Winning the tribological contest using a Digital Twin for PVD coated applications Surface Solution for Gears as an example

TRIBOLOGY 2025 – Materials Making the Difference

3rd of June 2025; Rolls-Royce Learning and Development Centre, Derby, UK;

Dr.-Ing. Emanuel Tack, Theresa Huben - Oerlikon Balzers, LI;

Vincent Hoffmann - Tribo Technologies, DE;

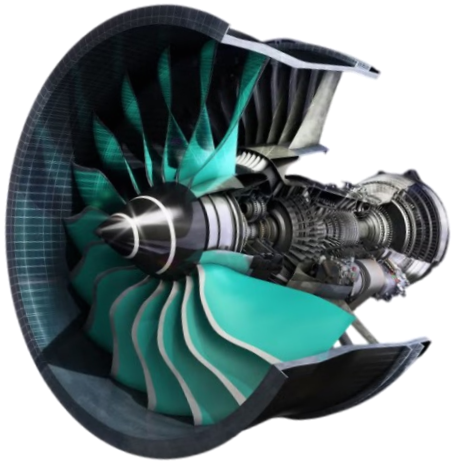
Motivation & Vision of the Project

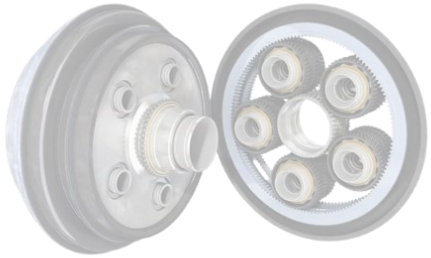
Optimizing Diamond Like Carbon coatings for gears
Vision of the Project

oerlikon balzers

Passenger Car

Aerospace





Industry

Increase the efficiency of gearboxes from various industries

Source: Rolls Royce, BMW, Vestas;

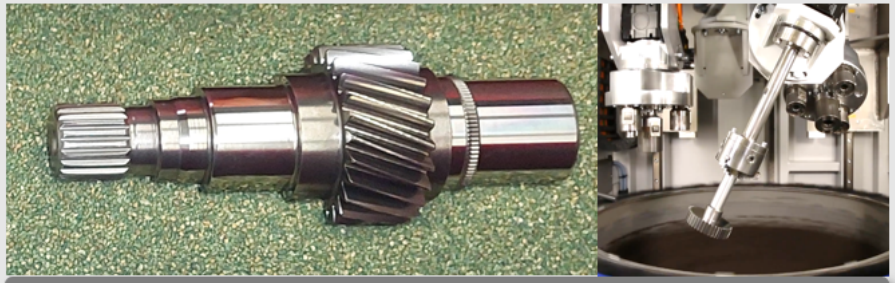
Aim, Challenges, Tasks

Optimizing Diamond Like Carbon coatings for gears
Aim, Challenges, Tasks

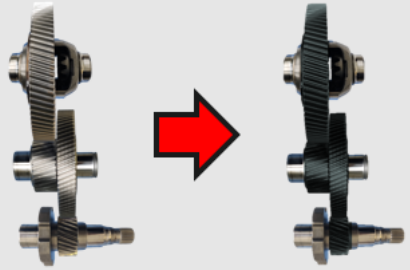
Electric Car

Increase the range

Aim:
- Increase the range of electric vehicles economically

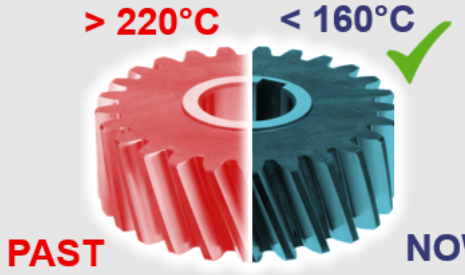


Suitable Surface Treatment

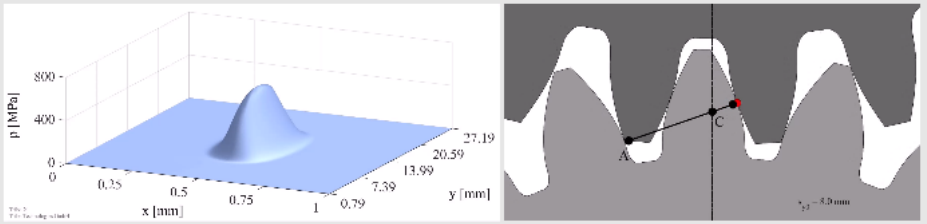


Coating architecture

Challenges:
- **Increase efficiency** of the reduction gear
- **Reduce frictional power losses**
- **Offer high-performance surface solutions for gears**
  - **surface pretreatment if needed**
  - **DLC Coating**



Control Substrate Temperature



*TEHL model of tribosystem

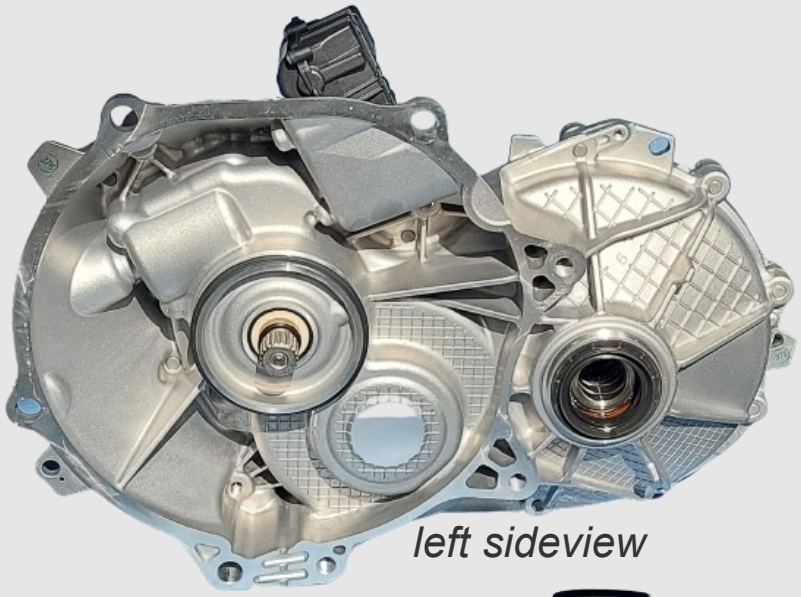
Tasks:
- create a **Digital Twin of the PVD/PACVD coating** plus substrate including:
  - **mechanical-technological properties**
  - **thermodynamical properties**
- **Control the substrate temperature during PVD/PACVD coating process**

*TEHL: thermal-elastohydrodynamic lubrication

EV Reduction Gears

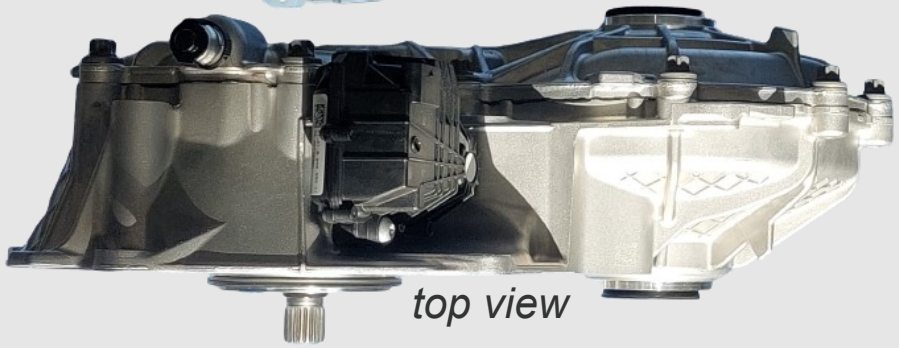
Optimizing Diamond Like Carbon coatings for gears
EV Reduction Gears

oerlikon balzers



left sideview

right sideview



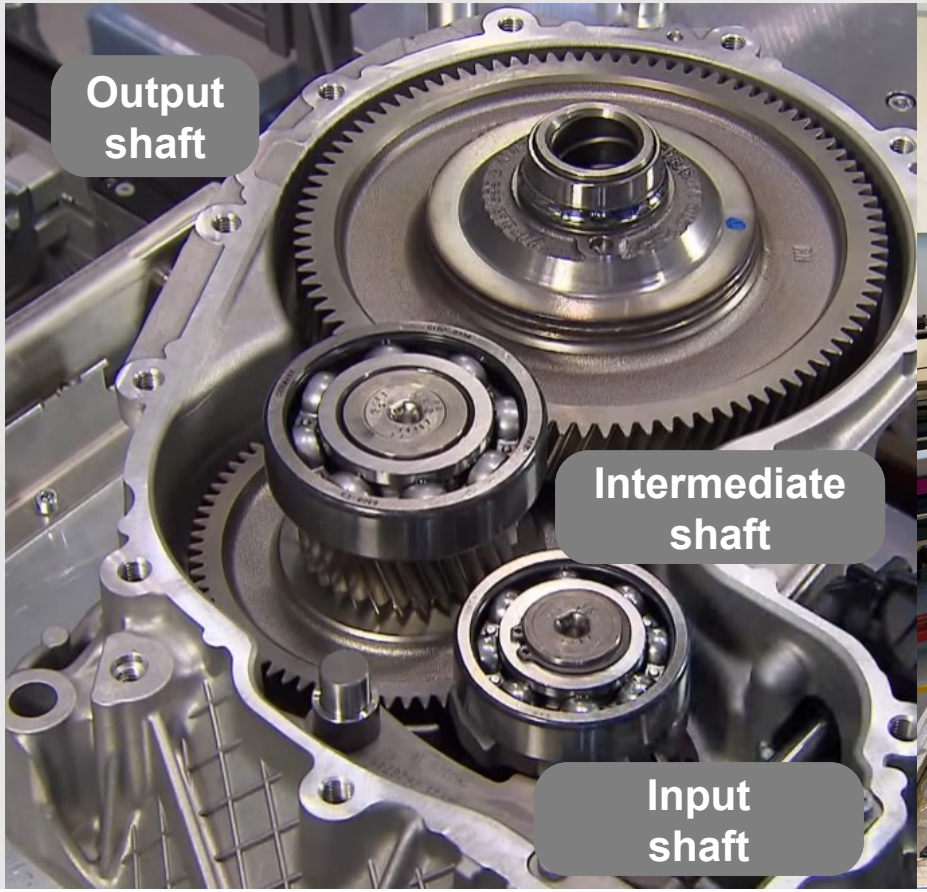
top view

BMW i3 Gear

Two-stage single-speed transmission - helical spur gear

Source: BMW

Optimizing Diamond Like Carbon coatings for gears
EV Reduction Gears



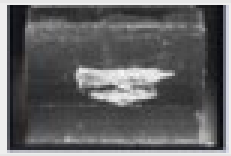
BMW i3 Gear

Two-stage single-speed transmission - helical spur gear

Typical gears failures // wear topics

Diamond Like Carbon coatings for gears
PVD/PACVD coatings for typical gears failures / wear topics

oerlikon balzers

DLC	Damage mechanism	Example	Typical location (at tooth)	Typical location (at gear)	Mechanism / progress
	Pitting		dedendum	specific teeth	contact fatigue
	Micropitting		dedendum	specific, soon all teeth	contact fatigue
	Scuffing		addendum	specific teeth	non-fatigue
	Adhesive wear		sliding regions	all teeth	mixed friction
	Tooth root fract.		30° root tangent pt.	specific teeth	bending fatigue

PVD/PACVD coatings avoid typical gear failures → don`t weaken the tooth root !

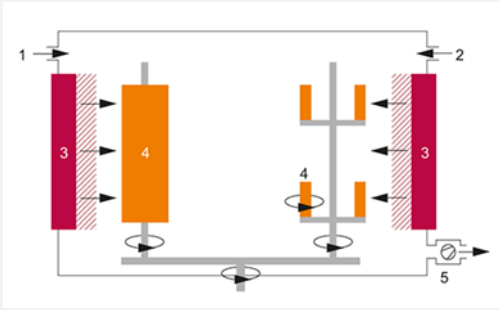
Different DLC Coatings

Diamond Like Carbon coatings for gears

Suitable coatings for gears

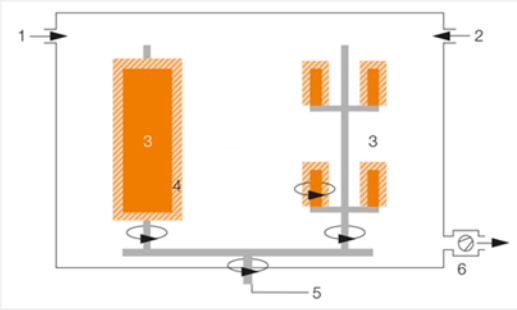
a-C:H:W "WC/C"

BALINIT® C



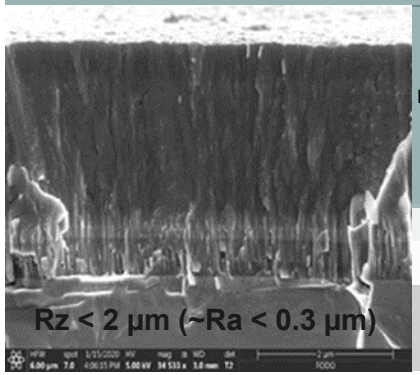
Sputtering

a-C:H



PACVD

Hardness: 12-15 GPa



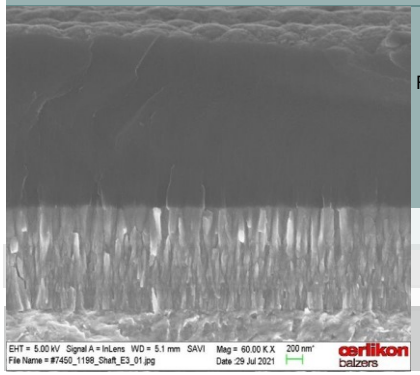
Functional layer **a-C:H:W**

CrWC

Cr

Substrate

Hardness: 20-25 GPa



Functional layer **a-C:H**

CrC

CrN

Cr

Substrate

a-C (HIPIMS*)

