Practical Design, Reliability and Service Life Predictions of Tribological Contacts

in Drive Systems of a Medium-Lubricated Pump, a self-sharpening Blade and a Toothbrush.

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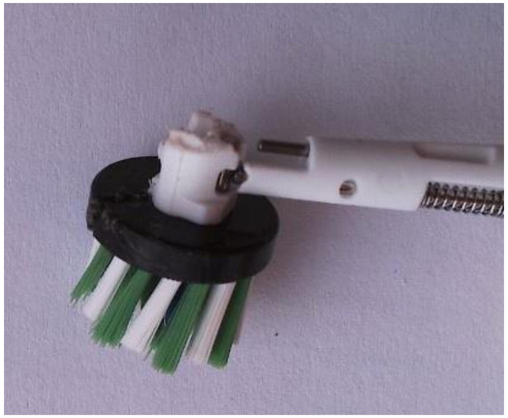
Design, Reliability and Service Life Predictions

- Challenges in product development
- Practical oriented 3 steps to decide for a reliable design
- Results in 3 design examples
  - Pump drives, Diesel fuel lubricated
    wear-mechanism: **fatigue**
  - Control of abrasive **wear**
    => protection and self-sharpening
  - Sliding **wear** in gear drives,
    tooth flanks

Pump

Self-Sharpening agriculture blade



Tooth-brush drive

Challenges in Product Development

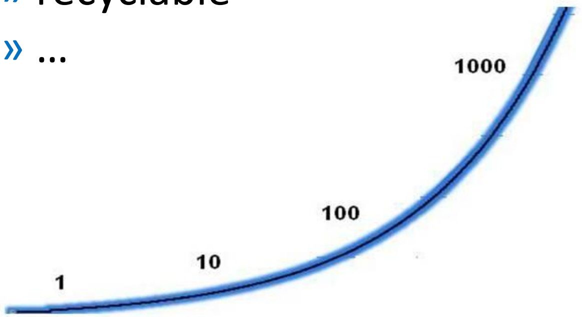
- “Design to …”
  vs. costs, milestones and timeline targets, delivery-dates

- Avoid failures
  do it right the first time, prevent use of non robust designs, late changes or even failures (cost rule of 10^{th})

- **decision making**, choose robust design and material selection in early state

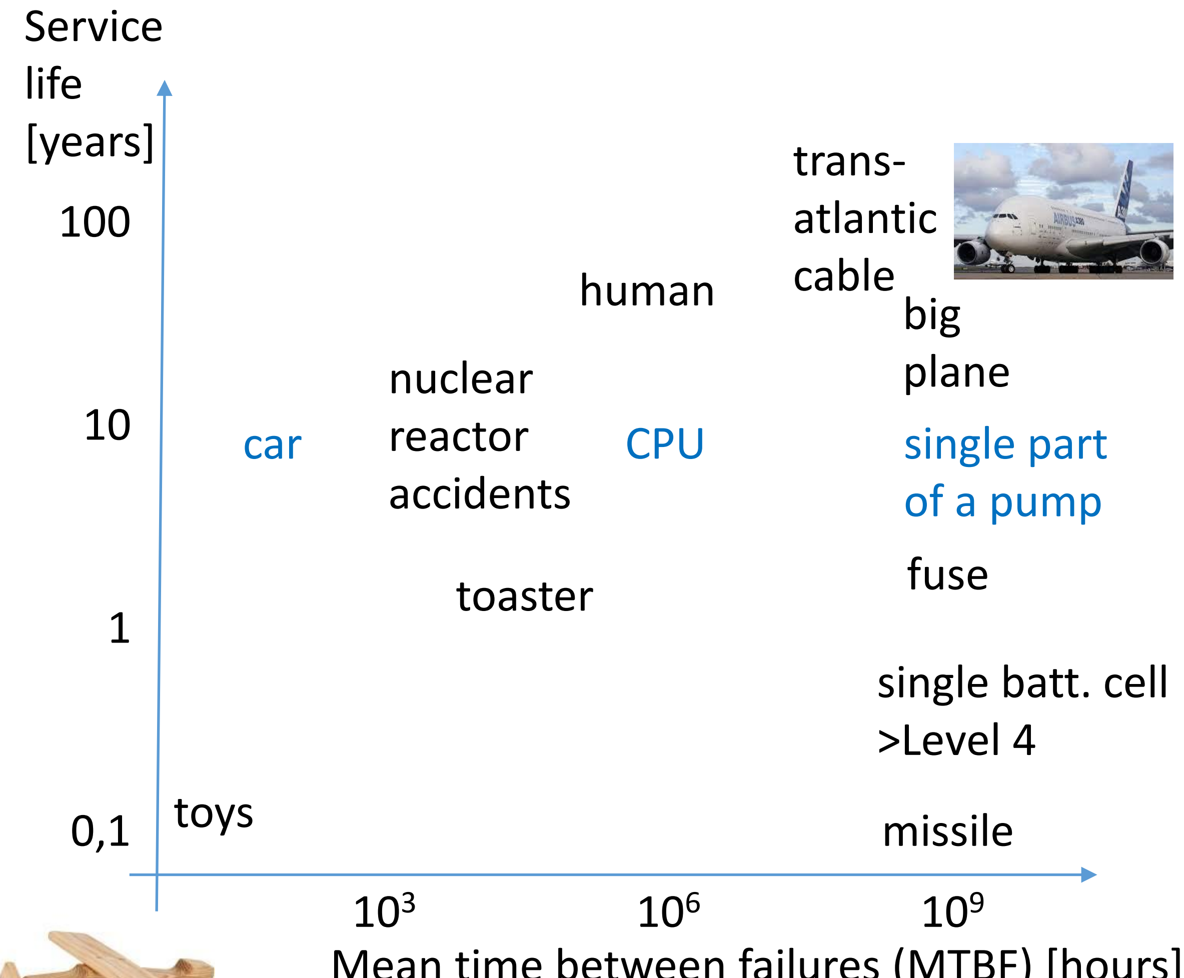
- investigation, description of all microscopic details still ongoing e.g. mixed friction
  => awareness of tribological complexity
  => **focus** on the correct reproduction of the behavior

