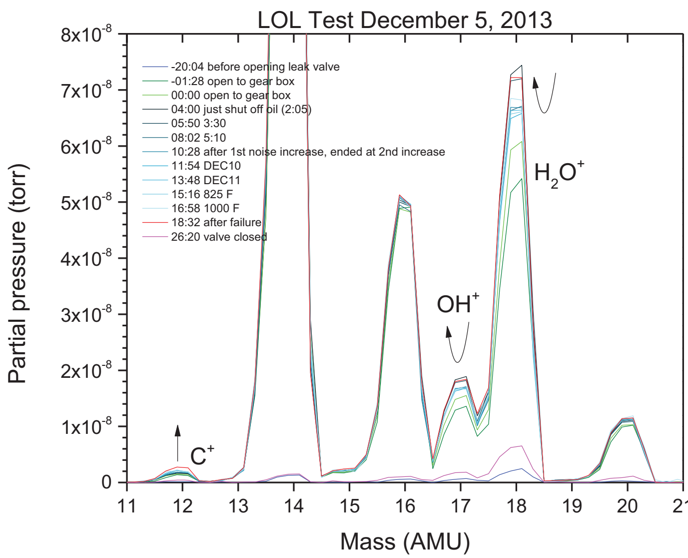


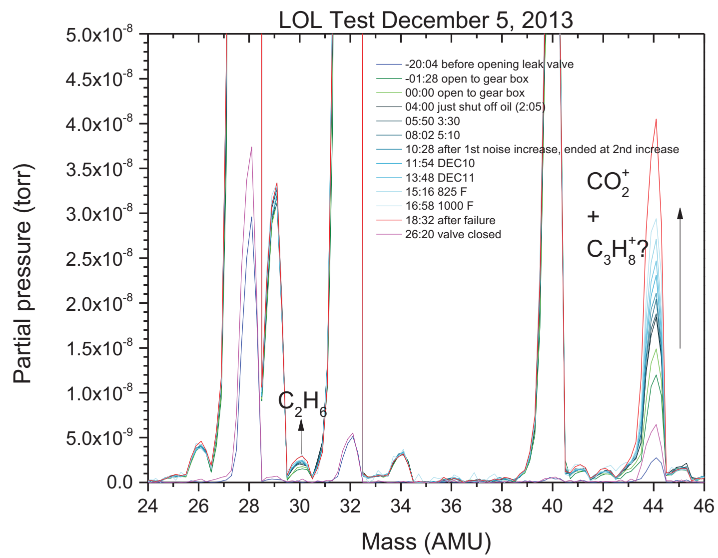
- **Support Material**

Exploration of gas evolution

Quadrupole Mass Spectrometer sampling gear box air







Exploration of gas evolution

- **Possibly interesting action is happening**
- **Needs better equipment**
  - Speed
  - Synchronization
  - Sensitivity
- **Issues with affecting tests**
- **Potential uses**
  - Detect looming failure
  - Insight into chemistry occuring