Arc evaporation

Benefits of arc technology

- ✓ High ionization of the evaporated flux
- ✓ Dense coatings
- ✓ Good adhesion

Sputtering

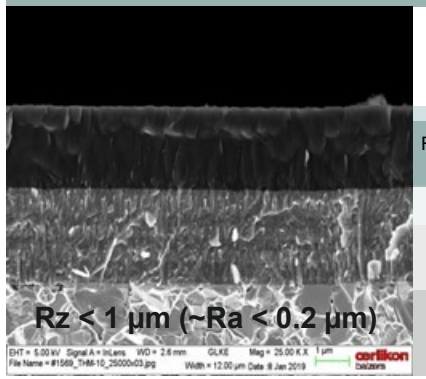
Benefits of conventional technology

- ✓ Smooth coatings (deposition with virtually no droplets)

BALIQ® CARBOS STAR

S3p® technology

Hardness: 30-35 GPa



Run-in **a-C:H**

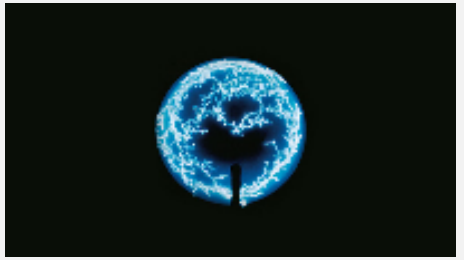
Functional layer **a-C**

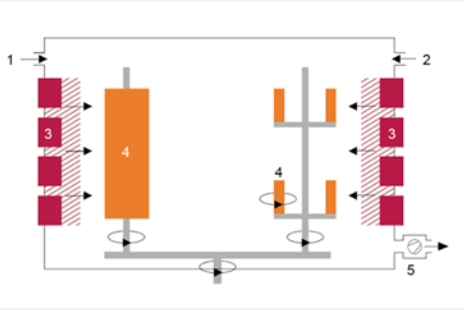
CrC

Cr/CrN

Substrate

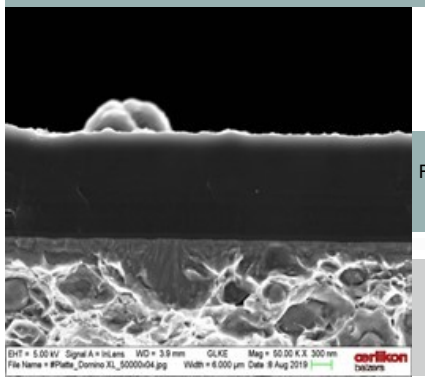
ta-C (Arc)





Arc technology

Hardness: 55-70 GPa



Functional layer **ta-C**

Cr

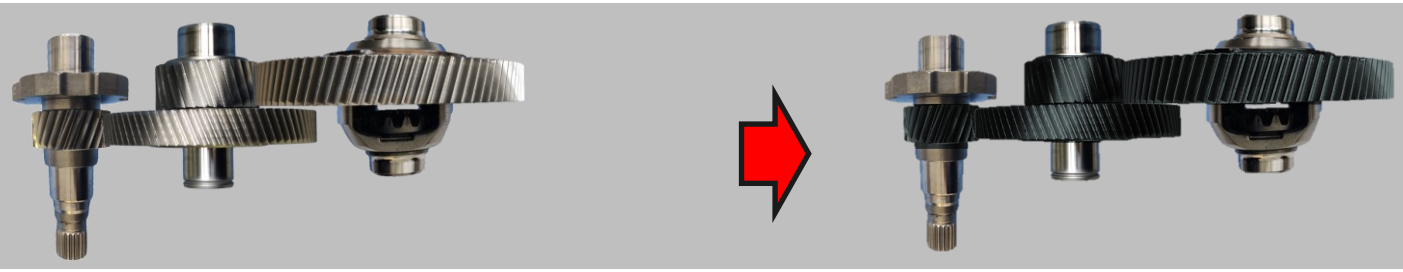
Substrate

**High-power impulse magnetron sputtering*

Different Levels for Testing the coating

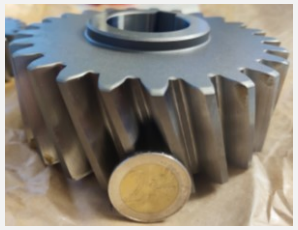
Diamond Like Carbon coatings for gears
Testing Specimen

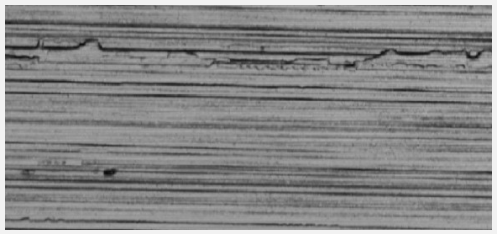
EV Gear Components

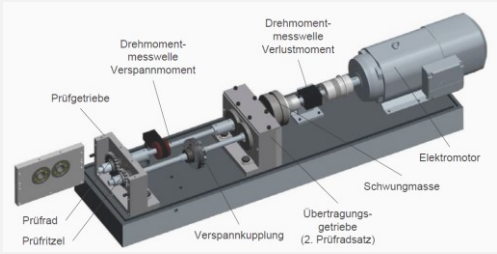


- shadowing effect
- Real Parts
- High effort to coordinate the tests and to get the real parts

Gear Components

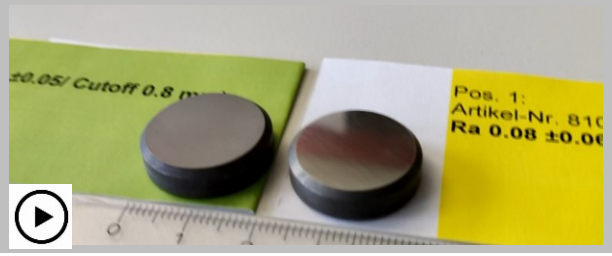






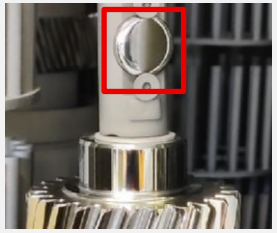
- shadowing effect
- Similar Parts
- High effort to coordinate the tests and to get the parts

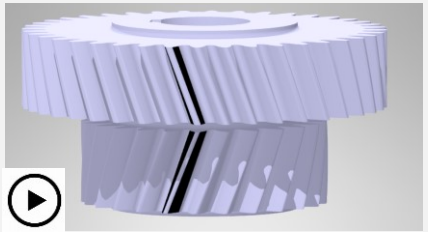
Flat samples inside Dummy Gear



- shadowing effect
- Specific Gear Roughness
- Specific Gear Material

Flat samples outside Gear





- Ideal smooth surface
- No shadowing effect
- Standard material

Digital Twin - SRV Tests

Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

SRV test

- Ball indenter
- Oscillating motion with high frequency
- Normal load applied to ball
- System:
  - Ball
  - Lubricant
  - Coated specimen

➢ **Goal: test of tribological system regarding wear resistance**

SRV test and simulation configurations

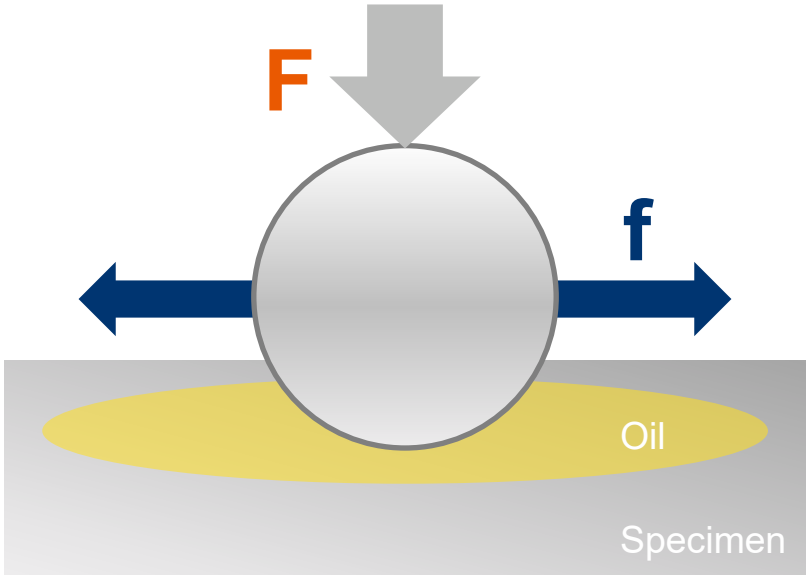
I. SRV Test "Boundary Friction"

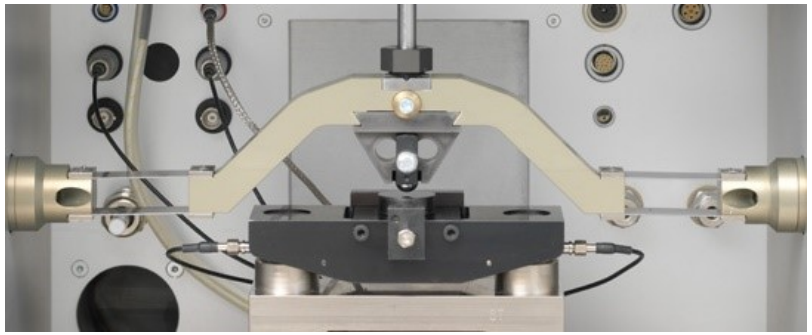
- High load
- Low frequency
- High temperature

II. SRV Test "Mixed Friction"

- Small load
- High frequency
- Low temperature

SRV test



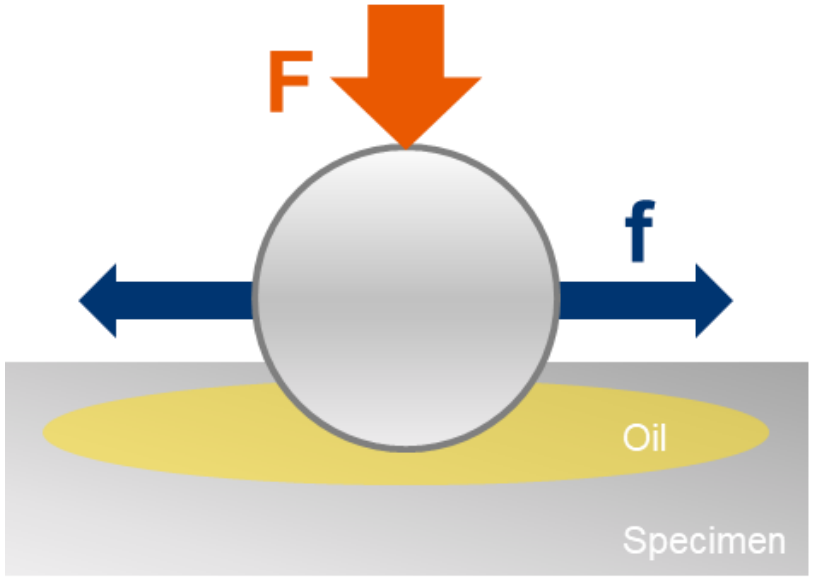


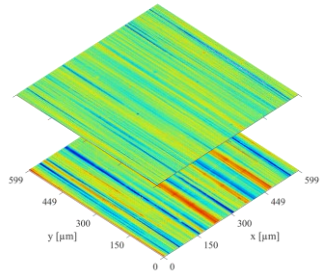
Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

Model Setup

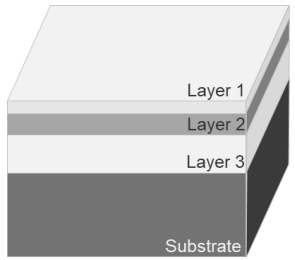
Geometry and Operating Conditions

- SRV test
- Lubrication via oil bath
- Strain focus test oriented on normed SRV test
- Mixed-friction test designed to generate hydrodynamic effect at the ball





Data	Boundary friction	Mixed friction	Unit
Ball diameter	10	10	mm
Stroke	4.6	4.6	mm
Frequency	20	30	Hz
Load	200	5	N
Temperature	150	35	°C

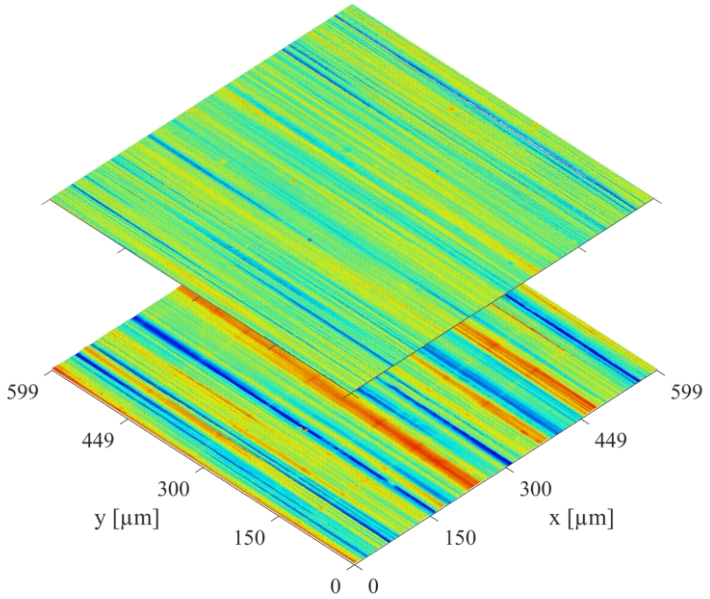


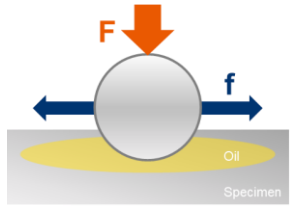
Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

Model Setup

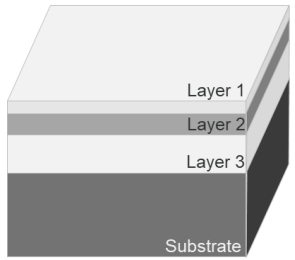
Surface Roughness

- Roughness significantly influences gap flow and contact
- Roughness consideration based on measured surfaces
- Contact of surface roughness modeled based on precalculated integral solid contact pressure curve
- Influence of surface roughness on gap flow modeled based on flow factors