- clear, smart, safe
- customer-oriented, market-oriented
- functional and appropriate
- suitable for demands
- strength-based
- material-appropriate
- manufacturable
- easy to assemble,, safe (poka yoke)
- testable
- ergonomic
- diagnose-, network-compatible
- recyclable
- …

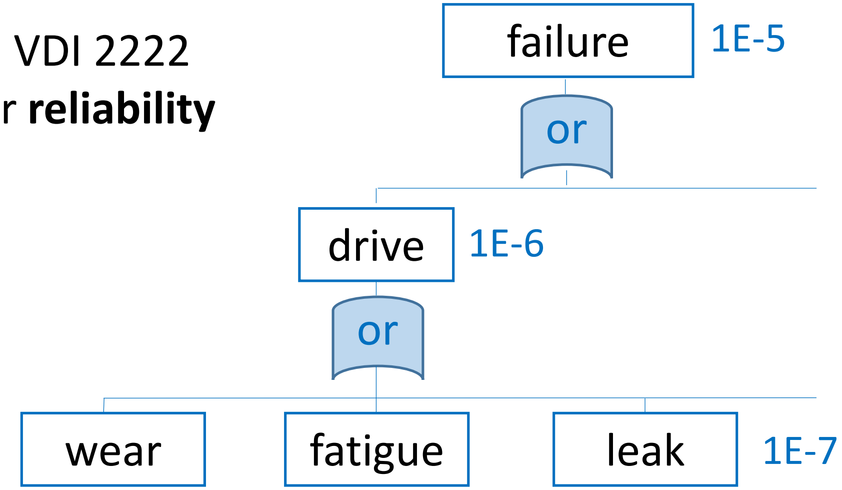


Challenges in Product Development

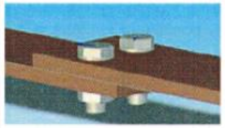
» Reach service lifetime (sustainability, CO_2) at required failure rate



Challenges in Product Development



- In established development processes e.g. VDI 2222 Reliability is not considered at all. However **reliability estimation** helps a lot in decision making.
- Design for Reliability
  Top down: Reliability goals based on Safety Integration Level SIL/ASIL/DAL
- Bottom up, for components and connections to compare different solutions and reach system reliability target

Connection method / Requirements	Bolt connection	Crimp connection	Solder	Weld connection
				
General				
disconnectable/detachable/ service-able/remountable	Y	N	N	N
Certification/release (automotive/aviation certification reasonable)	Y	Y	Y	Y
Reliability rating [IEC1709], [MIL-HDBK-217] [failures in E-9 hours]	0,5	0,26	0,069	0,05

Design, Reliability and Service Life Prediction Steps

1. Address + verify Requirements and Functions.
   Enables calc./simulation driven development,
   Analysis of **influencing** factors => robust Design

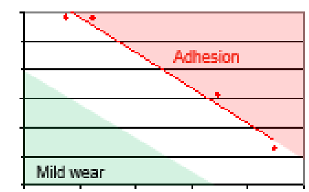
Parameters
dimensions
loads

f(x, y)

Service time, reliab.
safety factors
weight, costs

robustness optimize

2. Identify failure/Wear **Mechanism**
   e.g. wear maps and limits in parallel accelerated tests/tribometer
   avoid wear mechanism if possible (robustness, optimization)
   => **focus** on the main service time limiting mechanism

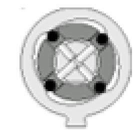


wear map

3. Evaluate resulting stress caused by loads
   vs. strength/resistance (material test)

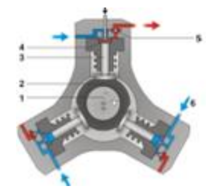
» Estimate **Reliability and Service time.**
  Verify and quality assurance with **Data** from products in production-accompanying testing and field (digital twins)
» Enable a methodical comparison of different **Design** solutions!

1. Drive Design Variants and Tribo-Contact Matrix

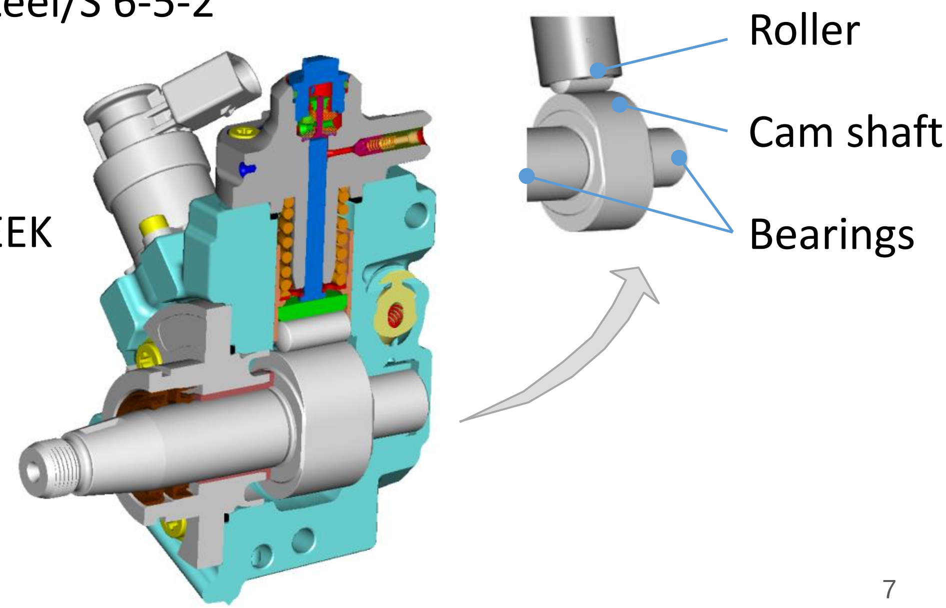


Design Variants comparison

- complex fuel distributing system in space limited center shaft => wear, cavitation
- vs. oscillating/reverse sliding contact => high quality surfaces
- vs. **Cam-Roller Drive** (dynamic motion, less and simpler parts)



