Tribology for Engineering Design

Designing for Lifetime Performance

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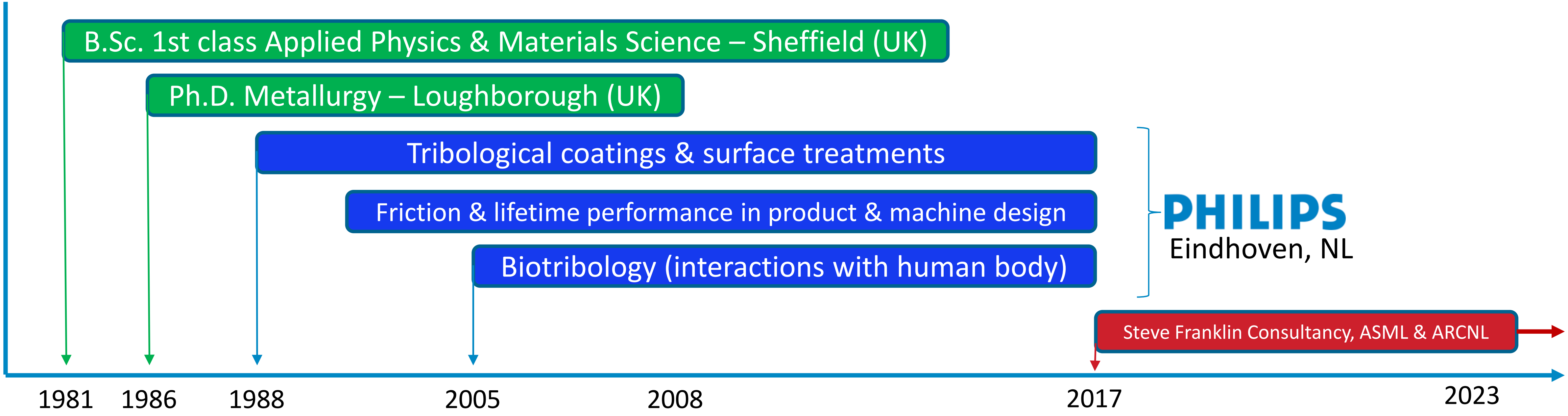
Content

- My background
- What is tribology?
- How to analyse a tribological case
- Case studies – focus on manufacturing examples

About me



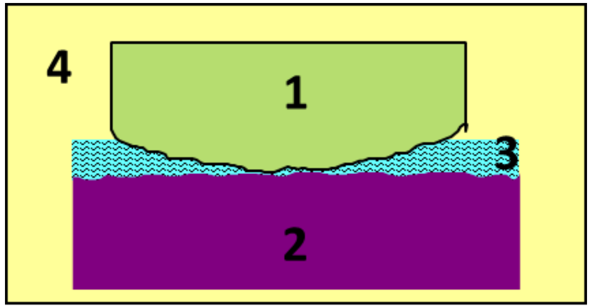
- Since 2017 as Steve Franklin Consultancy:
- 2017-2023: Group Leader Contact Dynamics at ARCNL (Dutch Research Institute)
  - Friction & wear behaviour in relation to ASML nanolithography machines
- Since 2008: Visiting Professor in Tribology at University of Sheffield (UK)
- Since 2023: Visiting Professor in Tribology at University of Amsterdam

What is tribology?

- Friction: tangential forces between moving surfaces
- Wear: loss or displacement of material on a surface
- Lubrication: means of affecting/controlling the above

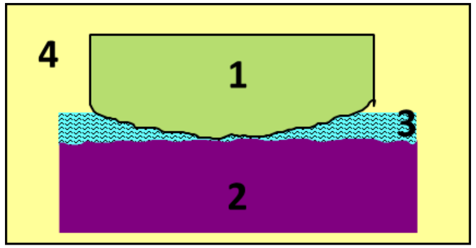
Friction and wear are *surface* phenomena

- Typically characterized by:
  - Friction coefficient μ: $$\mu = \frac{Friction\ force}{Normal\ force} = \frac{F_f}{F_n}$$
  - Specific wear rate K: $$K = \frac{Wear\ volume}{Normal\ force\ \cdot Sliding\ distance} = \frac{V}{F_n\ \cdot s}$$
- Not material properties
- Usually not constant over time
- Dependent on the local conditions
- Usually time-dependent



Tribological system

What can change the tribological system?



- **Lubricants can degrade:**
  - Evaporation, bleeding (greases), creep, contamination, reaction with plastics….
- **Wear particles:**
  - Often accumulate at the ends of motion in a sliding mechanism and affect the evolution of friction
- **Surface topography/roughness changes:**
  - Wear, tribo-chemical reaction, surface fatigue, etc.
  - Surface roughness decrease – often means decreased friction coefficient
  - But sometimes surfaces become very conforming $\rightarrow$ increase in friction coefficient
- **Surface composition can change:**
  - Material transfer, oxidation, corrosion, other chemical reaction, contamination, wear particles, dust…
- **Coatings can wear-off**
  - The underlying substrate is revealed
- **Environment changes (temperature, humidity)**
- **Operating conditions change, e.g**.
  - product management wants more performance for less money and e.g. increases speed or load
  - factory bosses want more productivity but less maintenance and e.g. increases maintenance intervals

Tribology is everywhere – part of everyday life

Tribology is essential to the functioning of all sorts of products and machine systems

Tribology is everywhere, including playing guitar!

BEAUJACKS

Beaujacks Rock

beaujacksrock

YouTube beaujacks

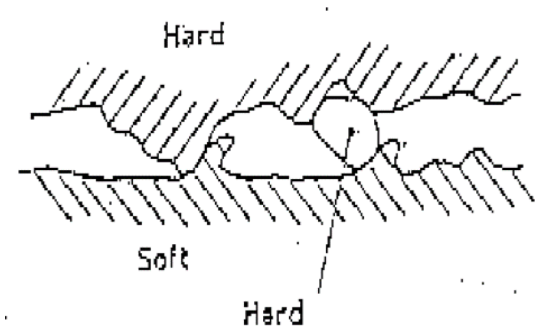
What is the impact of tribology?

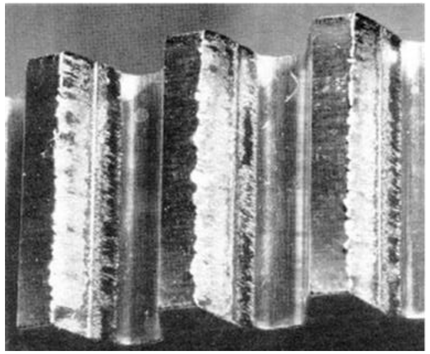
- Product function, e.g. shaving, contact lenses, plectrum ☺, etc. etc.
- Product reliability: consumer guarantee, company reputation
- Lifetime performance
- Equipment maintenance: downtime, maintenance & spare parts strategy, quality of manufactured products
- Energy use, costs and savings
- Manufacturing processes e.g. friction welding
- How products feel: tactile perception & comfort
- Safety & ergonomics: slip and grip
- Discomfort and trauma (e.g. devices in contact with the human body)

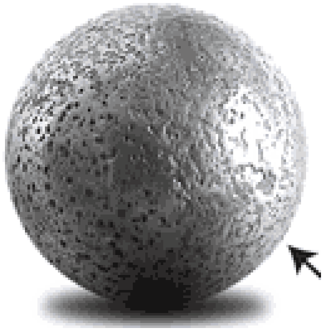
Tribology is everywhere

….but the basic principles and mechanisms remain the same

- **Friction** – tangential forces – arising from surface adhesion phenomena, abrasive ploughing, interlocking, non-perfect elastic behaviour, etc.
- **Wear** – loss or displacement of material – arising from adhesive transfer of material, abrasive ploughing, surface fatigue, (tribo-)chemical reaction, fretting, surface melting, etc.