Surface Data	Sign	Surface	Unit
Root mean square average roughness	RMS	0.170	µm
Average roughness	R_a	0.133	µm
Maximum peak to valley roughness	R_z	1.597	µm

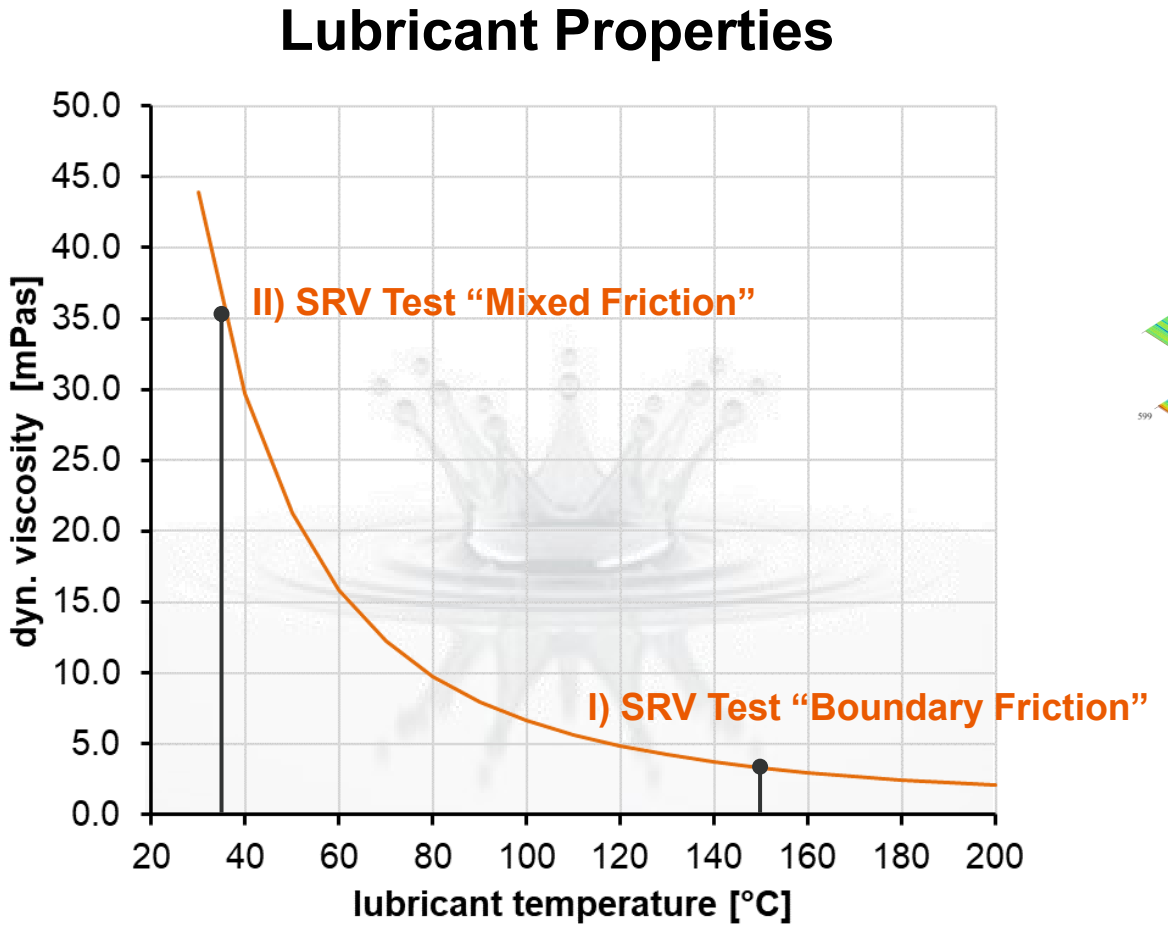


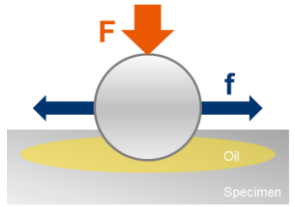
Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

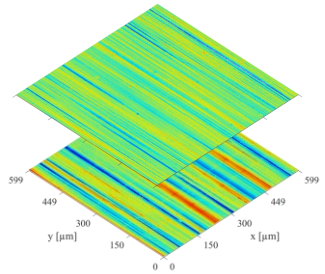
Model Setup

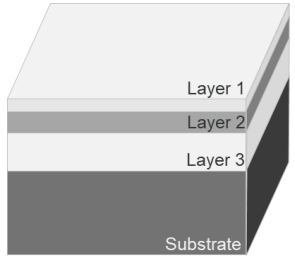
Lubricant Properties

- Properties of lubricant define the hydrodynamic pressure build up and friction significantly
  - Dyn. viscosity
  - Density
  - Thermal conductivity
  - Spec. heat capacity
- change with temperature, pressure and shear rate dependency
- consideration of lubricant properties in the simulation







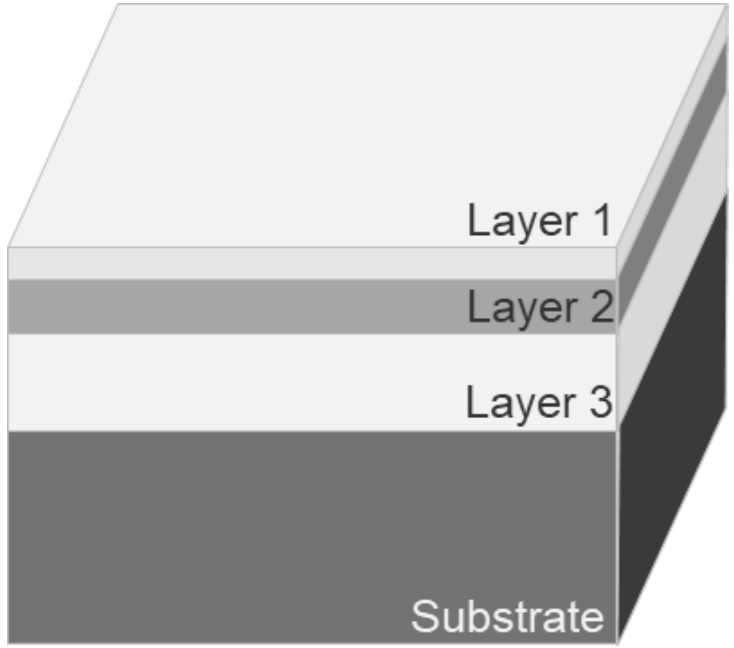


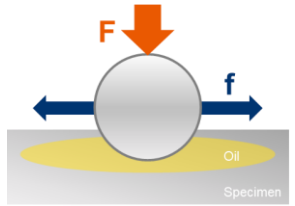
Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

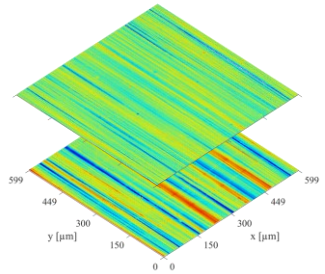
Model Setup

Modeling the Layer System

- Layer structure significantly influences
  - Strength and hardness
  - Wear
  - Friction
  - Thermal heating
- Modeling of substrate and coating with 6 sublayers with different mechanical and thermo-physical properties
  - E-modulus
  - Poisson ratio
  - Thermal conductivity
  - Spec. heat capacity

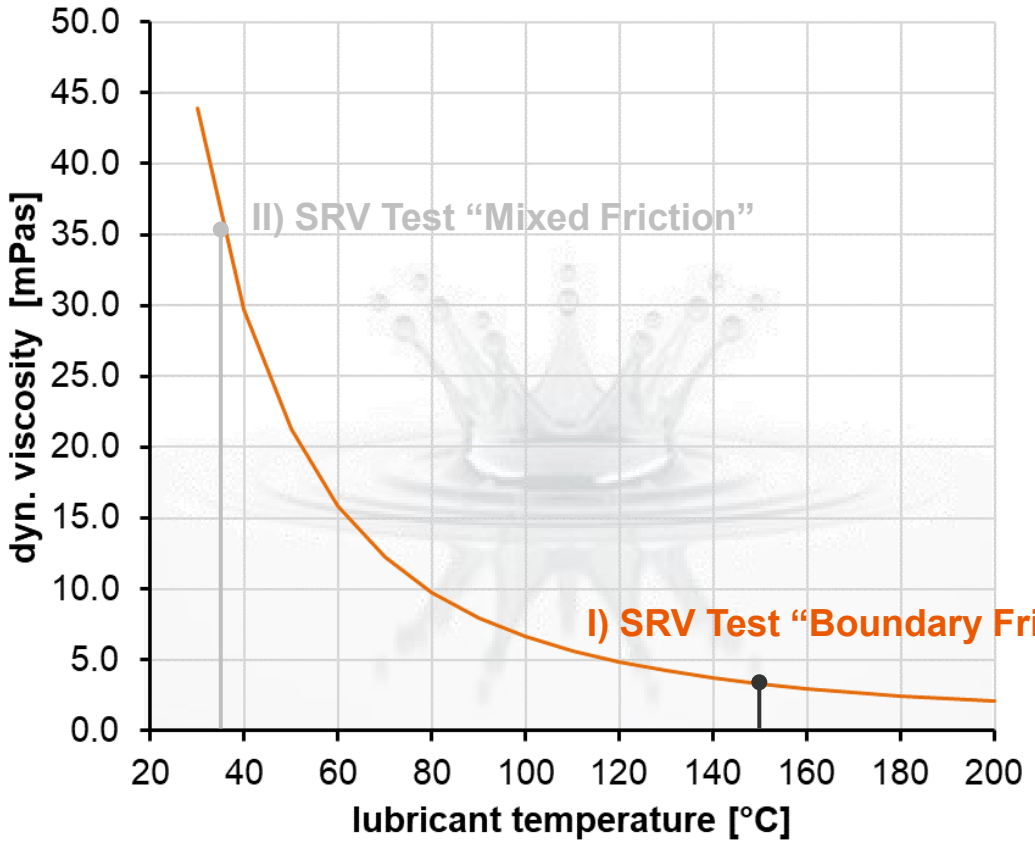






Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

I) SRV Test “Boundary Friction”



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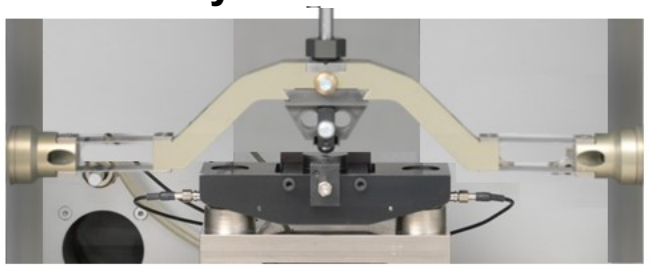
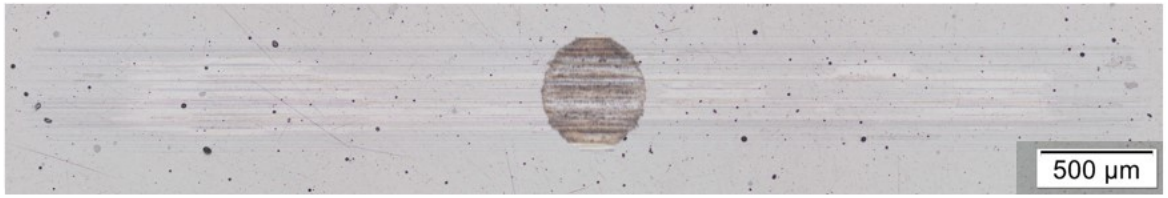
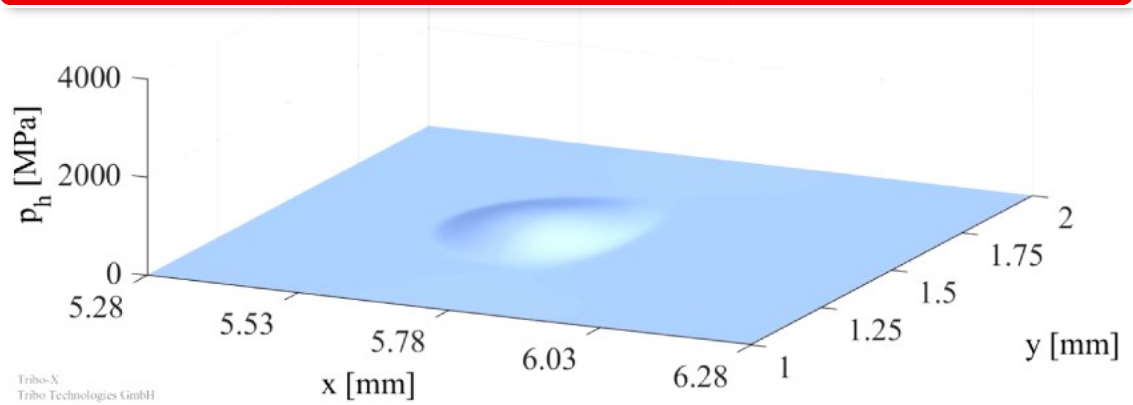




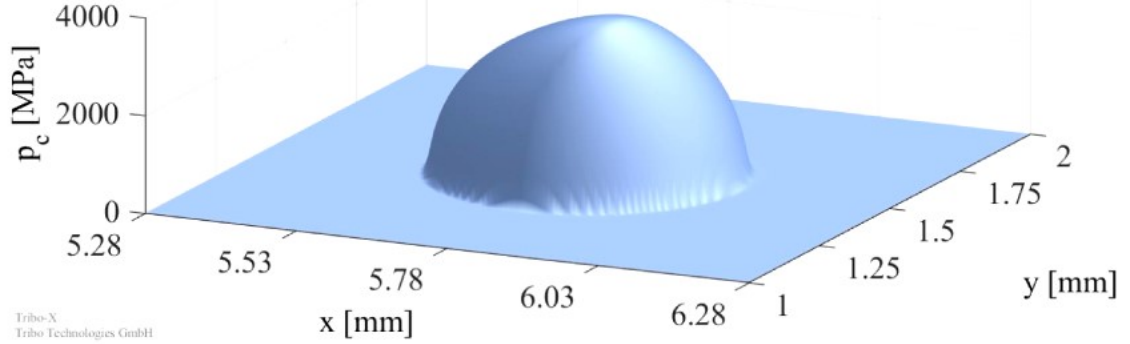
- Low hydrodynamic pressure build-up
- ➢ Contact is dominated by solid contact of rough surfaces