Component 1	Component 2	medium diesel fuel
Cam AISI 52100	roller high speed steel/S 6-5-2	
Roller S 6-5	journal bearing	
Cam AISI 52100	journal bearings PEEK	



1. Design of high pressure pumps: Challenges

» Automotive: Development of high pressure pump for 2000 bar+

\+ **pump drive changed from reverse sliding to Cam-Roller contact**,
which enables more robust design, low friction, high energy efficiency

\+ complete pump only lubricated with **medium Diesel fuel**
therefore more environmental friendly/cleaner combustion without any oil which could enters into fuel

» Required investigation and calculation models of contacts

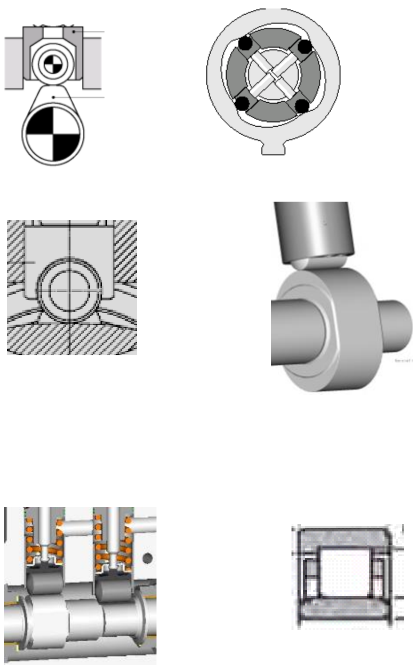
» Lake of understanding for medium lubrication concentrated contact
even rolling bearing supplier without knowledge

» **Reliability and service time** of rolling contacts under mixed lubrication condition

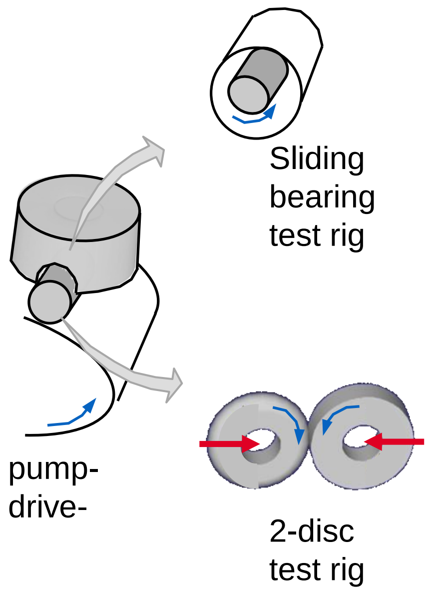
1. Design of high pressure pumps: Synergies

G|less contact engineering

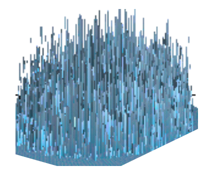
Comparable systems in field	Tribometer-Testing	Model and Simulation



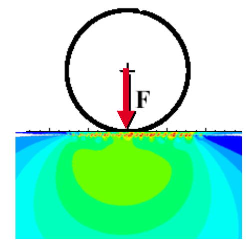
Field results, failure rates and experiences



Investigation and analyses of wear mechanisms



Pressure distribution



Stress distribution

Lifetime model

$$\ln\left(\frac{1}{S}\right) \propto N^e \int_V \frac{(\tau - \tau_u)^c}{z'^h} dV$$

Optimization

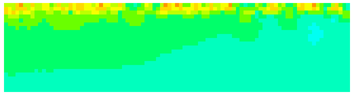
Service time and reliability prediction und calculation

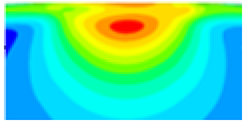
1. Design of high pressure pumps: Influences

Approach of most important stress based influences on **service time**

Analytical | Simulation

→ functions and requirements ↓ variables and influences	Load-cycles without failure due to fatigue
Design-parameter, design and manufacturing	
Geometry and tolerances	$L \sim p^{-8} \sim \tau^{-8}$
Diameter and tolerance	$L \sim d^{4}$
Length of contact and tolerance	$L \sim l^{4}$
Topographie, roughness, texture, running-in	L = f(macro-, micro-topo.)
Load + operational conditions	
load	$L \sim F_N^{-4}$
friction force	$L \sim \tau^{-8} \approx \tau_{xy}^{-8} \approx (\sigma_x \, \mu)^{-8}$
Residual stresses (e.g. annealing, treatments, run-in)	$L \sim \tau^{-8}$





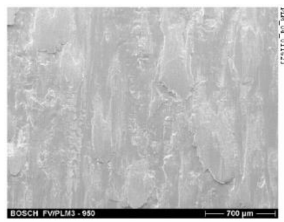
Lifetime model

$$\ln\left(\frac{1}{S}\right) \propto N^{e} \int_{V} \frac{(\tau - \tau_u)^{c}}{z'^{h}} dV$$

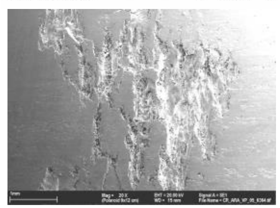
2. Mixed-lubrication failure Mechanism

Working area and limits of a concentrated contact (schematically)