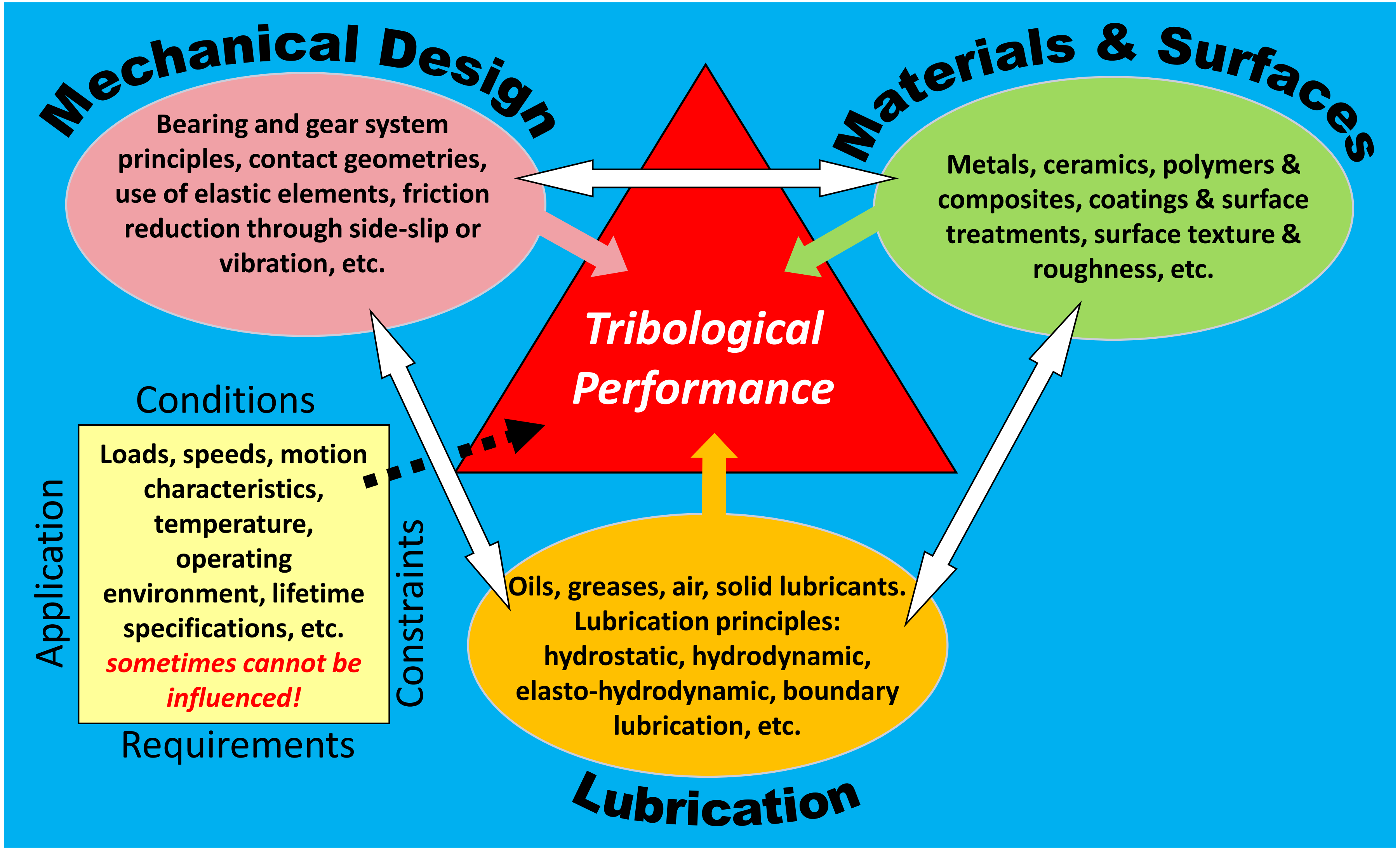




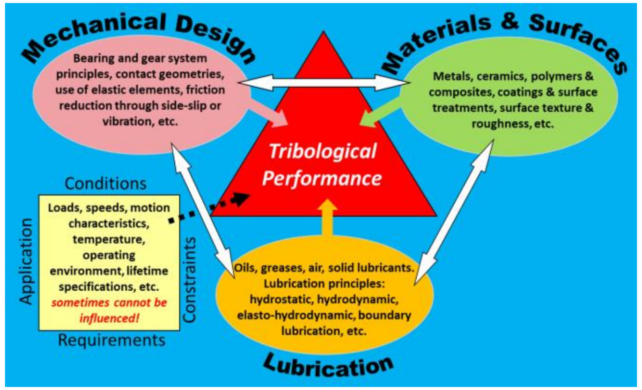


- Only the relative importances of these are different from case to case, and therefore the directions in which to seek solutions for improvement

Solution directions



General case analysis – tribological viewpoint 1



Functional & lifetime requirements

- What level of design is required?
  - Design from scratch
  - Design evolution based on a previous design
  - Troubleshooting a field failure

- What is the required function?
  - What does it need to do? What is important, what is not?
  - What are the main impacts if it goes wrong?
  - How is the required lifetime performance / reliability defined?
  - What limitations are there on friction and wear behaviour?

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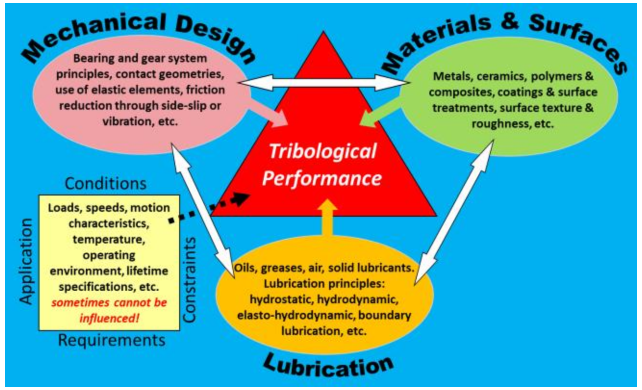
General case analysis – tribological viewpoint 2



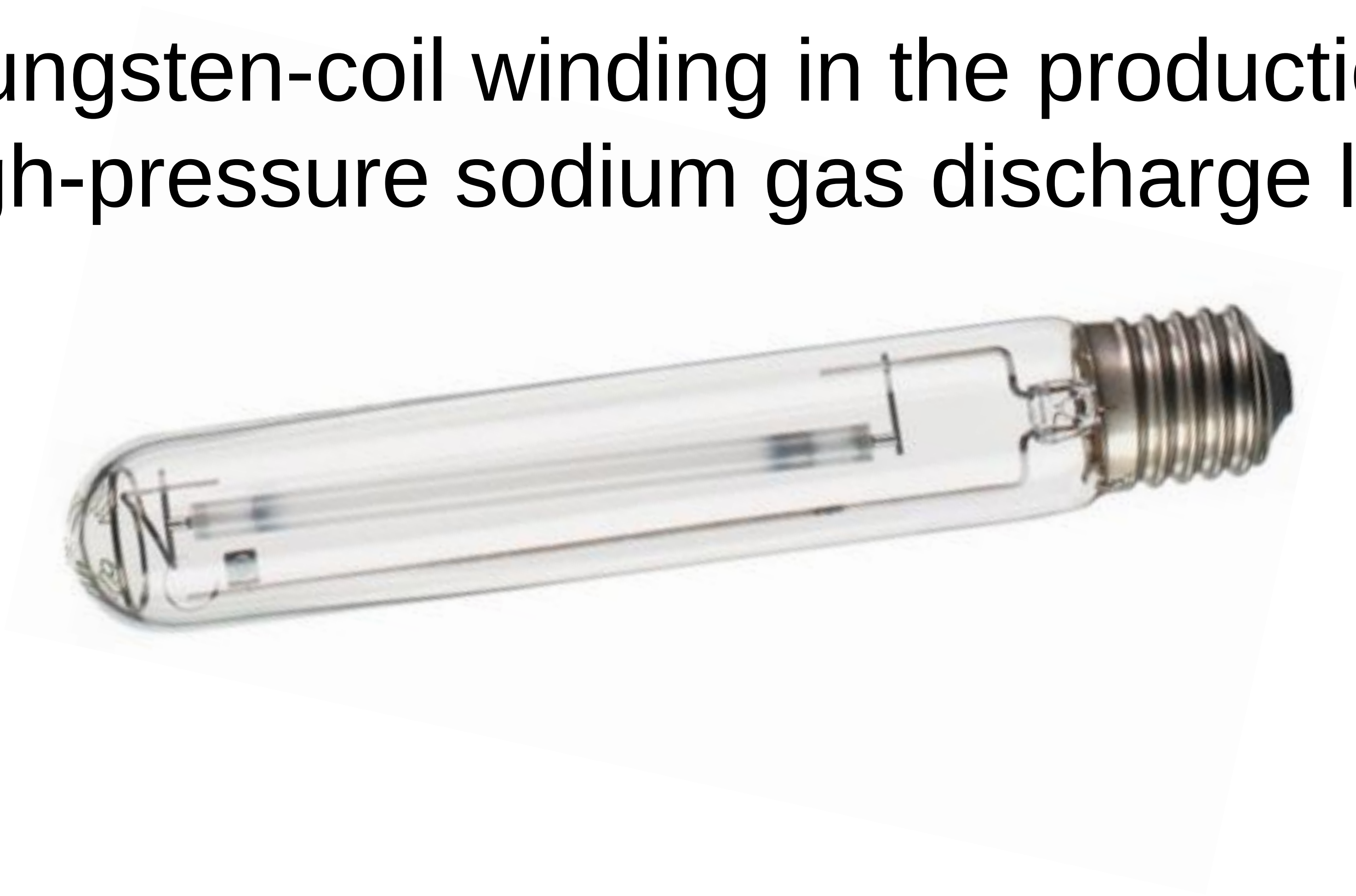
Derived information important for tribological behaviour

- Type of mechanical contact(s) – geometry?
- Type of motion – repeated or non-repeated in the same location?
- Loads, speeds?
- Exact materials and hardness?
- Surface roughness/topography?
- Environment – air/humidity/water/vacuum etc., temperature, particles, lubricants?

- Freedom for changes
  - Which of the above are <u>really</u> fixed and which could be modified if needed?