Data	Boundary Friction	Mixed Friction	Unit
Ball diameter	10	10	mm
Stroke	4.6	4.6	mm
Frequency	20	30	Hz
Load	200	5	N
Temperature	150	35	°C

Hydrodynamic Pressure



Solid Contact Pressure



Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

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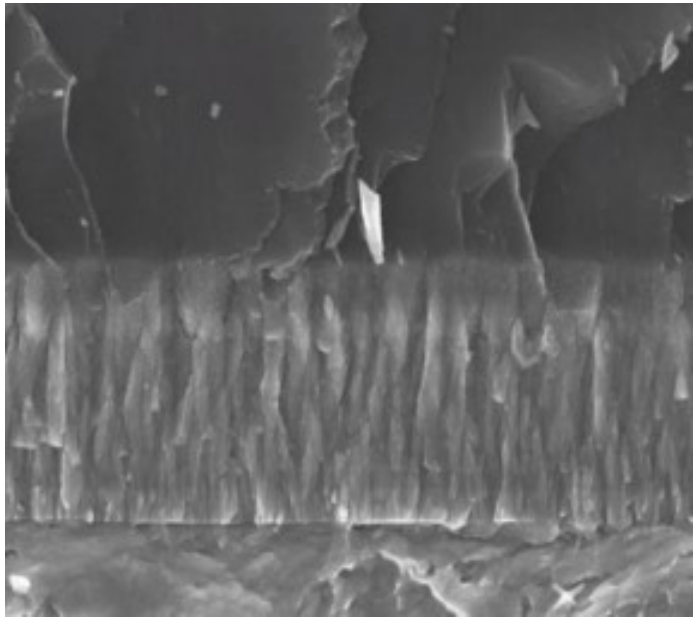
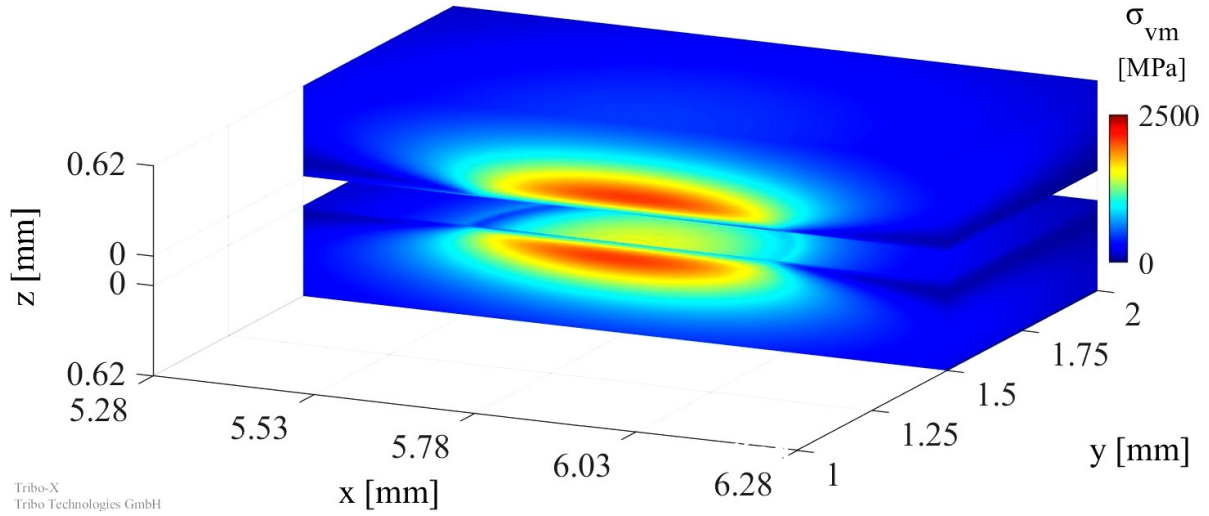


Von Mises Stress Distribution



Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

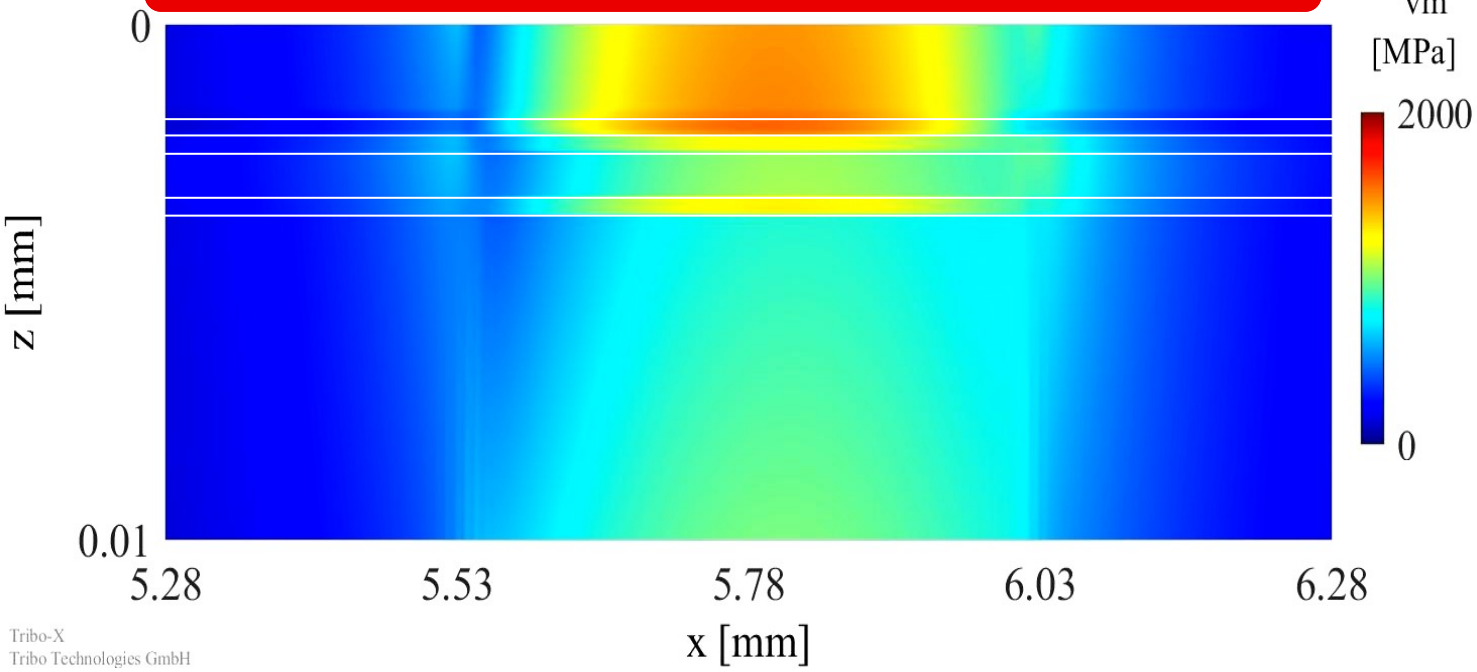
I) SRV Test “Boundary Friction”

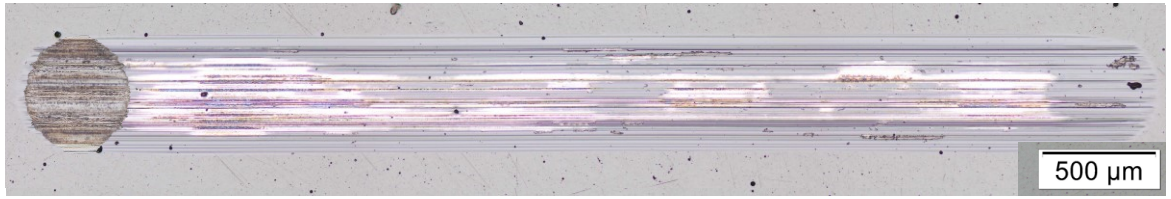
Analysed Coating System

Layer	Yield strength [MPa]	Simulated max. Stress [MPa]
a-C:H	> 20000	**1700**
Cr containing interlayers	8000-17000	**1000-1800**
Substrate	~ 6000	**2500**

- Due to size of indenter the stress maximum is located in substrate
- Stress is factor 8-10 below strength of material

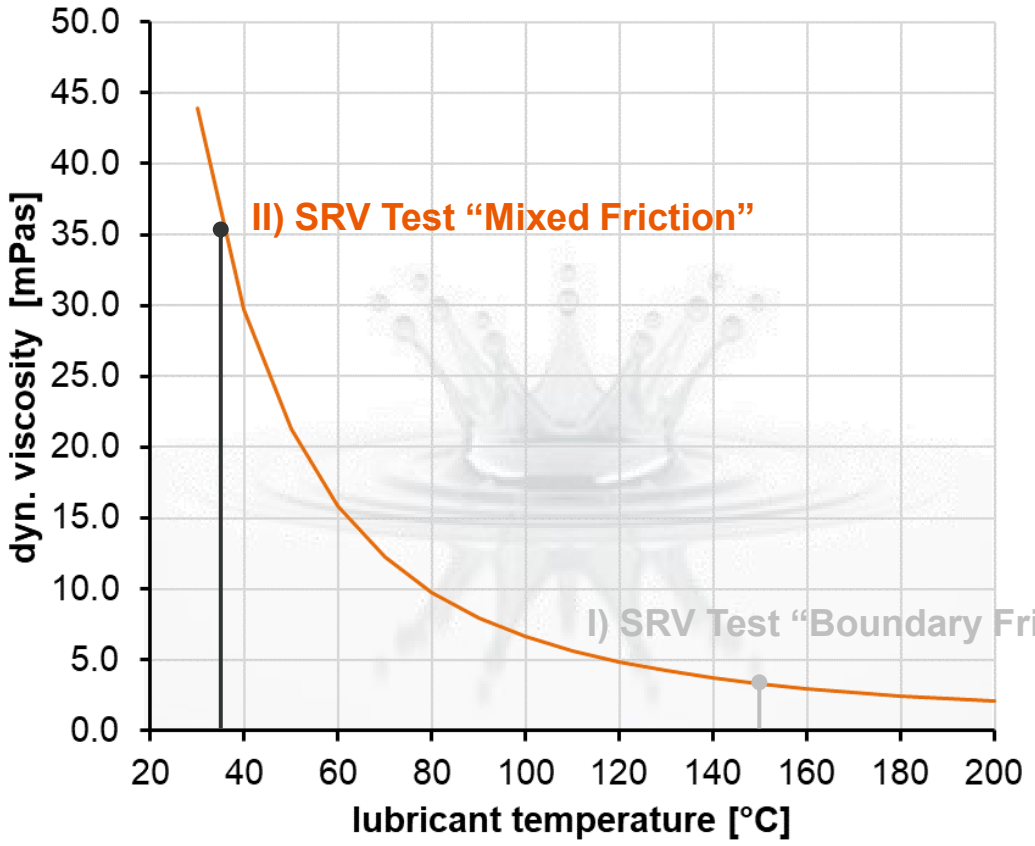
Von Mises Stress Distribution





Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

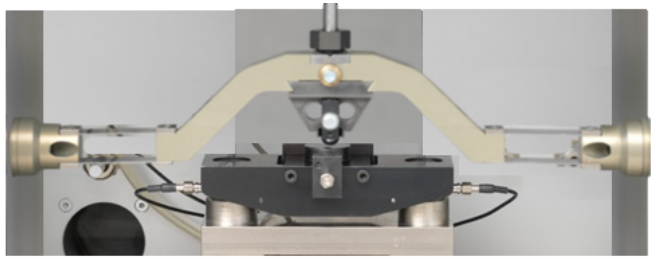
II) SRV Test “Mixed Friction”

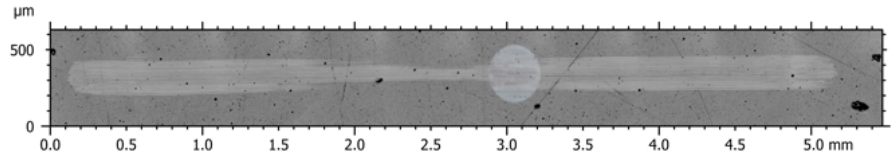


Data	Boundary Friction	Mixed Friction	Unit
Ball diameter	10	10	mm
Stroke	4.6	4.6	mm
Frequency	20	30	Hz
Load	200	5	N
Temperature	150	35	°C

Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

II) SRV Test “Mixed Friction”