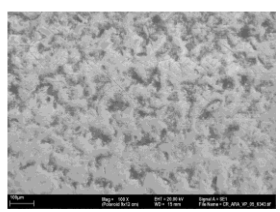
Adhesion

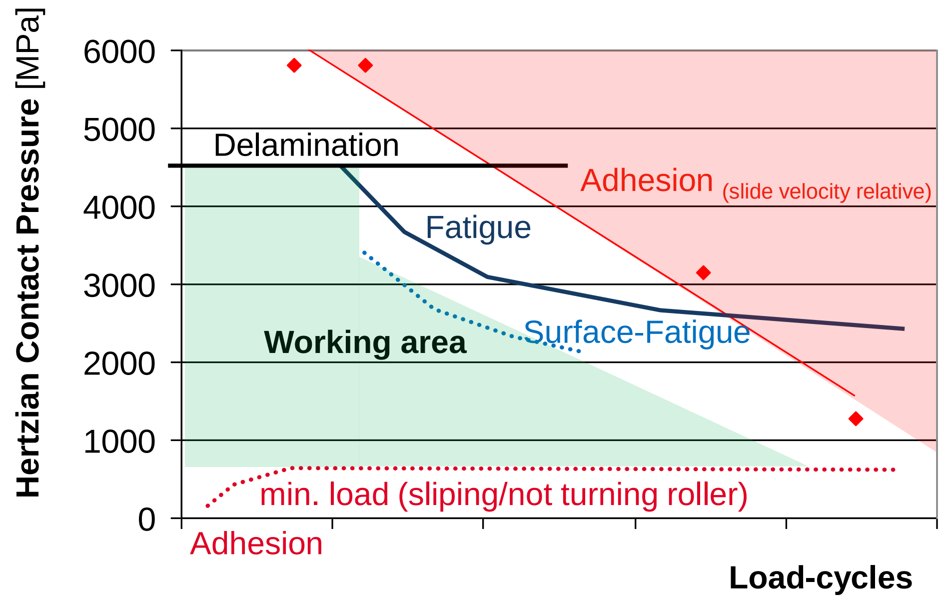


Fatigue
cracks/pitting



Surface-Fatigue
mikro-pitting
mixed lubrication

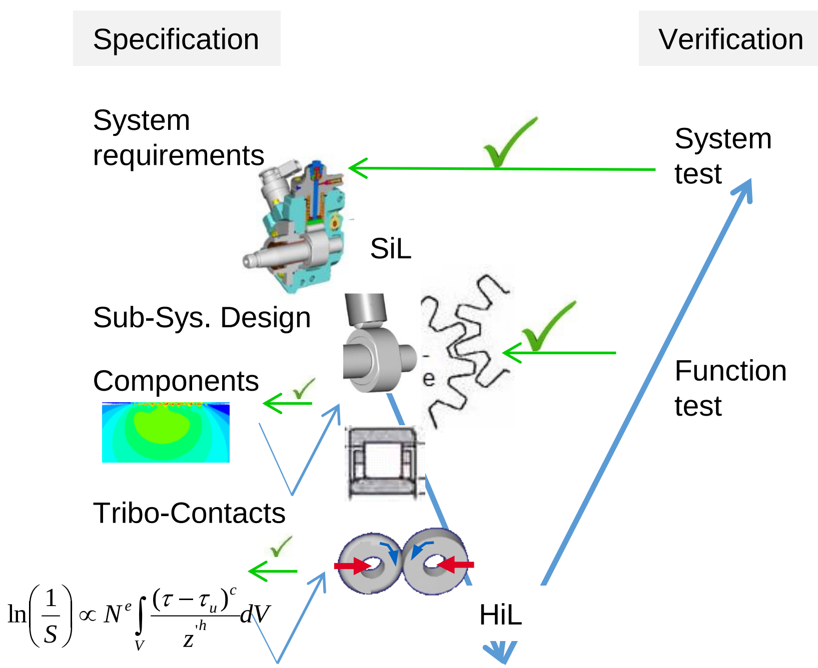


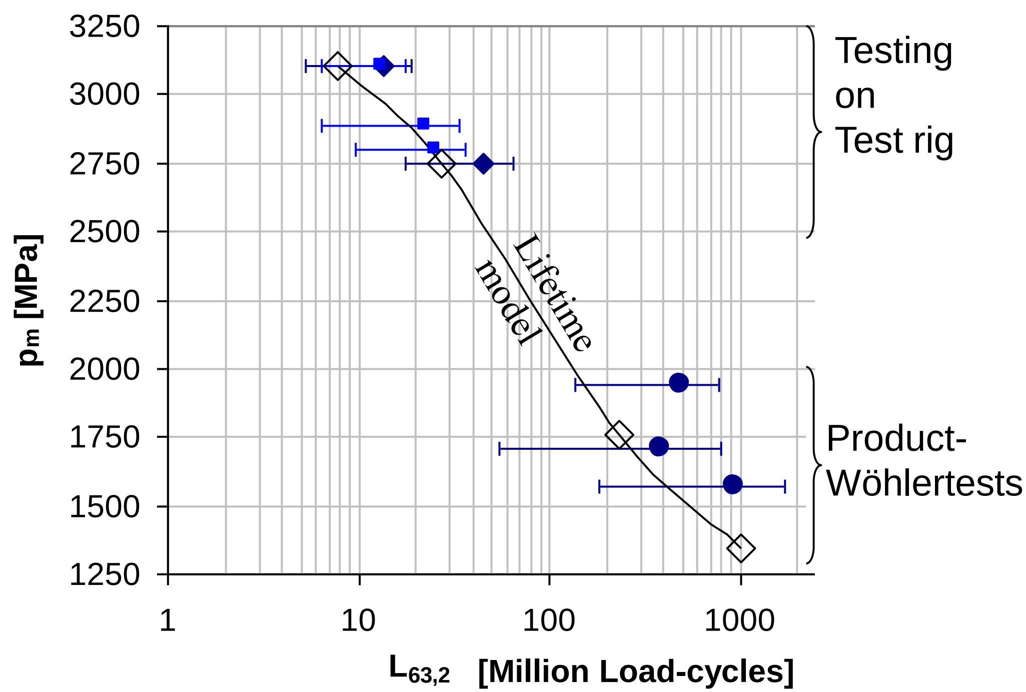


3. Verification and Service life time Model

Concept V-shape model Verification on component level: in the loop MiL, SiL, HiL

1. Evaluation of influences and failures modes
2. Tribometer testing an field Short Tribometer testing to verify strength and material behavior + verification in production accompanying and field data
3. Simulation and life time models => lifetime and reliability