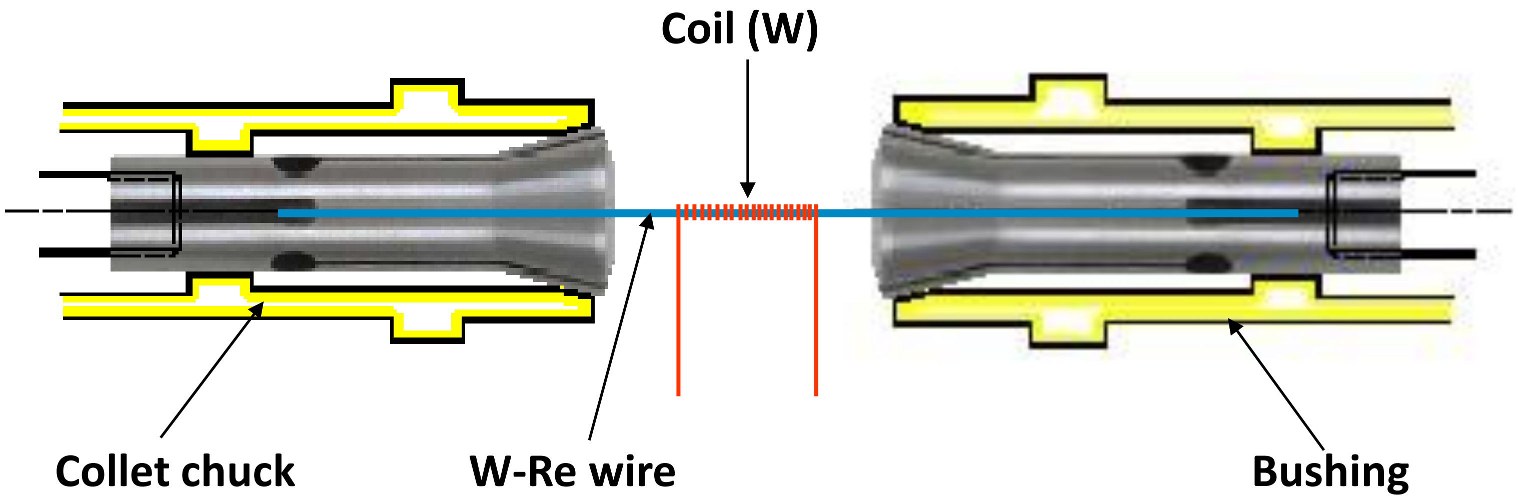
1. Troubleshooting case study

Tungsten-coil winding in the production of high-pressure sodium gas discharge lamps



Collet chuck (1/5)

- Production of high pressure sodium gas discharge lamps
  - Winding of W coil on Tungsten-Rhenium wire
  - W-Re wire is clamped in 2x collet chucks (supplied)
  - Current heats W-Re wire to ca. 2600°C for recrystallisation



Each chuck opens & closes 2x per 48s

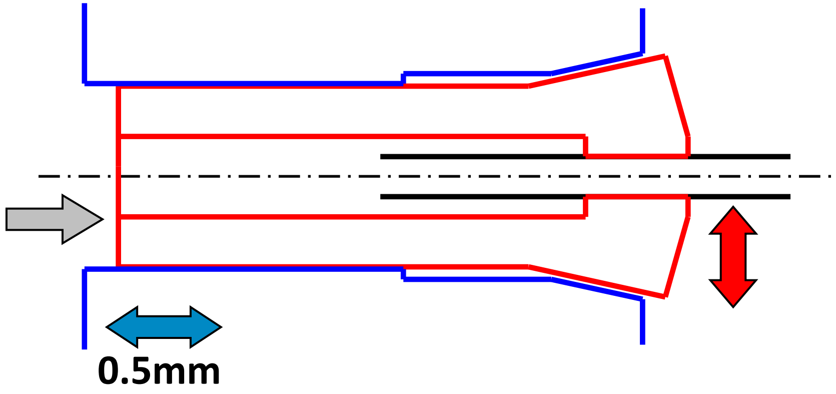
Collet chuck (2/5)

Problem: short lifetime through **seizure** in the bushing

- Lifetime per chuck < 1 week
- Replacement of seized collet chuck (3-6 x per day!)
- Repair by cleaning & polishing – repair time ca. 15 min.
- 24 collet chucks per machine, 20+ machines in use 24 hrs./day

Collet chuck – analysis (3/5)

- Relative motion ca. 0.5mm between collet chuck and bushing during opening & closing leads to adhesive wear & fretting
- Collet chuck - bushing clearance becomes smaller due to oxide debris, eventually leading to seizure



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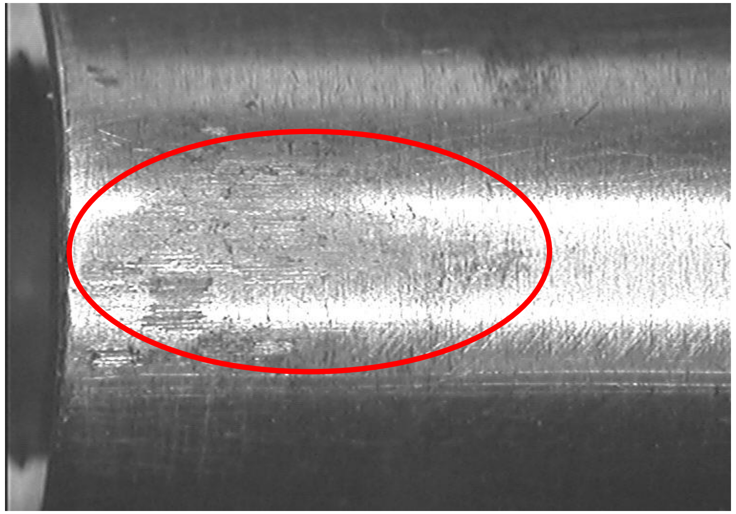
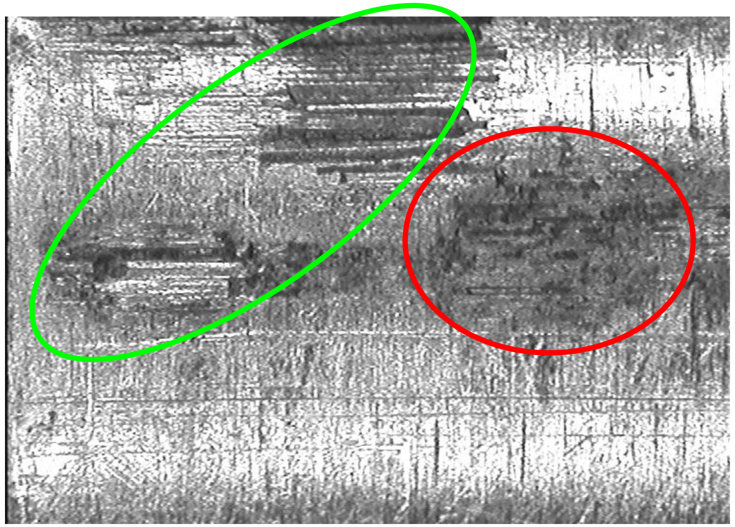
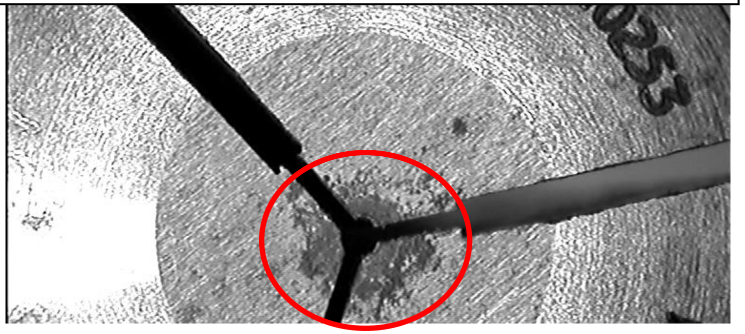
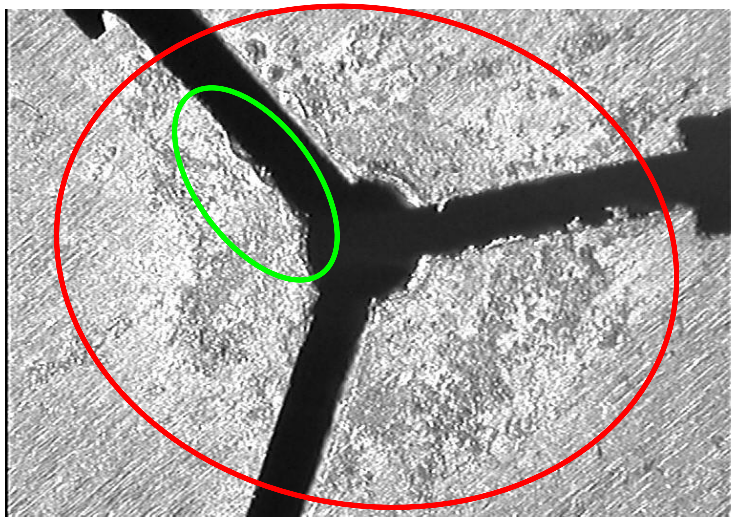
Collet chuck - analysis (4/5)