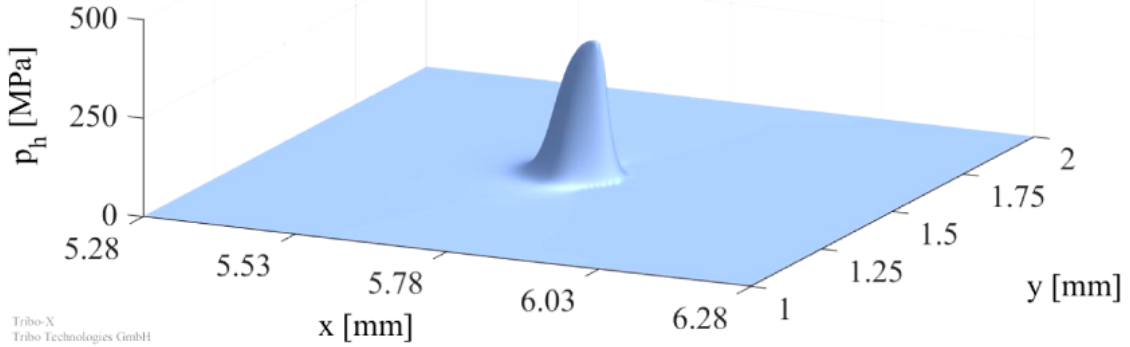




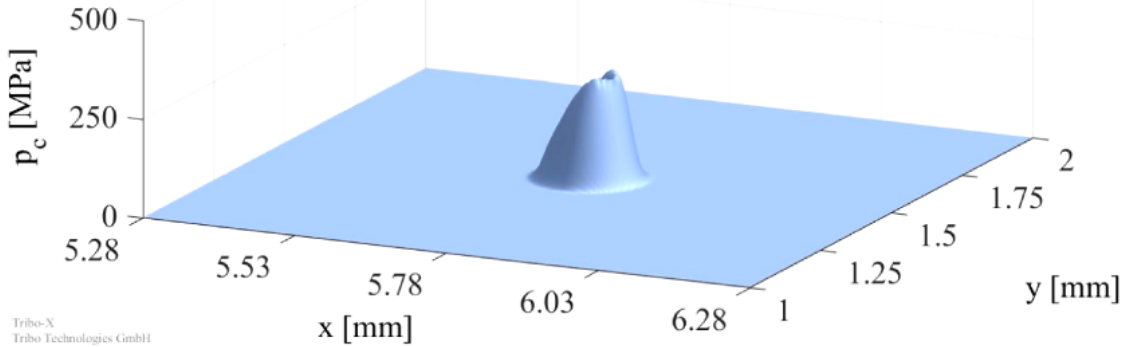
- Increased hydrodynamic pressure build-up
- Hydrodynamic pressure increases with increasing sliding speed

Data	Boundary Friction	Mixed Friction	Unit
Ball diameter	10	10	mm
Stroke	4.6	4.6	mm
Frequency	20	30	Hz
Load	200	5	N
Temperature	150	35	°C

Hydrodynamic Pressure

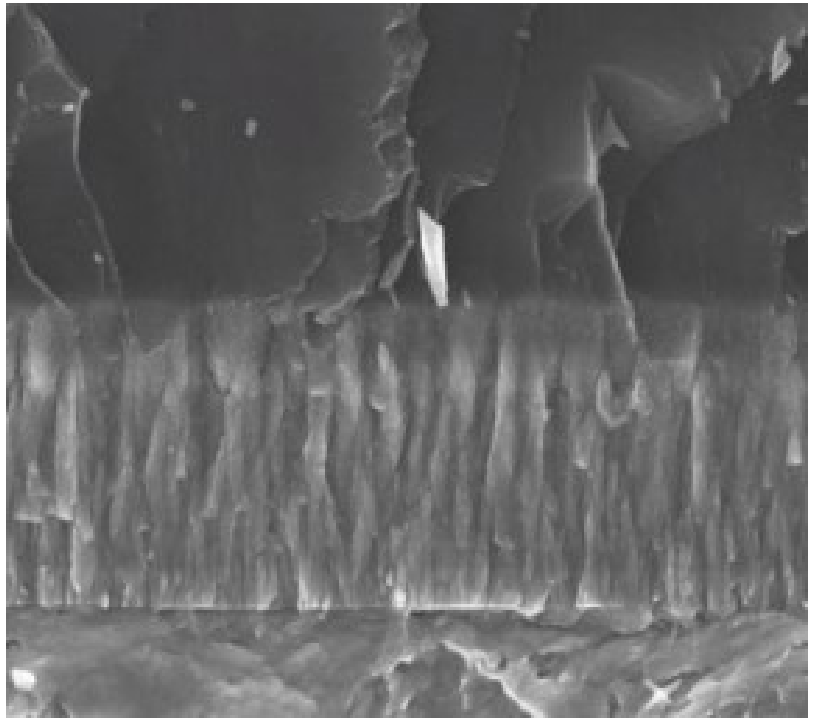


Solid Contact Pressure

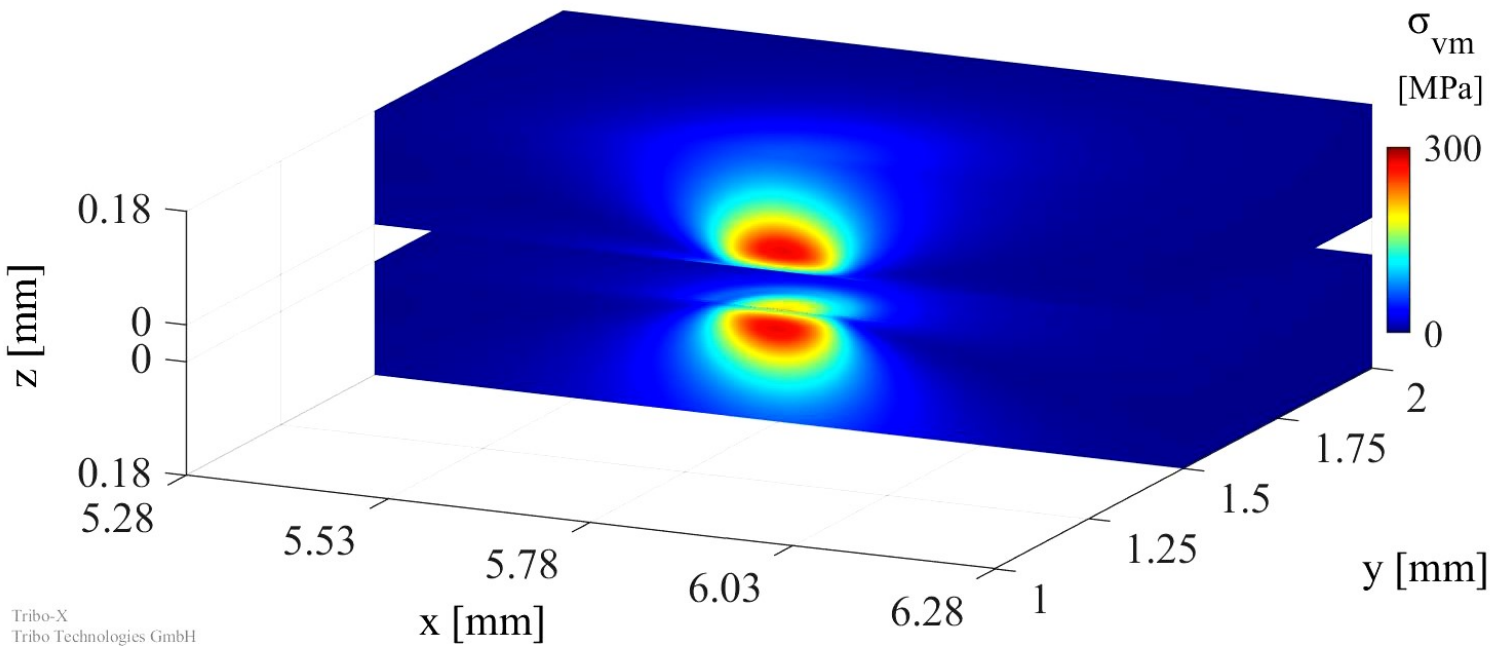


Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

II) SRV Test “Mixed Friction”



Von Mises Stress Distribution



Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

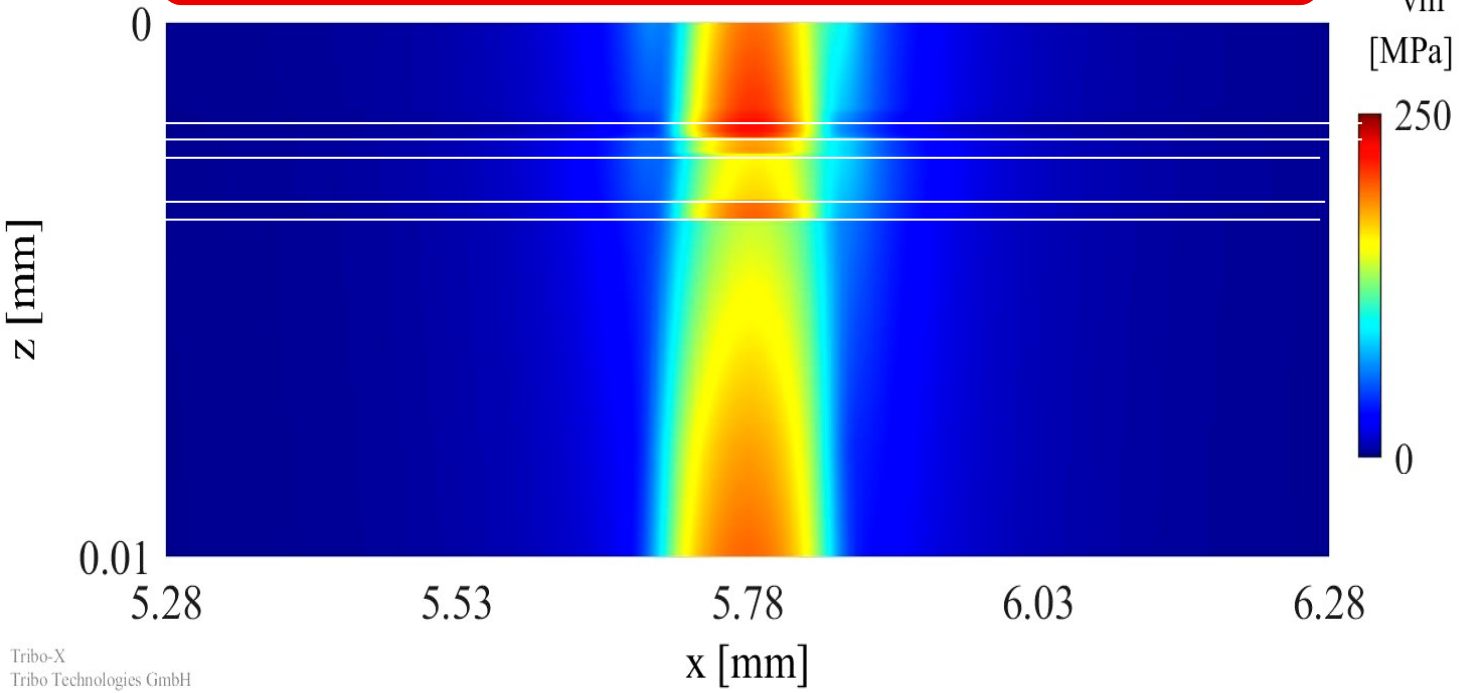
II) SRV Test “Mixed Friction”

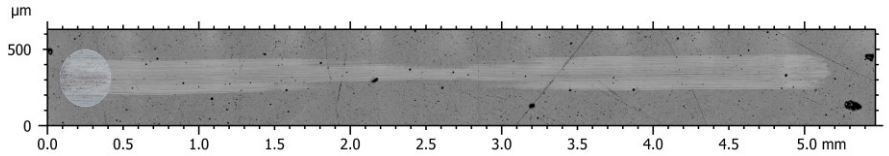
Analysed Coating System

Layer	Yield strength [MPa]	Simulated max. Stress [MPa]
a-C:H	> 20000	**220**
Cr containing interlayers	8000-17000	**140-240**
Substrate	~ 6000	**250**

- Due to smaller load the stress maximum is closer to the surface
- Stress is factor 60-90 below strength of material

Von Mises Stress Distribution

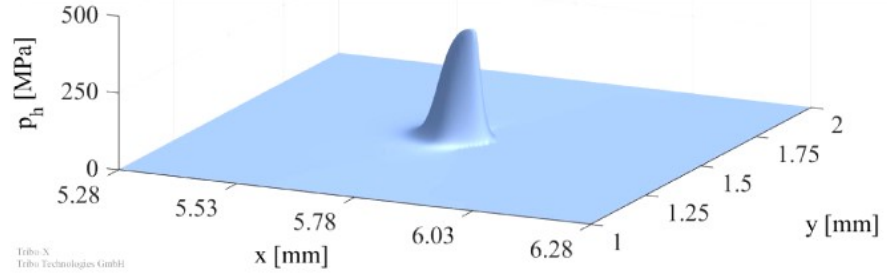


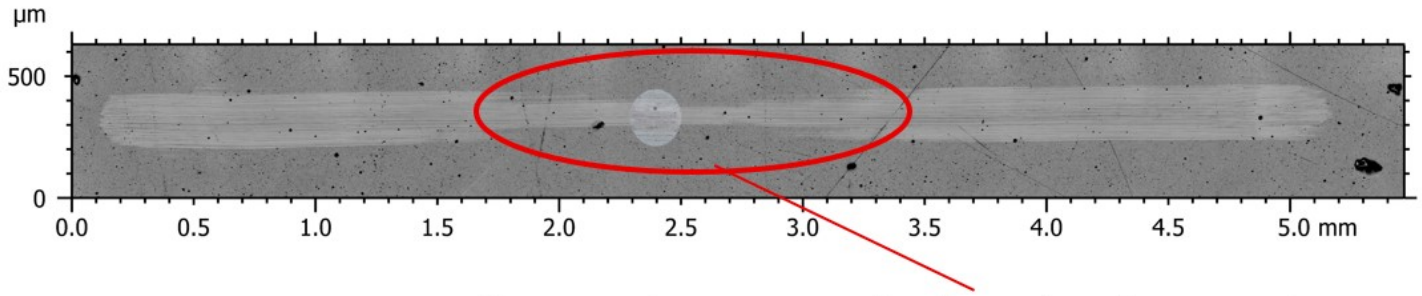


Diamond Like Carbon coatings for gears
Digital Twin - SRV Tests

II) SRV Test “Mixed Friction”