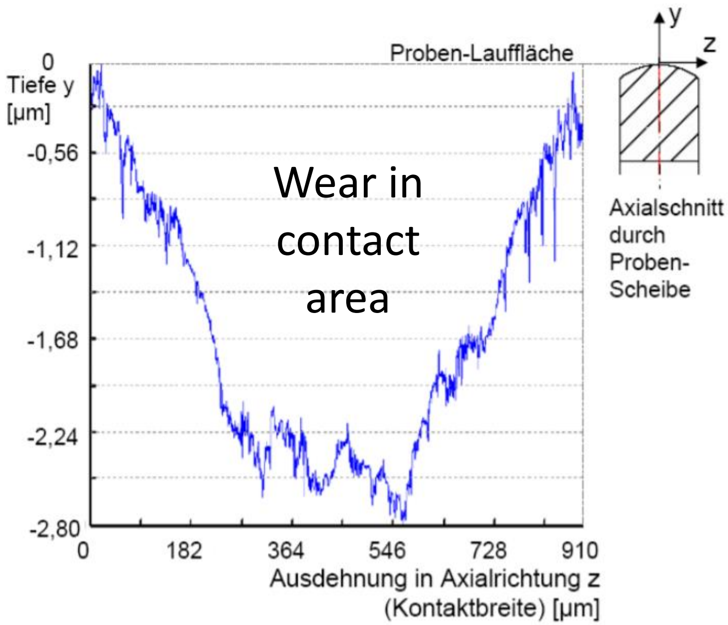
Wear: good or bad?

wear **positive** effects

» Pressure peak reduction, during run in process e.g. edges, roughness
» Run in grinding to increase tightness e.g. engine valve seats
» Crack removal / avoid surface crack propagation e.g. train tracks
» Self sharpening effect e.g. cutting tools, agriculture blades

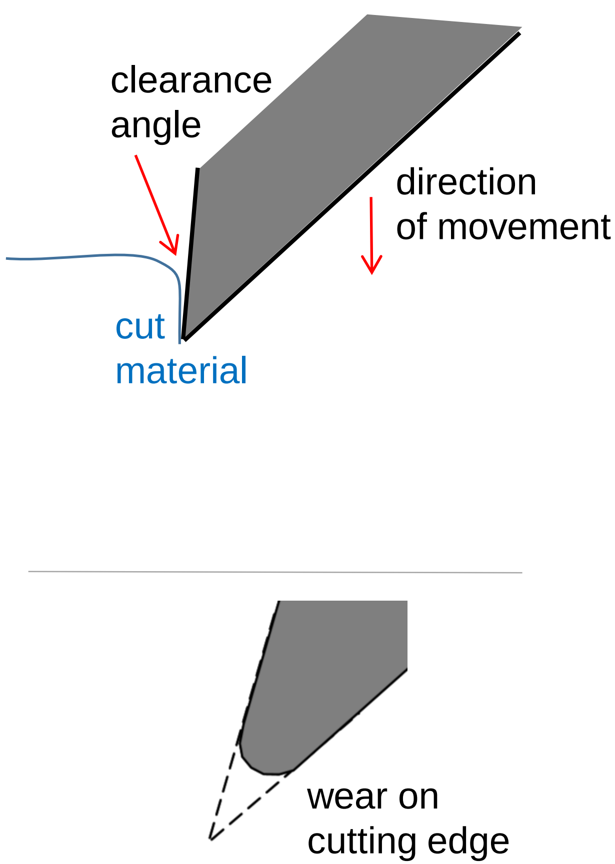
wear **negative** effects

» Loss of material e.g. blades get dull, wear parts
» Loss of isolation e.g. eMobility
» Loss of corrosion protective coating/layers e.g. offshore photovoltaic
» Loss of strength, fracture e.g. ICE tire breakage
» Changes in operation e.g. increase of clearance