- fretting (red)
- *adhesive wear / other damage* (green)

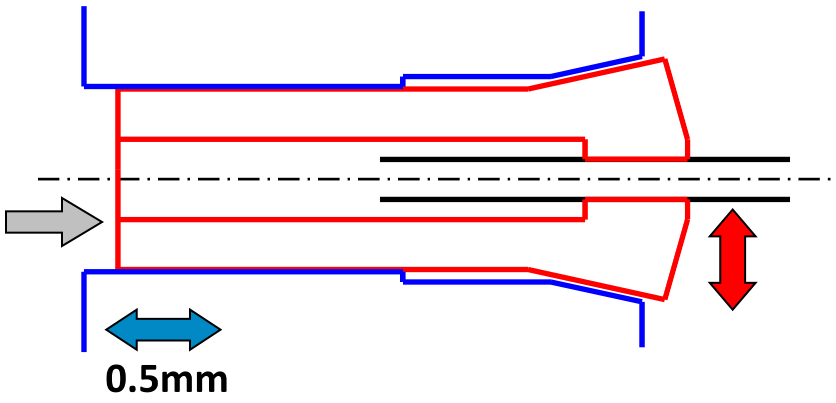




Collet chuck – solutions (5/5)

- *No options for basic material combination change or lubrication*

- Tolerance control - minimum clearance 5μm (was 2-15μm)
- Coatings on collet chucks:
  - DLC (a-C:H, 1800 HV)
  - MoS_2-based hard coating (1500 HV)



In-machine tests:
Lifetime was 1 week
8x collet chucks with increased clearance, 8x +MoS_2, 8x +DLC

Lifetime to seizure:

Clearance+ only:	**12 weeks**
+ MoS_2:	**24 weeks**
+ DLC: still running:	**32 weeks +**

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2. Design verification case study

Lifetime of seals of vacuum pipettes in a pick & place machine

Can the lifetime requirement be expected to be met in the design?

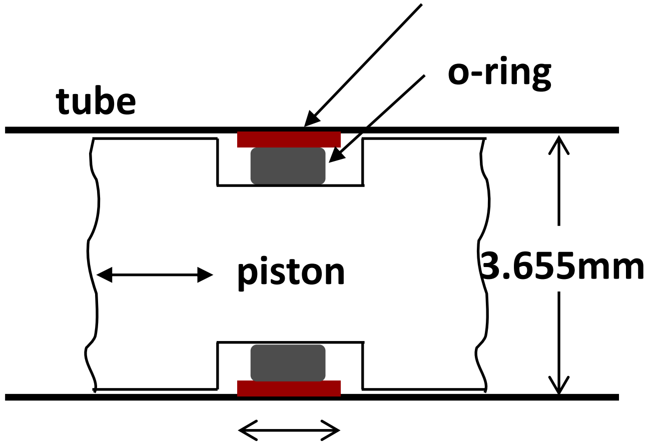
Lifetime of seals

Rulon = fibre reinforced PTFE composite

Rulon seal

Vacuum pipette for placing SMD electronic components on PCB's in a pick-and-place machine

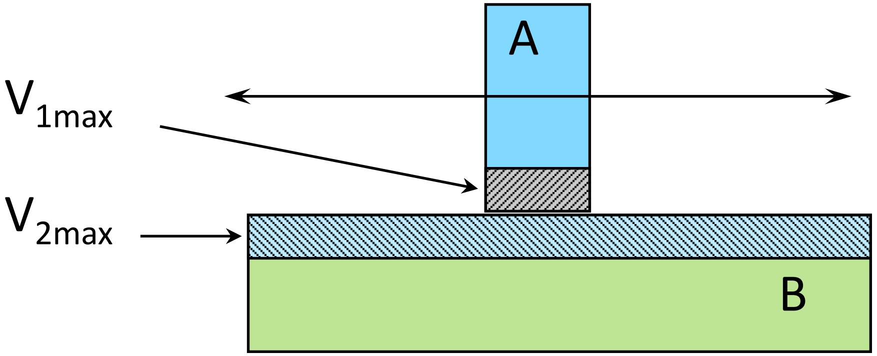
<u>Investigation of seal lifetime of vacuum pipette</u>



Sliding wear: the specific wear rate, K

- Also known as "Wear factor" or "K-factor"
  - $V = K*F_N*S$ K has units [m^3/N.m]
  - V = Volume of wear [m^3]
  - F_N = Normal force [N]
  - S = Total sliding distance [m] = v.t (v = sliding speed)
- In a design, the allowed wear volume V usually depends on the allowed wear *height* based on allowed clearances, tolerances, etc., and may be different for different surfaces

In this case, $V_{1max} < V_{2max}$:

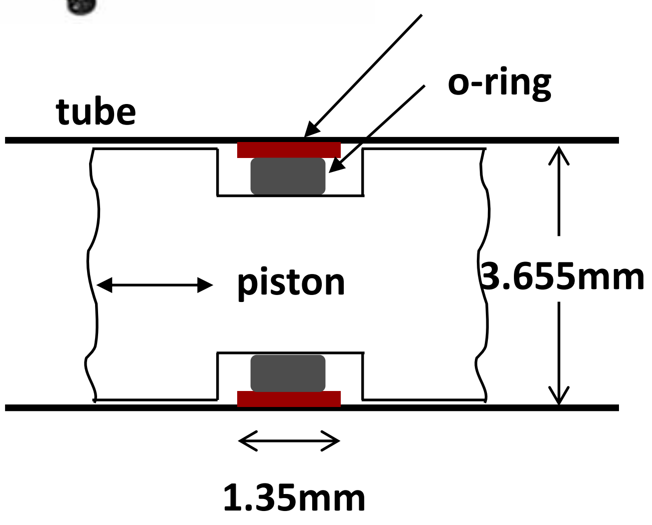


- K(allowed) is calculated for both surfaces A & B
- Compare with test data. K(*allowed*) should preferably be ≥ 10x K(*tested*)

Lifetime of seals

Investigation of seal lifetime of vacuum pipette

- Measured friction force Rulon/tube = 0.1 N
- Friction coefficient Rulon/tube = ca. 0.2
- Width of Rulon seal = 1.35 mm
- Seal makes contact over whole circumference
- Allowable wear of seal diameter = 10 µm
- **Required lifetime = 10^6 cycles**
- Stroke = 12 mm
- 1 cycle = 2x stroke
- *From lab tests,* K-factor Rulon against steel = 5×10^{-16} m^2/N



$$K = V / (F_N * s)$$

Can the lifetime requirement be expected to be met ?

Rulon = fibre reinforced PTFE composite

Seal lifetime calculation

V = expected wear volume

- $K_{allowed} < V / (F_N * s)$
  - $F_N \approx 0.1 / 0.2 = 0.5$ N
  - s = $10^6 \times 12 \times 10^{-3} \times 2 = 24000$ m

$$V = \left[\frac{\pi}{4}\cdot\left(\left(3.655\cdot 10^{-3}\right)^2 - \left(3.645\cdot 10^{-3}\right)^2\right)\right]\times 1.35\cdot 10^{-3} = 7.74\cdot 10^{-11}\ \mathrm{m}^3$$

- $K_{allowed} \approx 65 \times 10^{-16}$ m^2/N (c.f. expected 5×10^{-16})

- *Conclusion: the lifetime requirement is expected to be met with a safety factor ≈ 13*

3. Design case study

Selection of Coatings for Application in Wrist-Watch Mechanisms

Background and goal

- Mechanical wrist-watch mechanisms
- ≈100 lubrication points
- Difficult access, labour- intensive
- Lubricant degradation limits lifetime to ≈8 years

- Main question: do coatings have the potential to replace critical liquid lubrication points in selected watch mechanism components?

1. Paper study → preselection of 8-10 coatings
2. Laboratory evaluation experiments, sample level → 3-4 coatings
3. Laboratory evaluation experiments, component level → 1-2 coatings
4. System level: controlled experiments

Application performance priorities

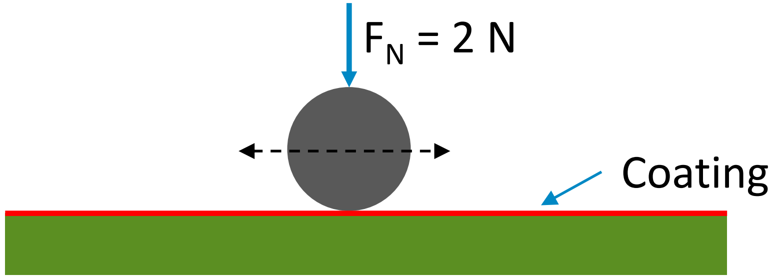
Most important performance considerations for the application:

1. Short run-in period to achieve stable friction behaviour
2. Stable friction behaviour after run-in
3. Low sensitivity of friction & wear behaviour to RH of environment
4. Low coating wear rate