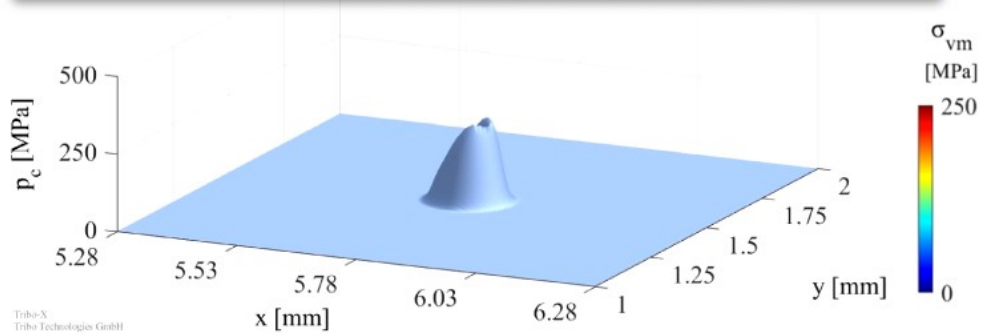
Hydrodynamic Pressure



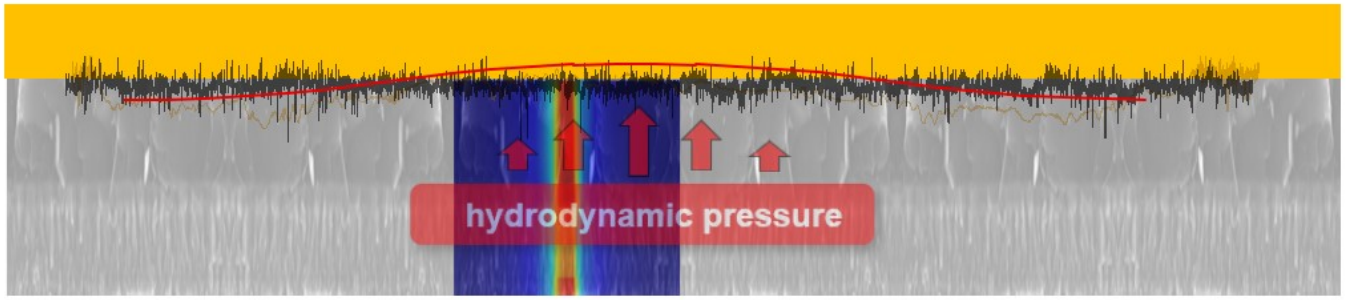


Decreased wear generation in center of wear mark

Solid Contact Pressure

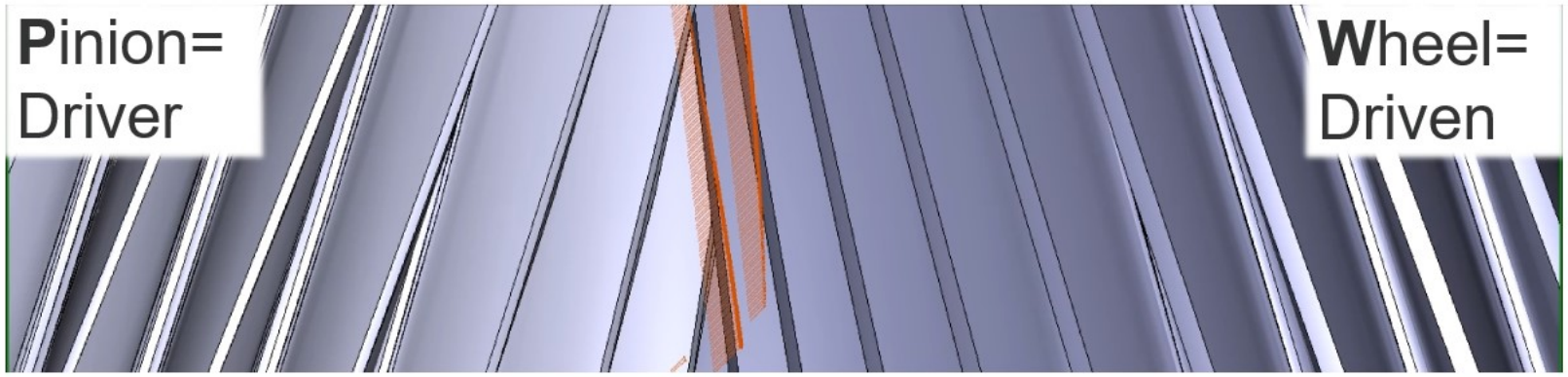


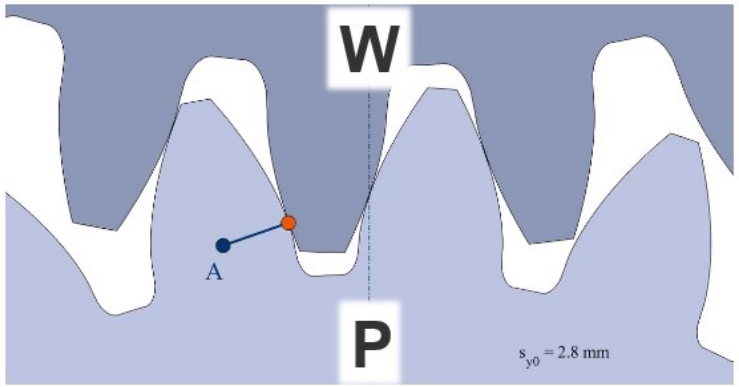
Wear over time

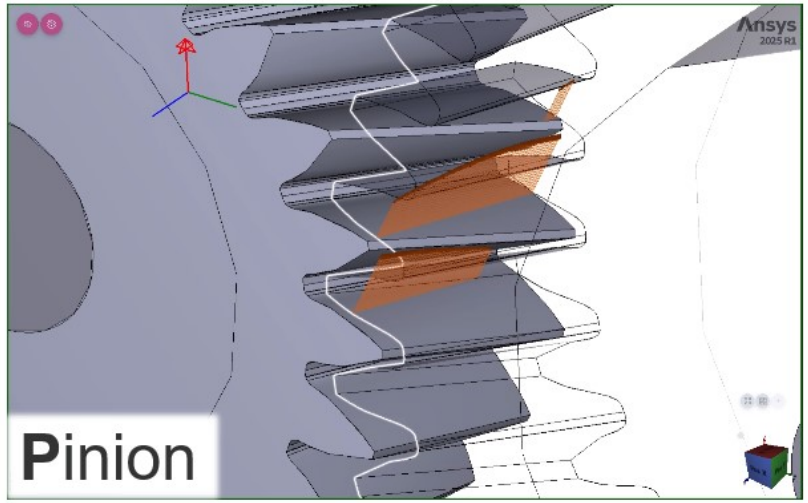


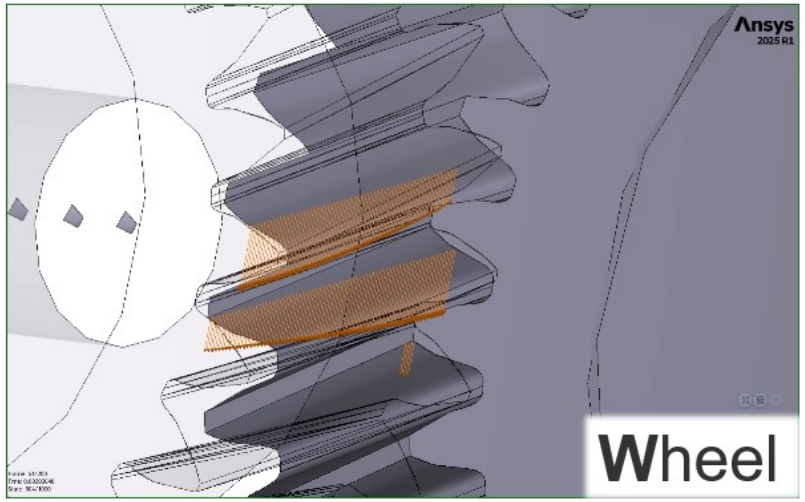
Digital Twin - helical spur gear

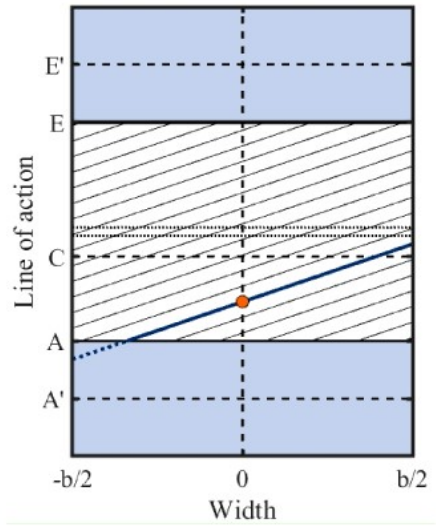
Optimizing Diamond Like Carbon coatings for gears
Digital Twin - helical spur gear





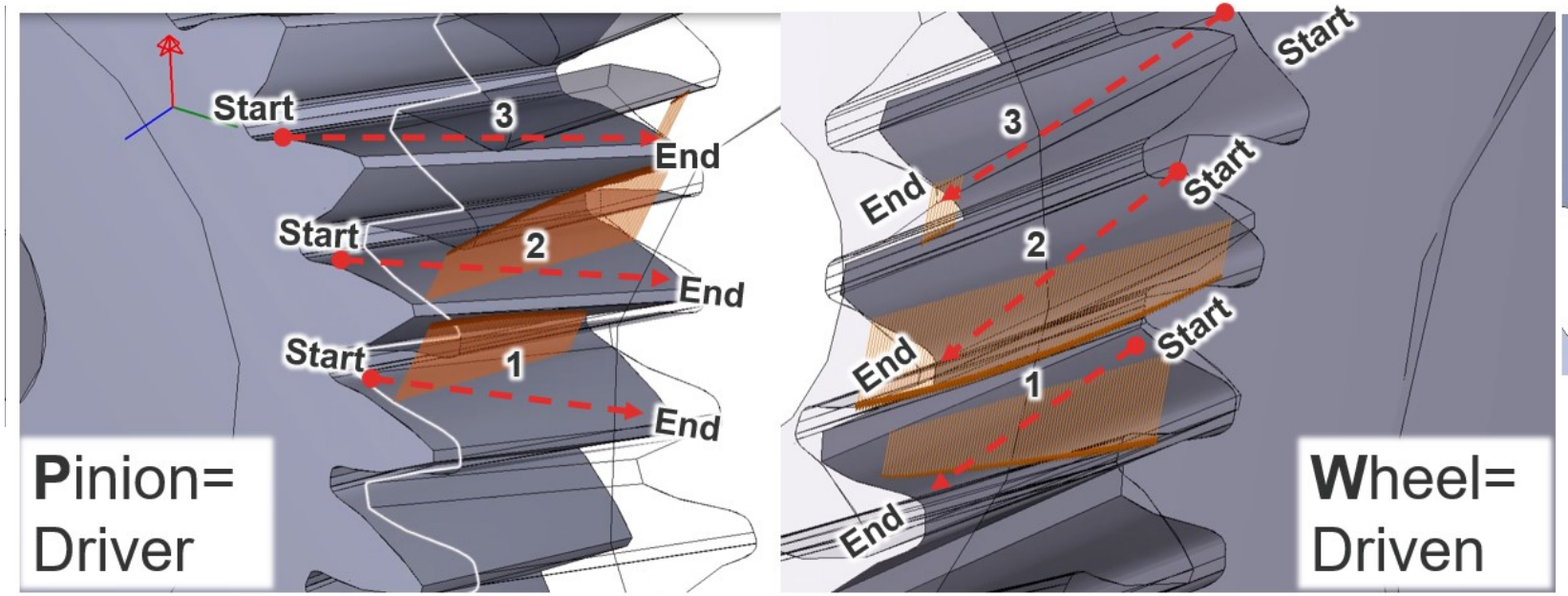


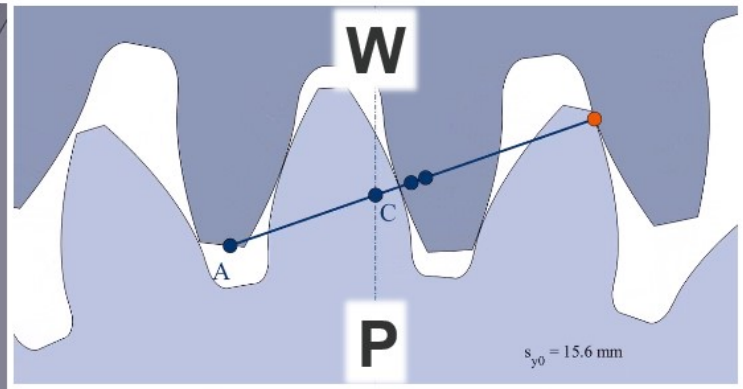


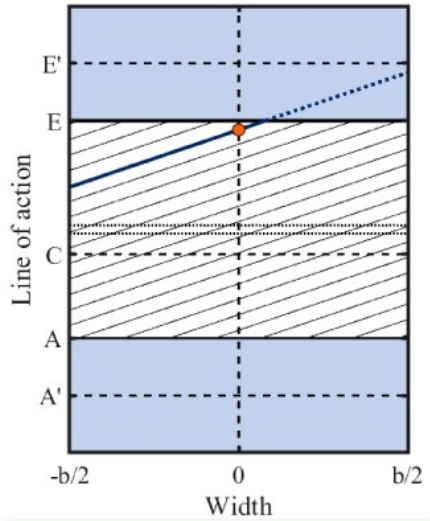


Contact line from one edge diagonale to the other edge

Optimizing Diamond Like Carbon coatings for gears
Digital Twin - helical spur gear