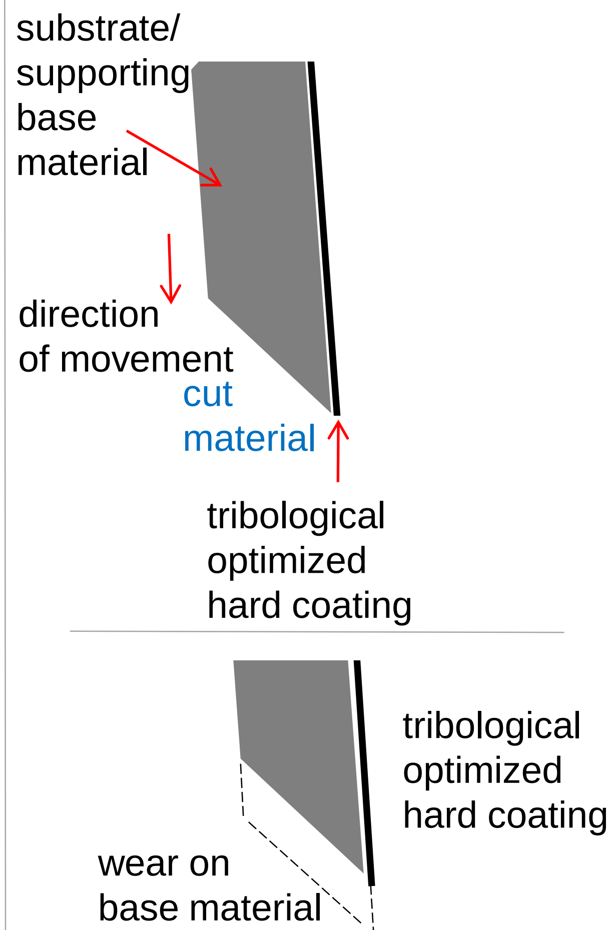


1. Design for abrasive wear Control

traditional cutting process
with wear on cutting edge

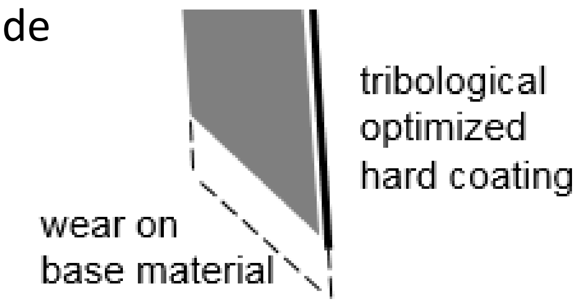


Schematic design based on
bionic principals of a tooth



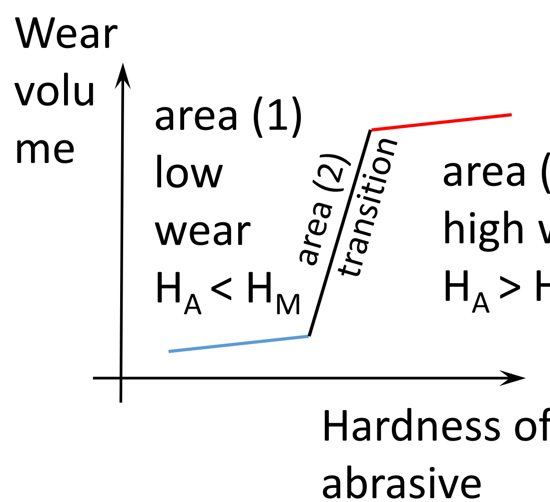
2. Dominating wear mechanism: Abrasion

» Design for self sharpening e.g. agriculture cutting blade



» Dominating wear mechanism: abrasion

» Influences on abrasive wear
hardness ratio of the base and coating material H_M to the abrasive medium $H_{A.}$
=> Chosen material defines Wear-rate.
=> Coating required in low wear area.

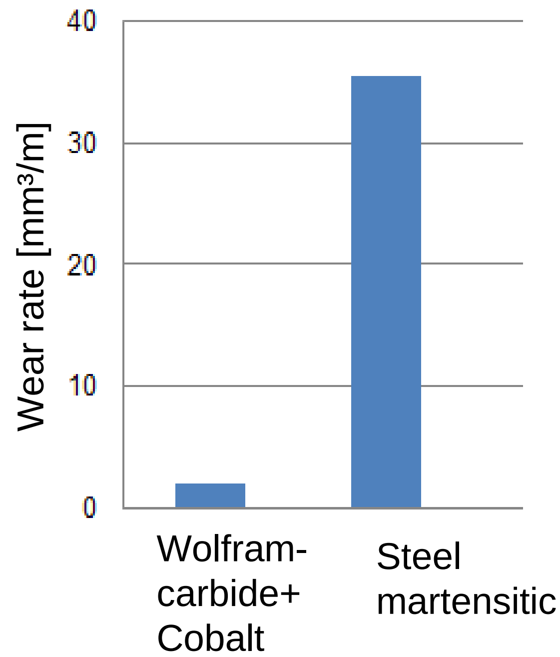


3. Strength and Service life time

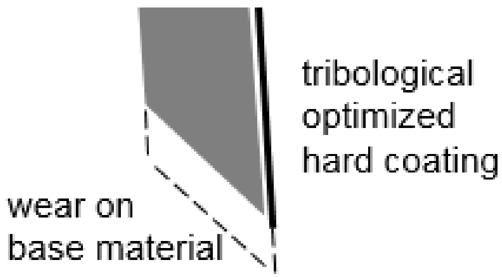
- Strength
  Abrasive Wear Test ASTM G65

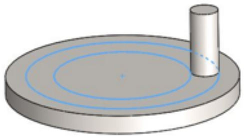
- Coatings
  - Diamond like carbon **DLC**
    Chemical vapor deposition (CVD)
    expensive high end coating

  - **Wolfram-Carbide** on martensitic steel via thermal spray seems to be
    more economic and offers comparable good results



- Field data
  blade after ~ 350 hours



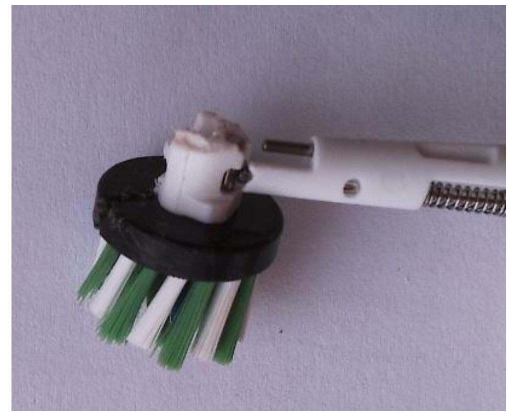


1. Design for service life: Variants and Influences

G|less contact engineering

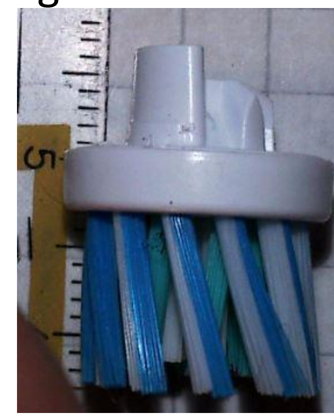
- Design comparison/selection
  main influencing factors
  - contact pressure and distribution
  - material combination
  - "lubricant" vs. dry