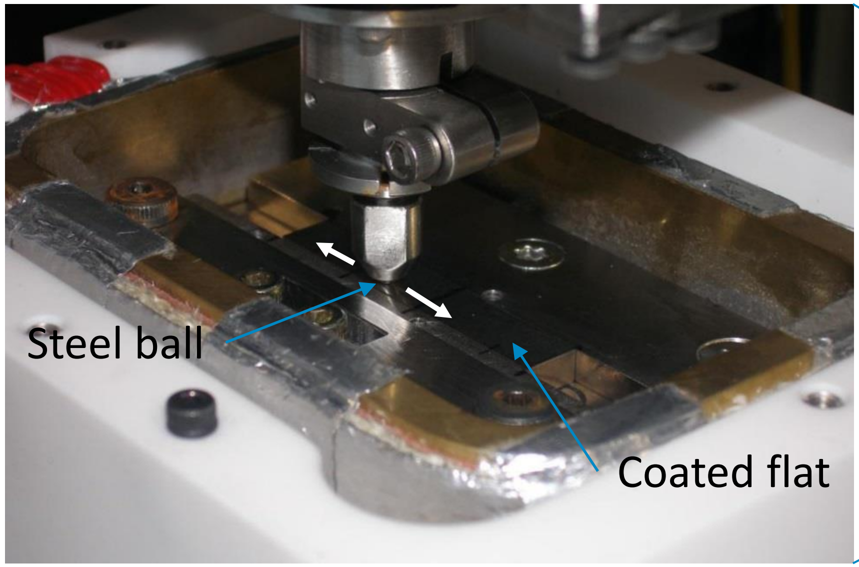
- Low average friction coefficient after run-in

Experiments

- Ball-on-flat reciprocating sliding tests, 8x coatings
- Uncoated steel ball 440C, diameter 4.5 mm
- Stroke = 10 mm
- Sliding speed = 10 mm/s
- Controlled humidity: 25°C, 30% and 70% RH
- Sliding distance 720m (= 20 hrs. test duration)
- 3x repeat tests
- Tests carried out in random order



Substrate: tool steel X160CrMoV 12-1 (1.2379), hardened HV700, polished R_a 0.05µm



Bruker UMT with humidity control

8x Coatings (preselected in paper-study)

Sample#	Coating	Thickness [µm]	Hardness [GPa]
*Ti-MoS2	15% Ti-doped MoS_2	1	15
*Cr a-C	20% Cr-doped a-C	2.5	12-16
ta-C	ta-C	2	40-100
a-C:H (1)	a-C:H (1)	2 - 2.5	12-15
a-C:H (2)	a-C:H (2)	3	25
a-C:H (3)	a-C:H (3)	3.5	45
a-C:H/a-Si:O	a-C:H/a-Si:O	2.5	18
a-WC:H	a-WC:H	3	10-20

Substrate: tool steel X160CrMoV 12-1 (1.2379), hardened HV700, polished R_a 0.05µm

**D.G. Teer, New Solid Lubricant Coatings, Wear 251 (2001) 1068–1074*

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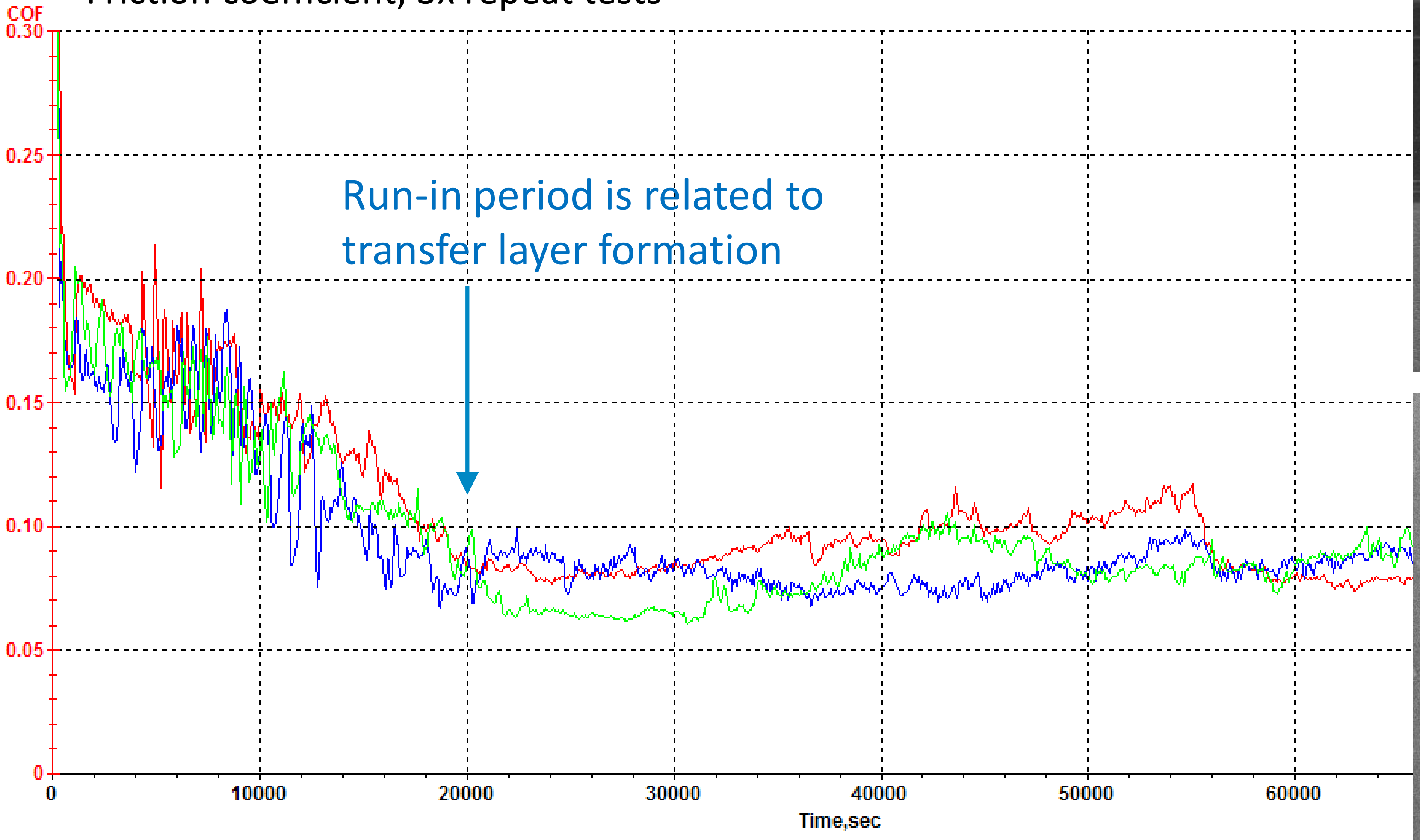
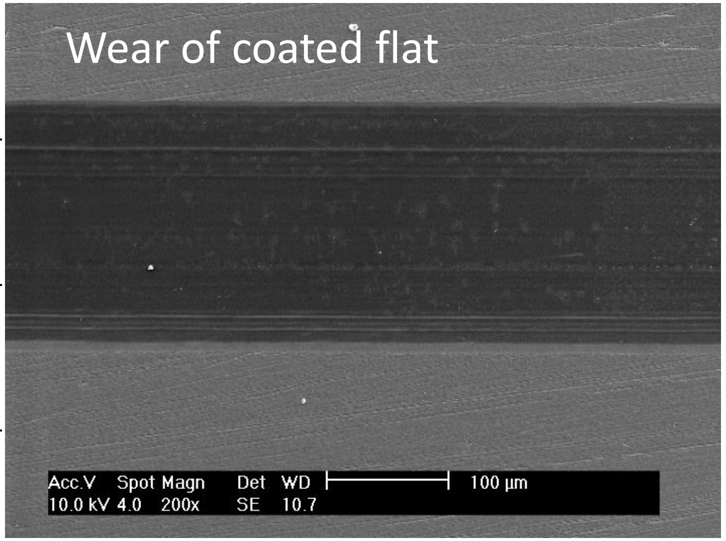
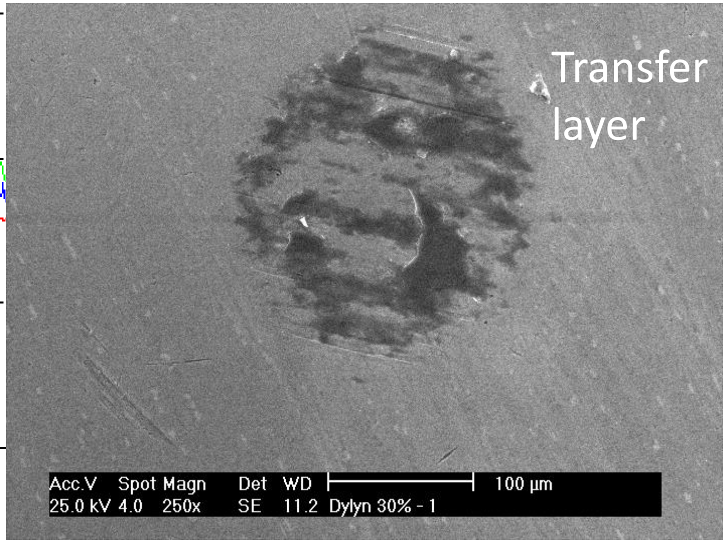
Results example: a-C:H/a-Si:O, 30% RH