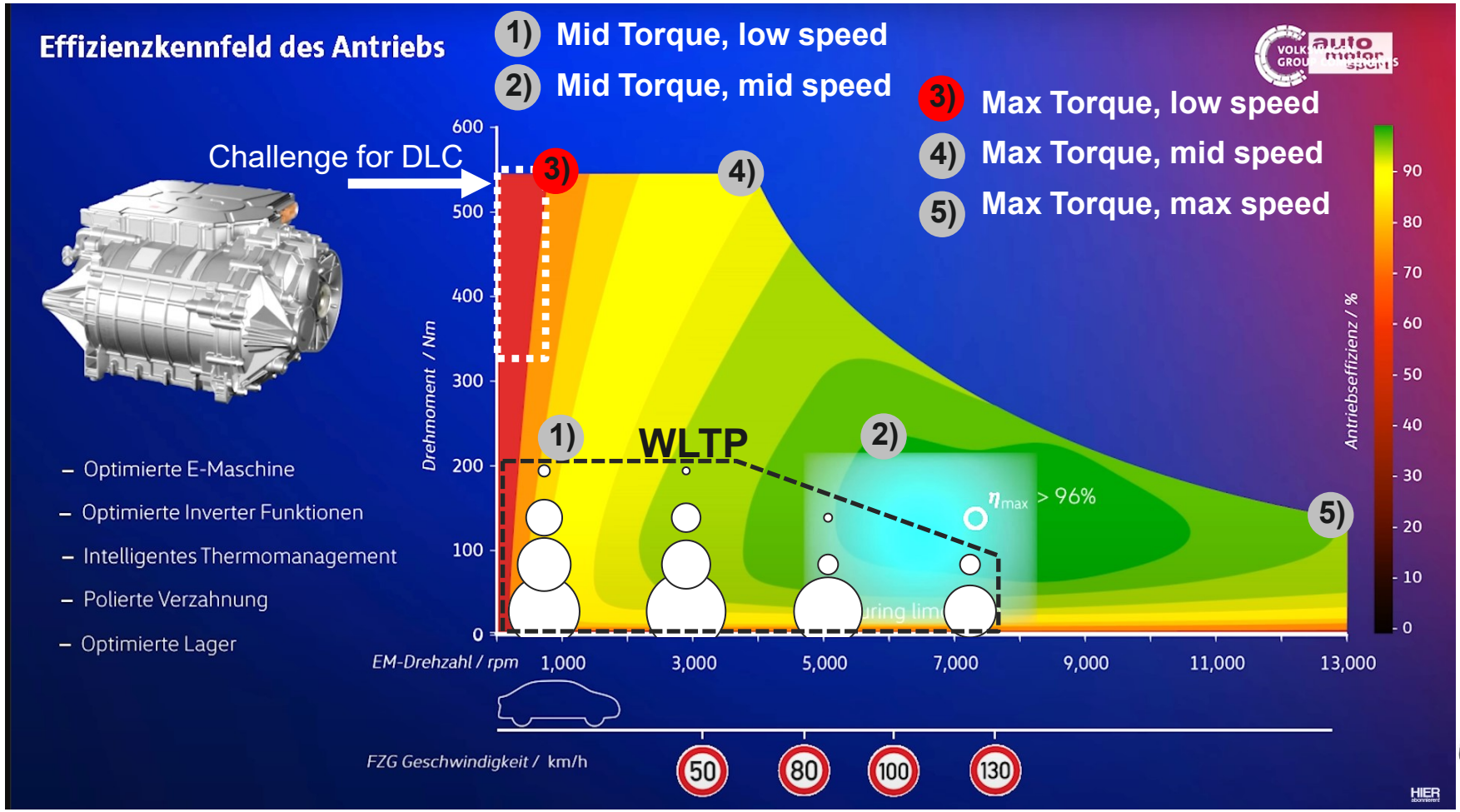


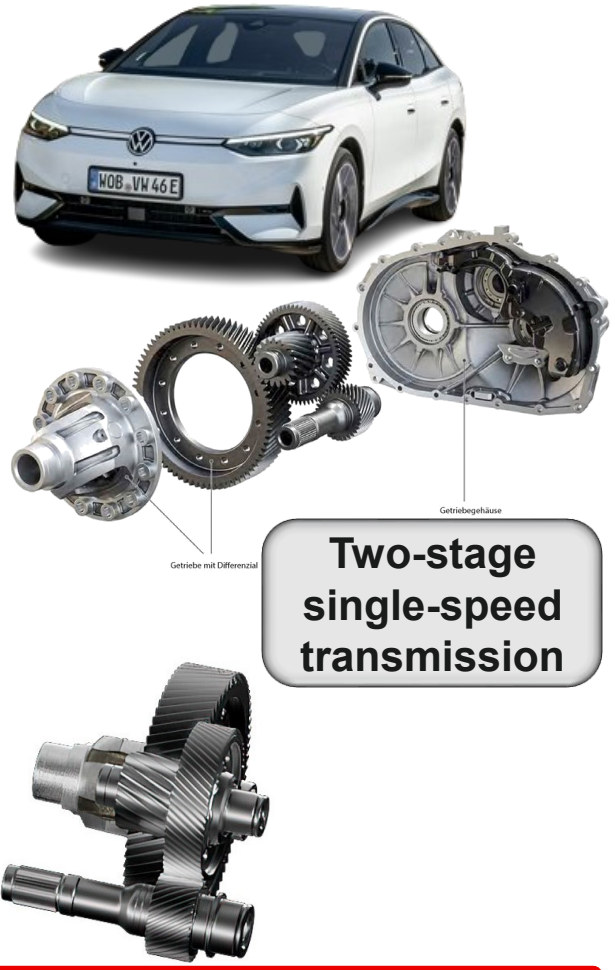




Contact line from one edge diagonale to the other edge

Optimizing Diamond Like Carbon coatings for gears
Digital Twin - helical spur gear



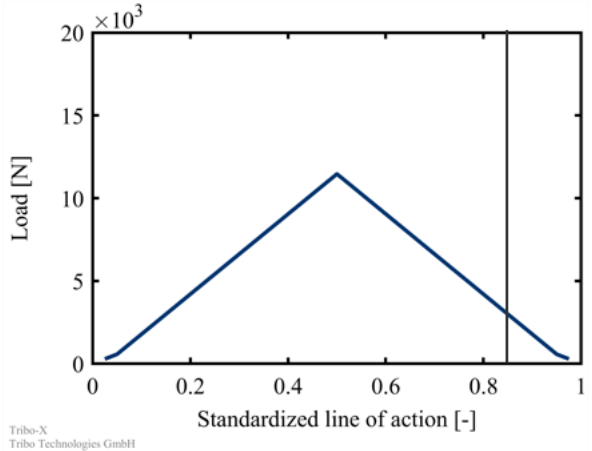


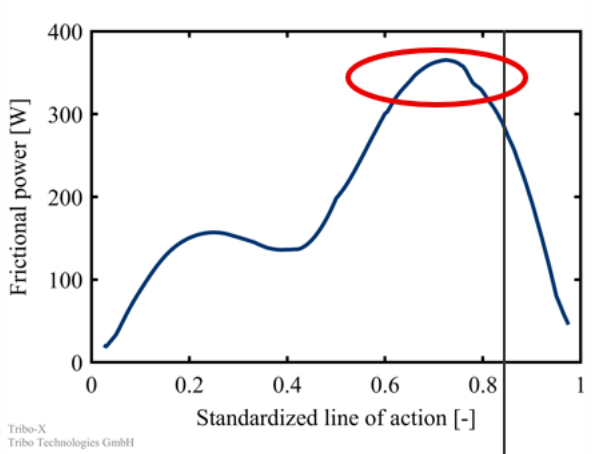
Challenge for DLC coatings at high load and low speed

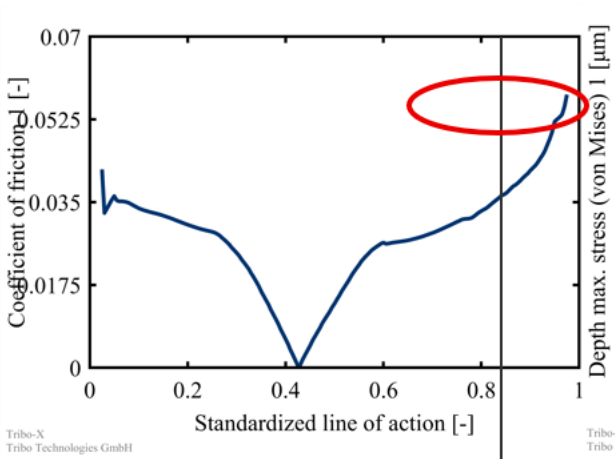
Sources: Auto Motor und Sport -- VW ID7; VW; *WLTP frequency distribution

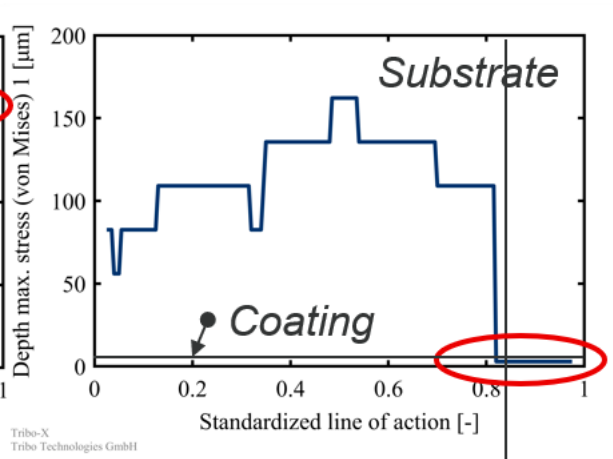
Optimizing Diamond Like Carbon coatings for gears

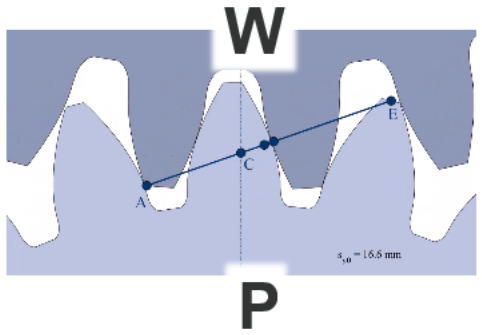
Digital Twin - helical spur gear - max torque, low speed

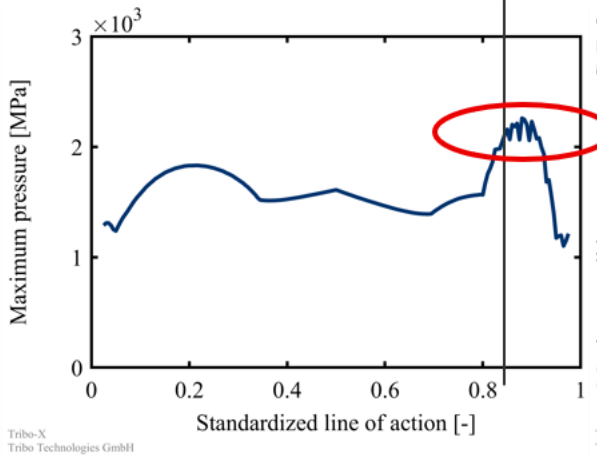


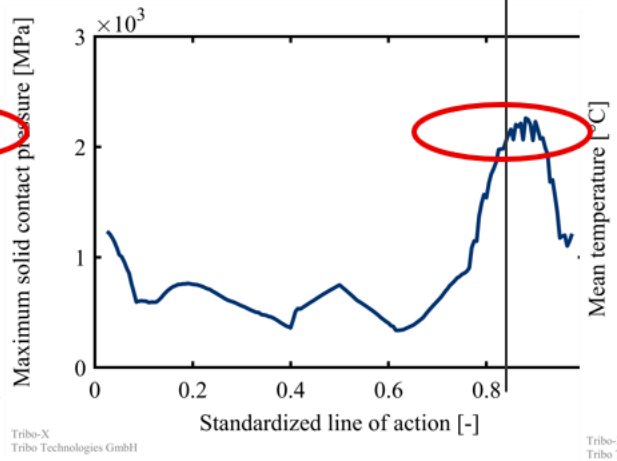


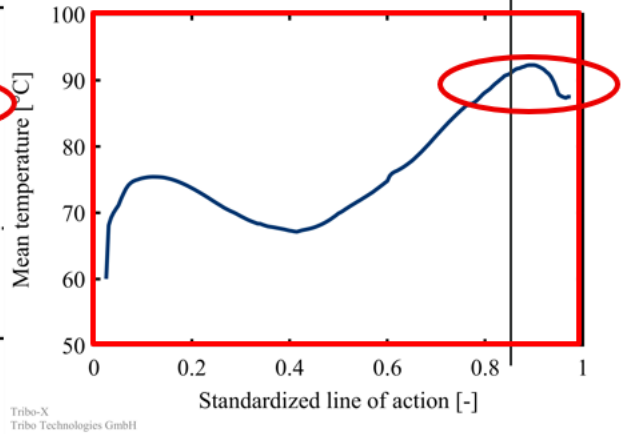








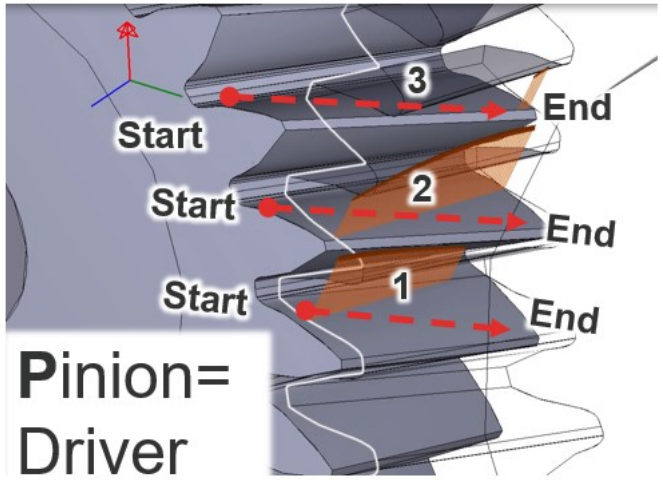


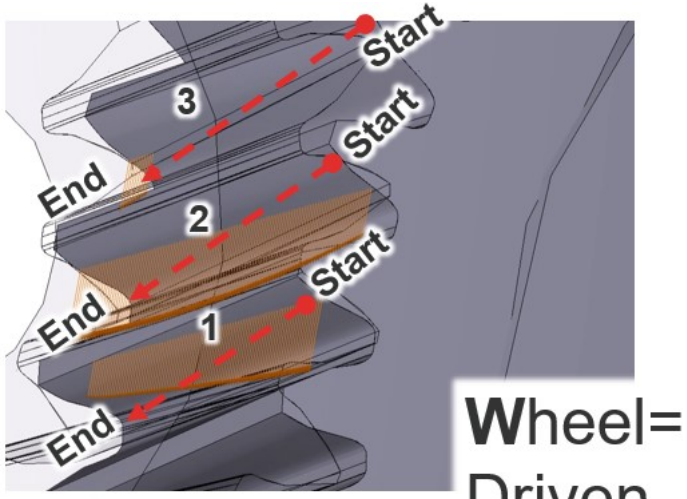


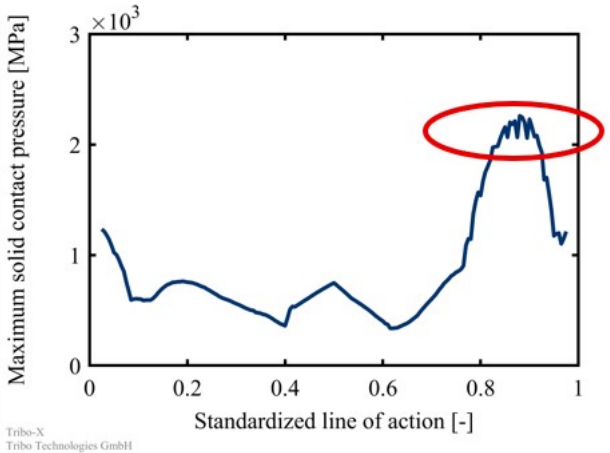
Stress inside the coating reaches maximum at the end of each tooth contact (line of action)