ex-centric



- metal inserts
- many parts
- difficult assembly
+ low friction
+ lifetime

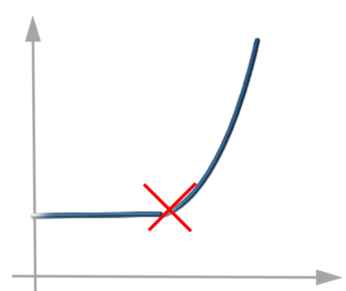
gear drive

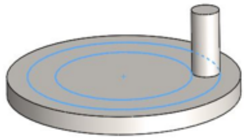


- Plastic material
  pressure limits
- higher friction
  higher loads
+ cost savings

- Optimization - optimized gears, lubrication and motions
  => lower contact pressure
  => avoid breakage, deformation, adhesion/scuffing, …

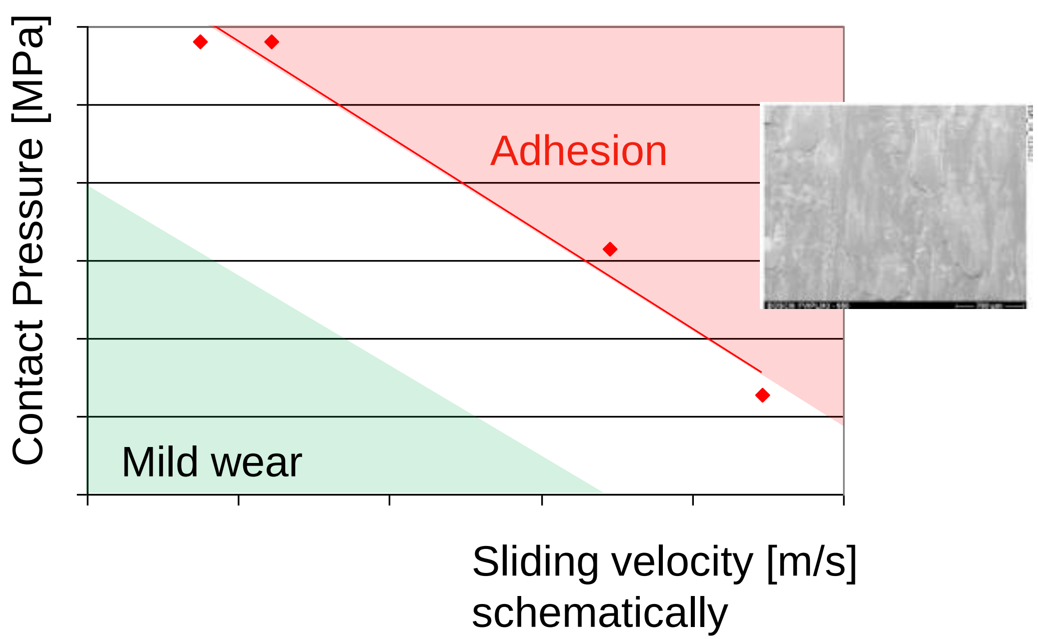
- Mixed lubrication regime,
  mild **wear** is dominating and lifetime limiting

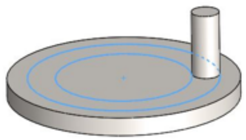




2. Wear Mechanism

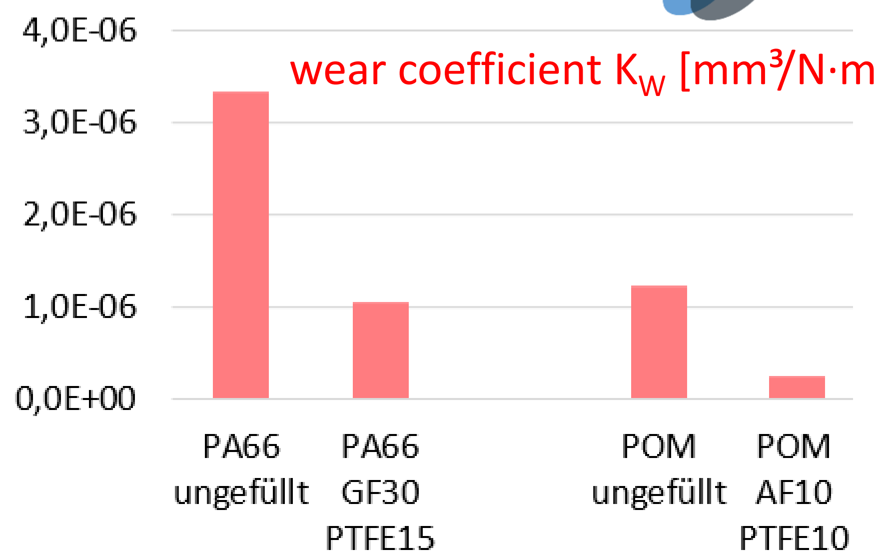
» Lifetime relevant mechanism is mild **wear**