Friction coefficient, 3x repeat tests







Steel ball

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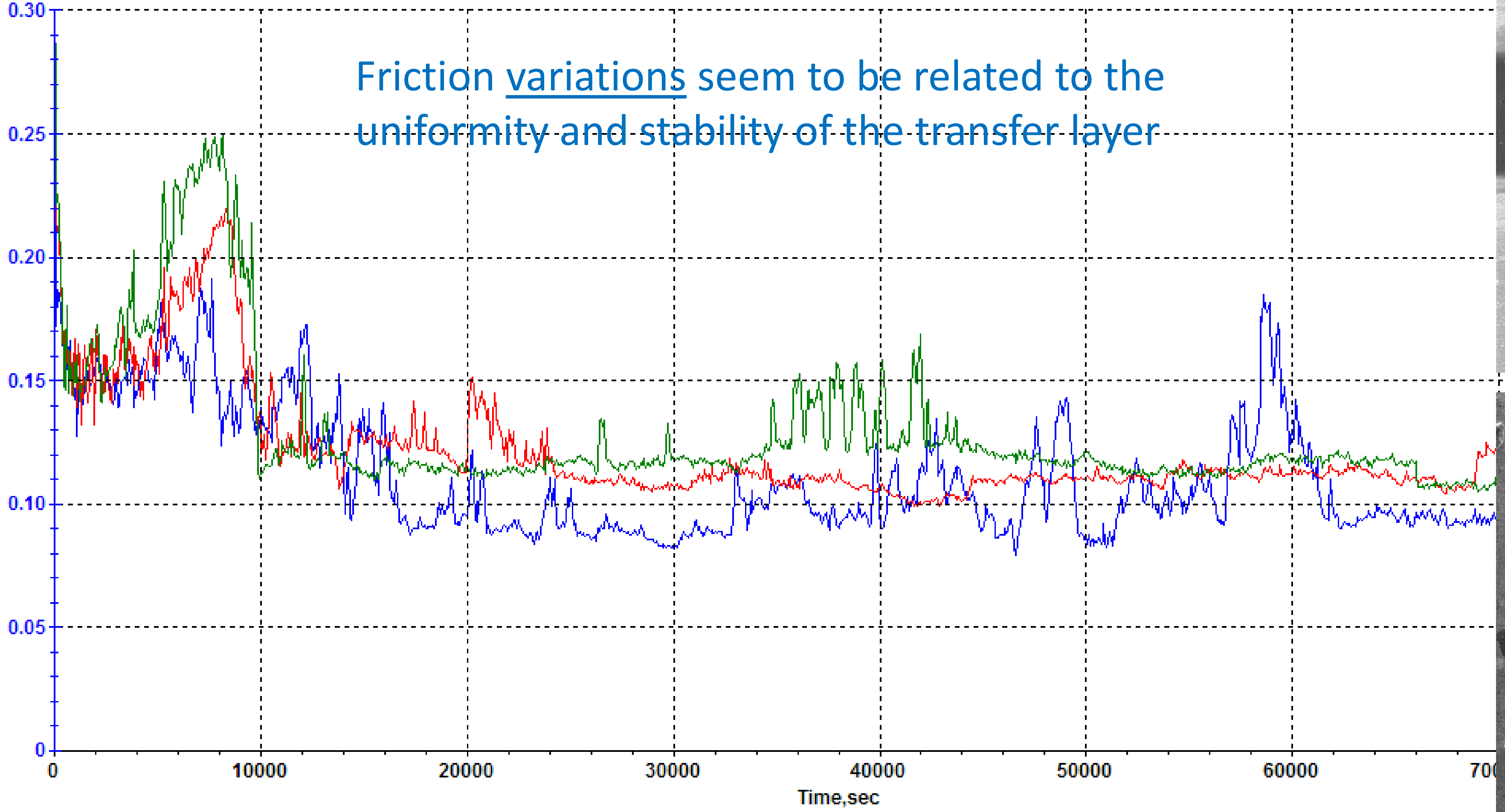
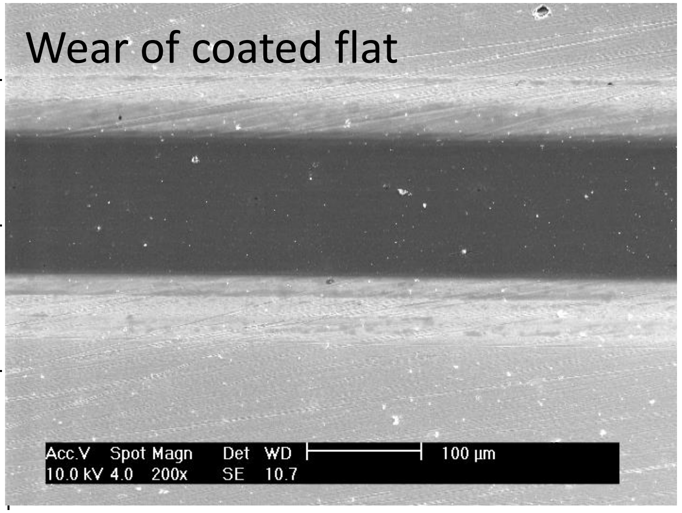
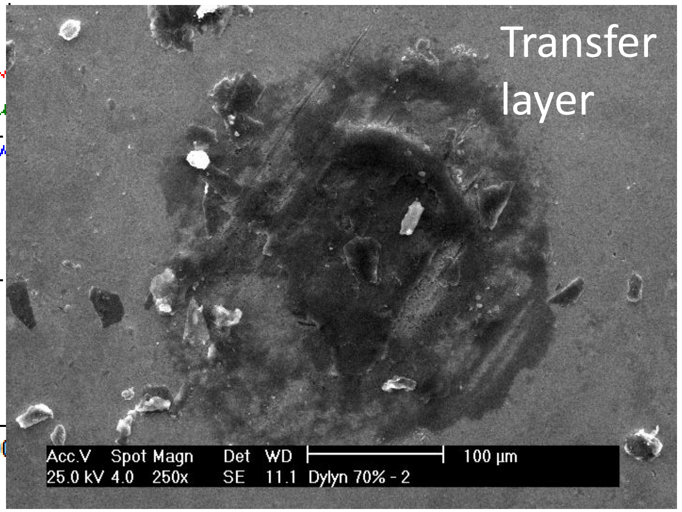
Results example: a-C:H/a-Si:O, 70% RH

Friction coefficient, 3x repeat tests



Friction variations seem to be related to the uniformity and stability of the transfer layer

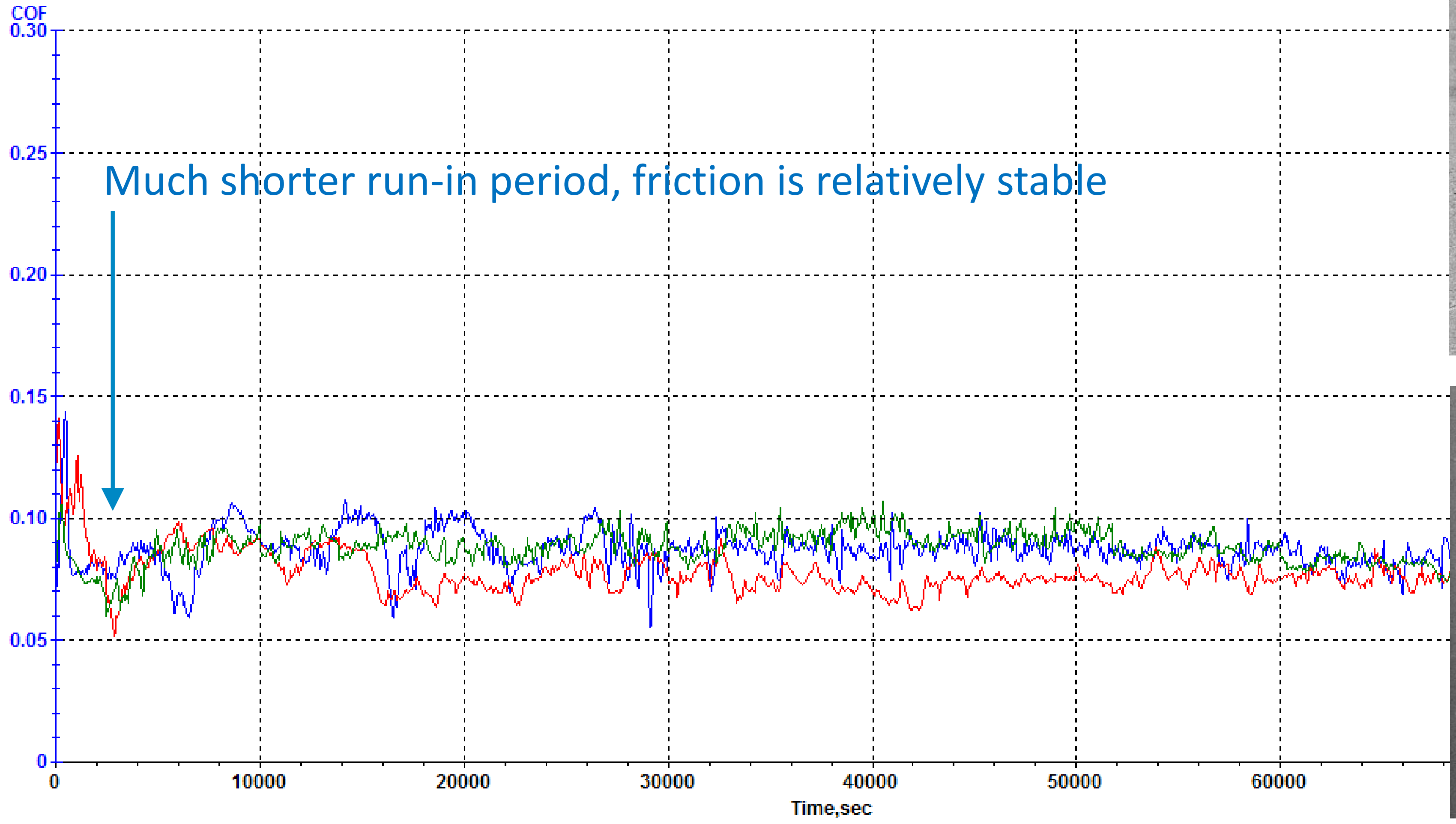


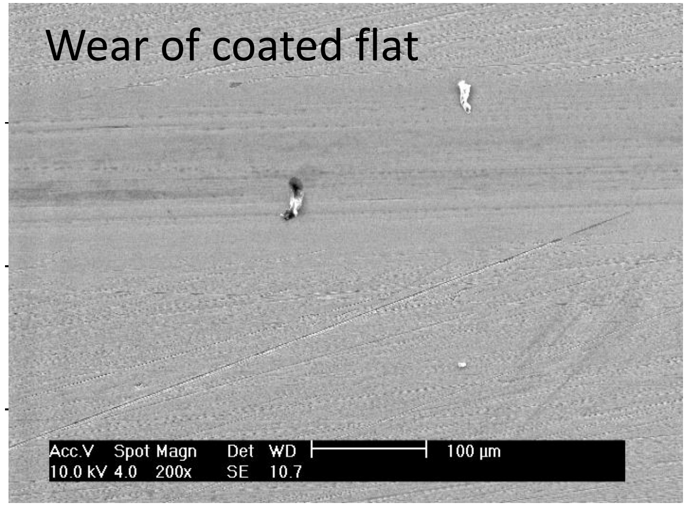


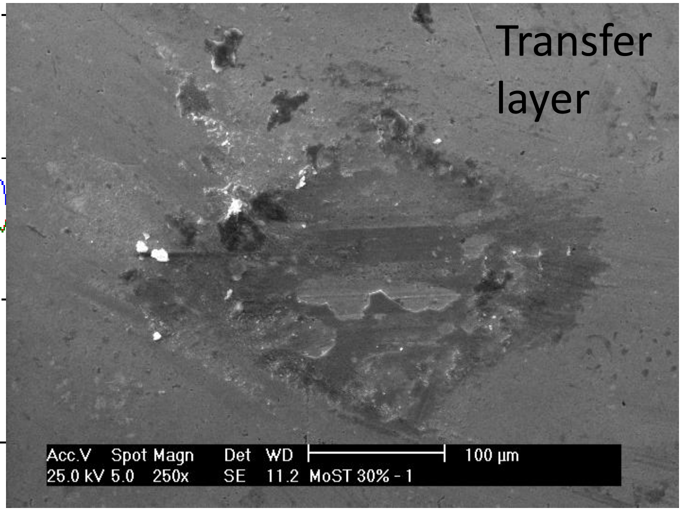
Steel ball

Results example: 15% Ti-doped MoS_2, 30% RH

Friction coefficient, 3x repeat tests







Steel ball

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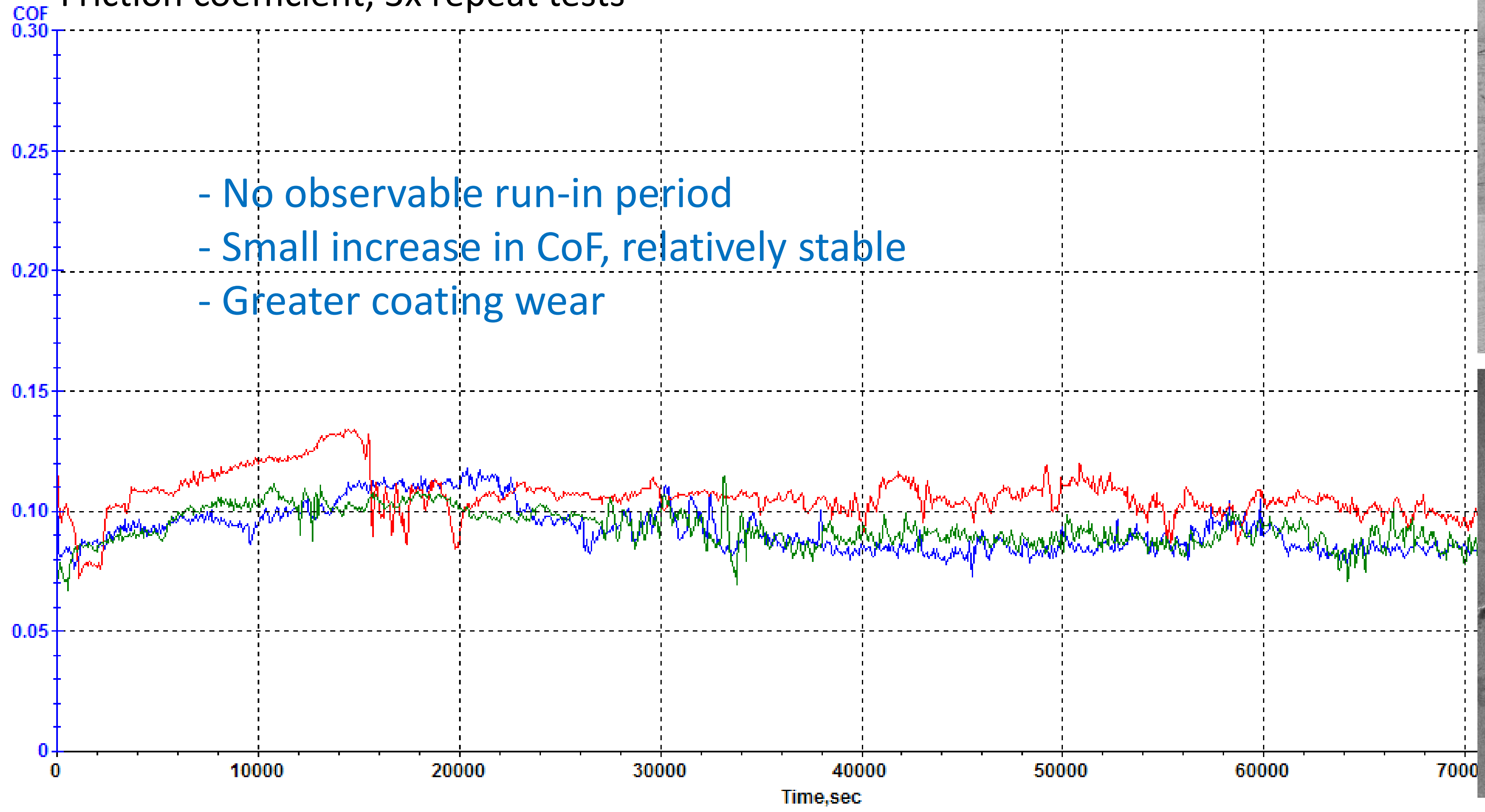
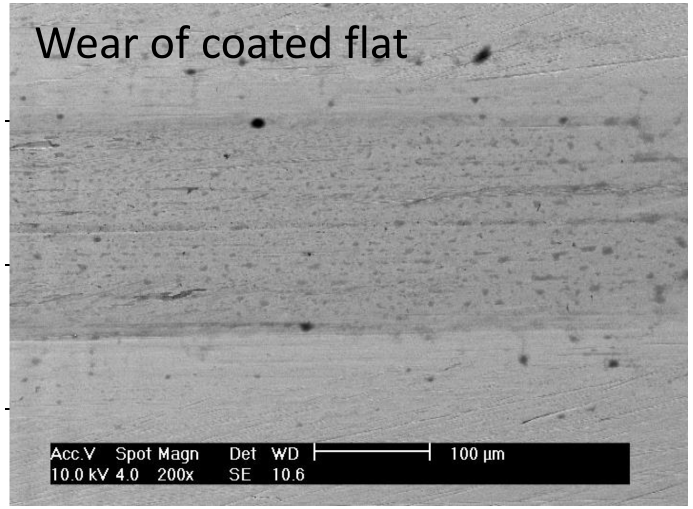
Results example: 15% Ti-doped MoS_2, 70% RH