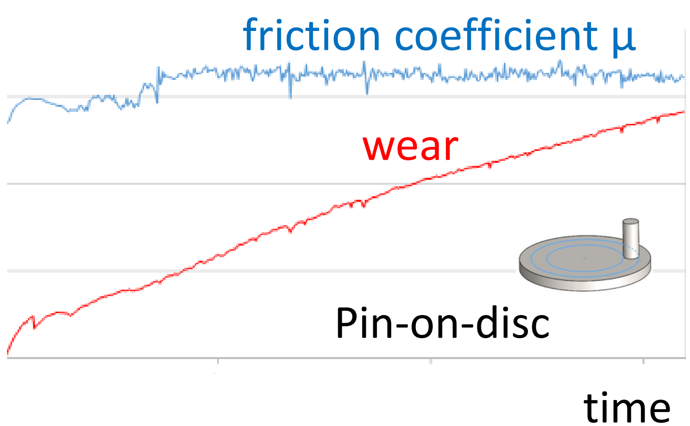


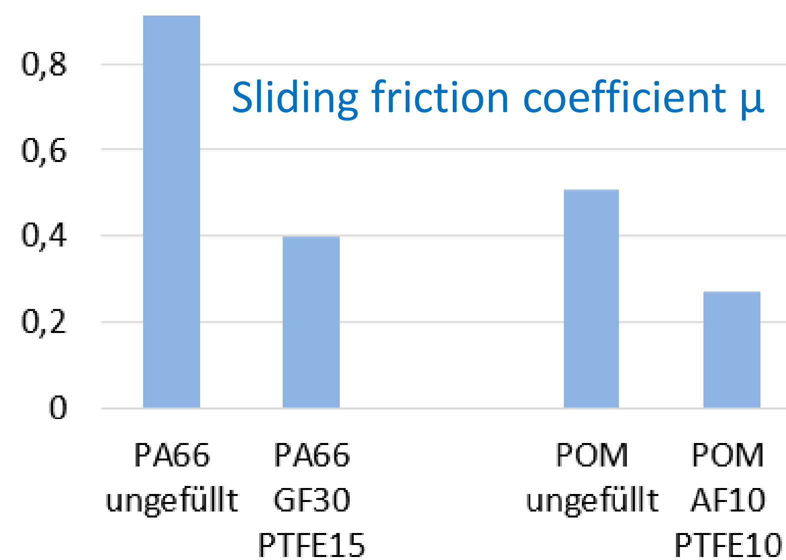


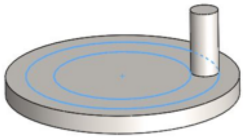
3. Strength and Service time

- Strength/wear resistance
  Derivation max. bearable normal load from experimental determination of wear coefficient K_W as a function of influencing factors (DoE)



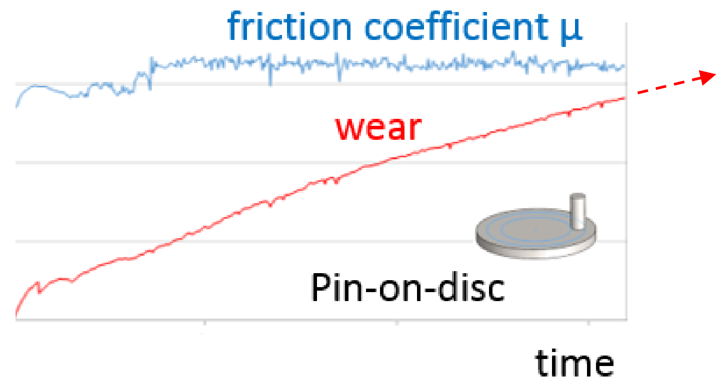






3. Strength and lifetime Wear Prediction

Goal for Service Lifetime is reached. Model allows Wear prediction on different Levels



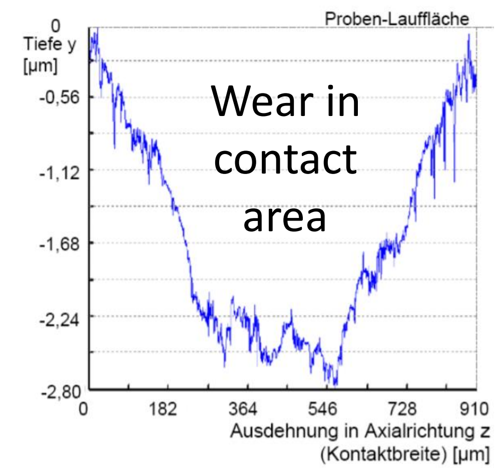
1. Analytical e.g. archard wear, VDI 2736

» within linear wear/steady-state wear regime extrapolation possible

» material suppliers offers wear rates and friction coefficient (pin-on-disc or accord. ASTM)

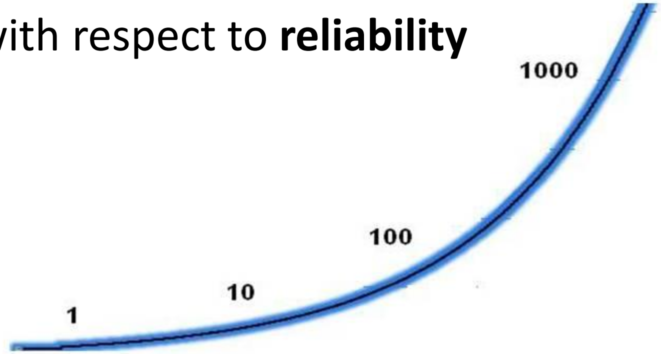
2. Local and iterative e.g. in FEM contact analysis load+sliding => wear <=> wear => load/stress

3. serial production parallel/accompanying testing field results => prediction method based on adaptive continual learning



Summary

» Shown easy however systematic approach
enables a methodical **comparison** of different design solutions
evaluates design components and influences also with respect to **reliability**



1. **Functions and requirements** are considered
   Influences are evaluated to find robust designs

2. **Failure mechanism** are avoided if possible.
   However in focus are service time limiting Mechanism.

3. Tribometer testing supports/verifies Strength and Material behavior.
   In addition life time Models, production accompanying and field **Data** are considered

» Approach has been successful applied in several design projects e.g.
to estimate **fatigue** in concentrated contact and
to control **abrasive** wear for self-sharpening and
to estimate sliding **wear** in different contacts.

Thank you for your attention!

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