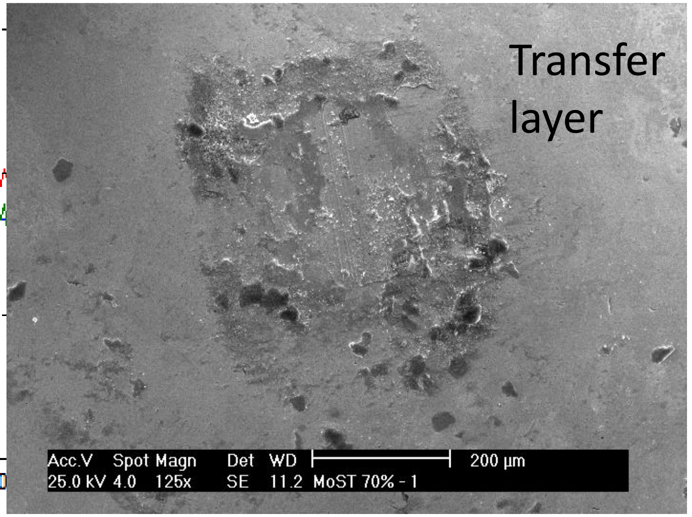
Friction coefficient, 3x repeat tests



Wear of coated flat



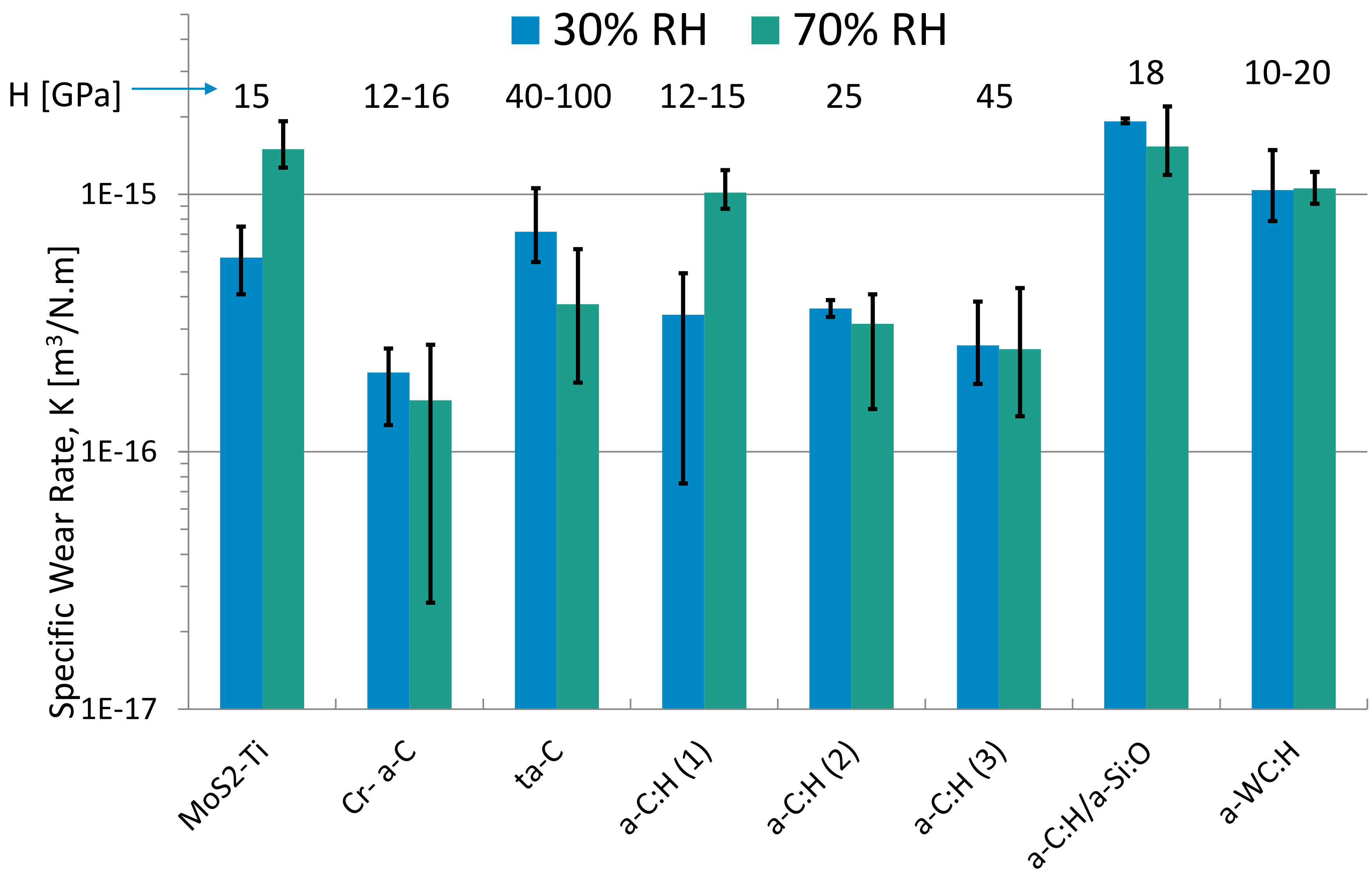
Transfer layer



Steel ball

Wear results summary

Wear rate does not correlate with hardness



Assessment

Main question:
Do coatings have the potential to replace critical liquid lubrication points in selected watch mechanism components?

Most important performance considerations for the application:

1. Run-in period (should be short)
2. Friction variations after run-in (should be low)
3. Sensitivity to RH of environment (should be low)
4. Coating wear rate (should be low)

- Average friction coefficient after run-in (should be low)

Assessment

BEST
MIDDLE
WORST

Relative assessment within category

Performance rating: 1 — 4 — 2 — 4 — 3

Performance criteria for application

Coating	Run-in distance [m]	Ave. COF, 30% RH [-]	Ave. COF, 70% RH [-]	Friction variation	Coating wear rate $*10^{-16}$ $[m^3/Nm]$, 30% RH	Coating wear rate $*10^{-16}$ $[m^3/Nm]$, 70% RH	COF sensitivity to RH	Wear sensitivity to RH
⇨ Ti-MoS2	< 10	0.07 - 0.09	0.08 - 0.11	BEST	5.7	15.0	BEST	WORST
⇨ Cr a-C	100	0.05 - 0.08	0.07 - 0.09	MIDDLE	2.0	1.6	BEST	BEST
ta-C	100	0.07 - 0.14	0.11 - 0.14	WORST	7.2	3.7	MIDDLE	MIDDLE
a-C:H (1)	< 20	0.1 - 0.2	0.15 - 0.3	MIDDLE	3.4	10.2	WORST	WORST
⇨ a-C:H (2)	< 10	0.11 - 0.15	0.1 - 0.13	MIDDLE	3.6	3.1	BEST	BEST
⇨ a-C:H (3)	< 10	0.1 - 0.15	0.1 - 0.17	MIDDLE	2.6	2.5	BEST	BEST
a-C:H/a-Si:O	200	0.07 - 0.11	0.09 - 0.13	MIDDLE	19.2	15.3	MIDDLE	MIDDLE
a-WC:H	100	0.09 - 0.17	0.15 - 0.21	WORST	10.4	10.6	WORST	BEST

⇨ Selected for next stage = component-level evaluation

Questions?

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Expertise in Tribology & Materials Technology

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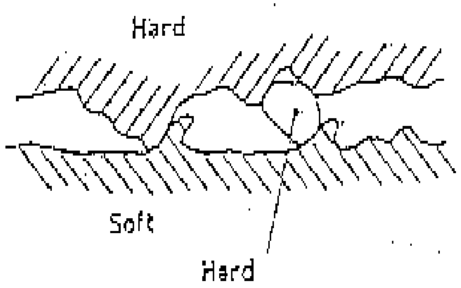
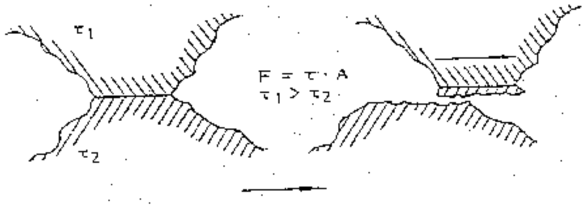
(Wear = loss of material from the surface)

Wear mechanisms

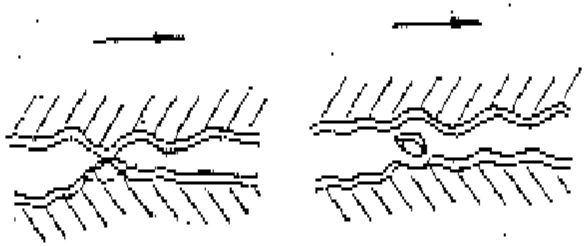
- Surface melting (polymers)
  - *$(p.v)_{MAX}$ exceeded*
- Abrasive wear
  - *micro-cutting / ploughing*



- Adhesive wear / material transfer
  - *cold-welding, then shearing of weak points*



- Surface fatigue
  - *repeated surface stressing -> cracks -> wear particles (pitting) or worse*



- Fretting (chemical wear)
  - *low amplitude oscillation, trapping & oxidation of wear debris -> wear acceleration*

- Erosion – *fluids & gasses, often with particles*