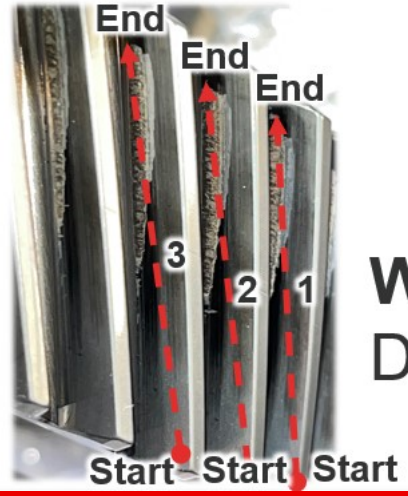
Optimizing Diamond Like Carbon coatings for gears

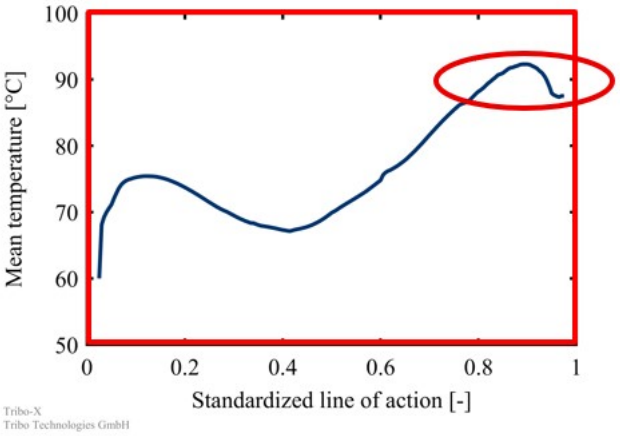
Digital Twin - helical spur gear - max torque, low speed









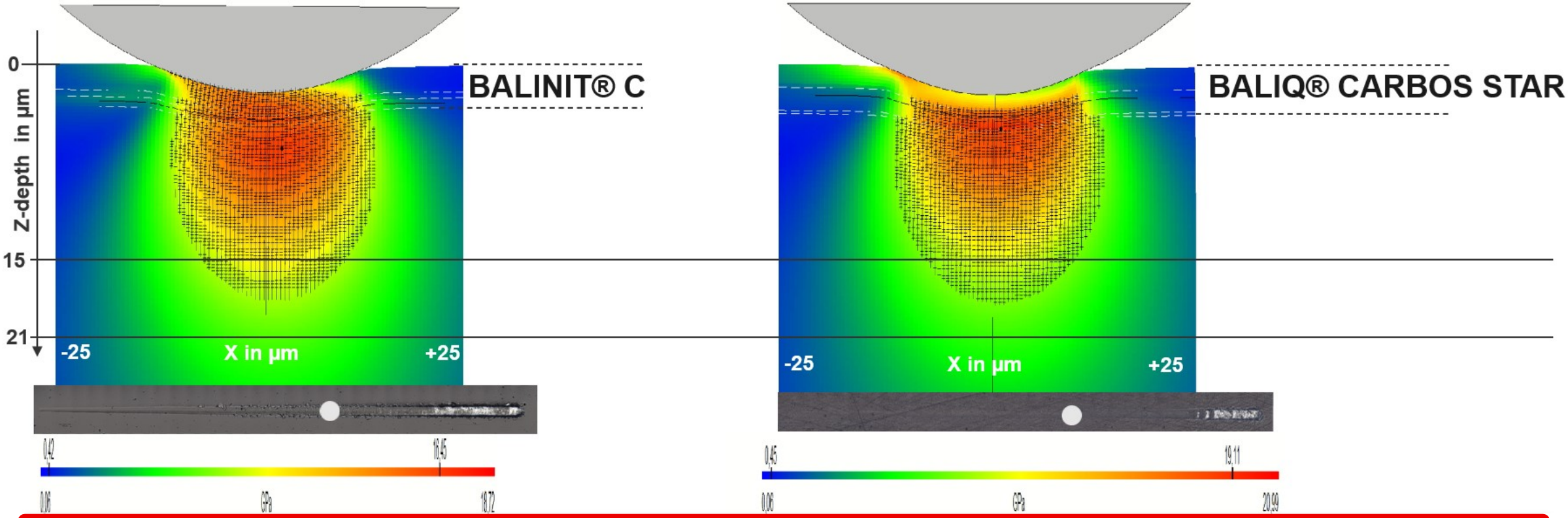


Comparison simulation with reality → it matches! This selected coating is NOT suitable for the Tribosystem

Digital Twin - Scratchtests

Optimizing Diamond Like Carbon coatings for gears
Simulation of Scratchtests

Load 1-10N; track 0-2000 µm; R_tip = 50 µm; + black cross means: von Mises stress > yield strength



BALINIT® C (WC/C) has less yield strength compared to BALIQ® CARBOS STAR (a-C)

Tribometer tests

Diamond Like Carbon coatings for gears
SRV® Tests on flat samples from Dummy Wheel

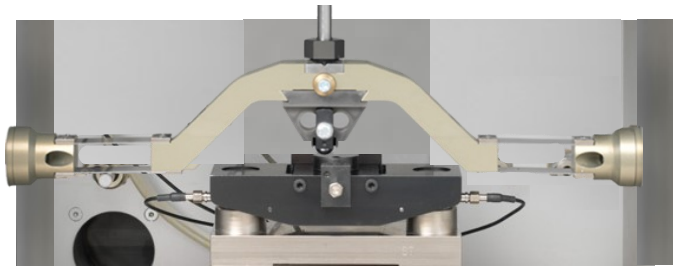
oerlikon balzers

LUBRICATED & HEATED SRV5 Tribometer Test in Boundary Lubrication Regime

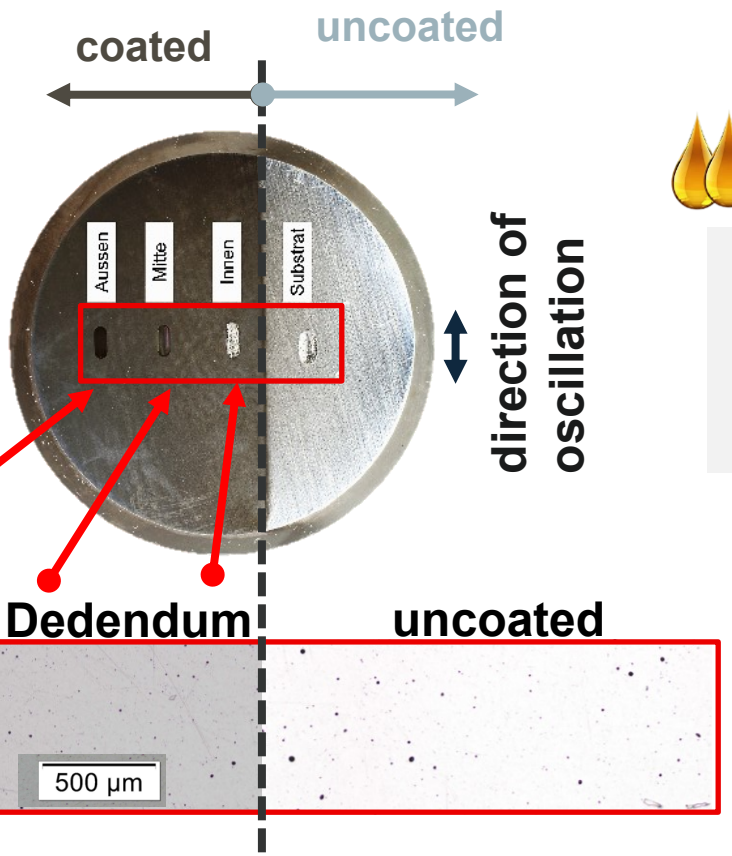
Oil (fully additivated)	Value	Unit
Viscosity @ 40°C	< 25	mPas
Viscosity @ 100°C	< 5	mPas

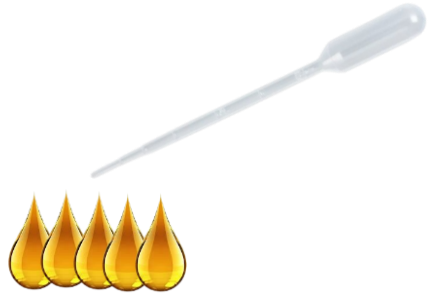
Data	Value	Unit
Ball diameter	10	mm
Stroke	1	mm
Frequency	50	Hz
Load	(50 for 30 sek.); 300	N
Temperature	80	°C
Duration	30	min

Roughness	Rz	Unit
Ball 100Cr6	G10	µm
Special flat sample*	1	µm

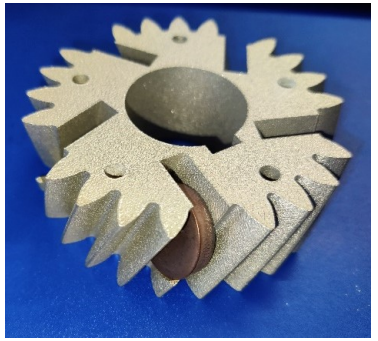


Tests based on ISO 19291





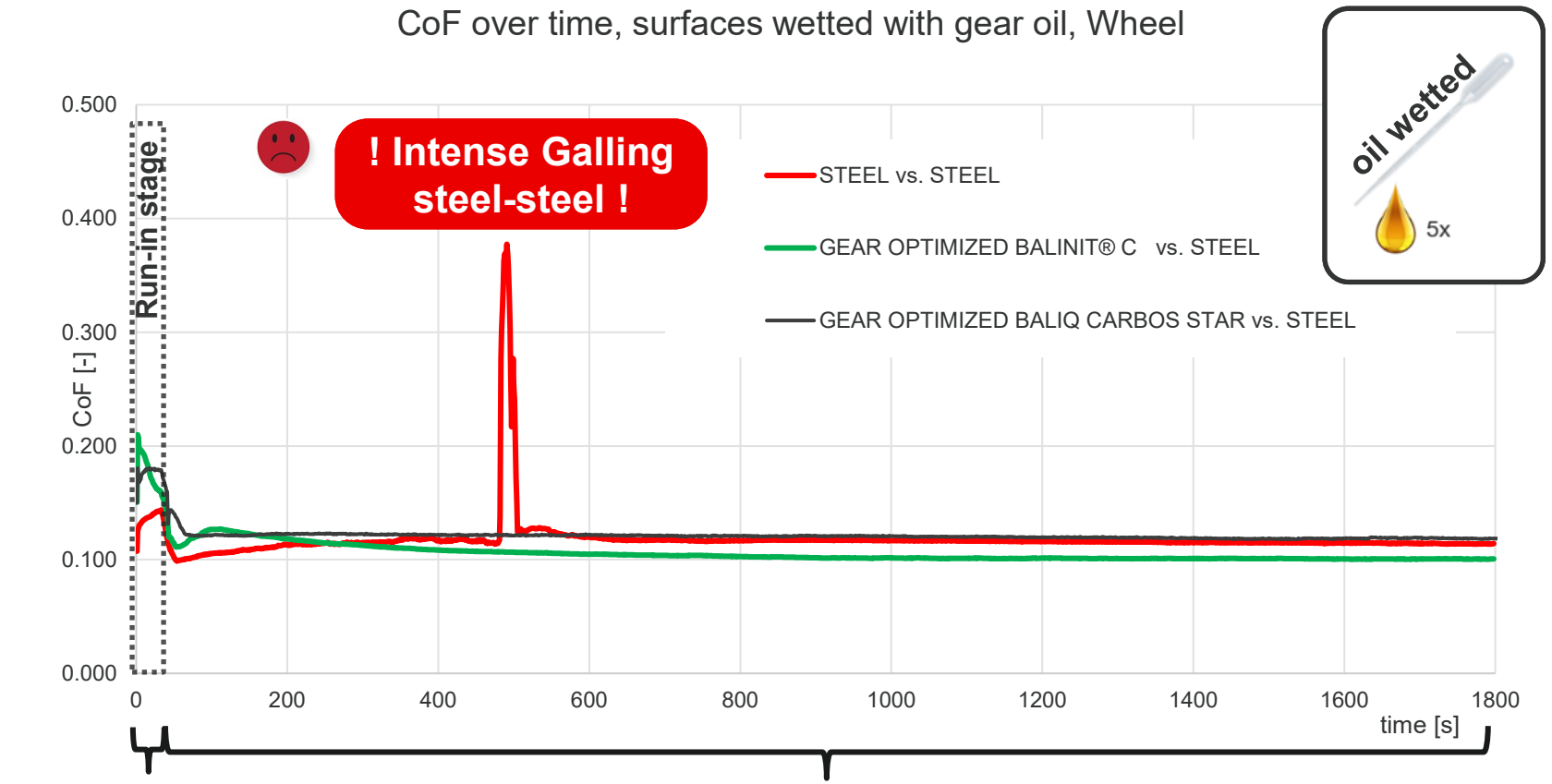
Only **5x drops of low viscosity gear oil** to be in the lubrication regime of **boundary lubrication**

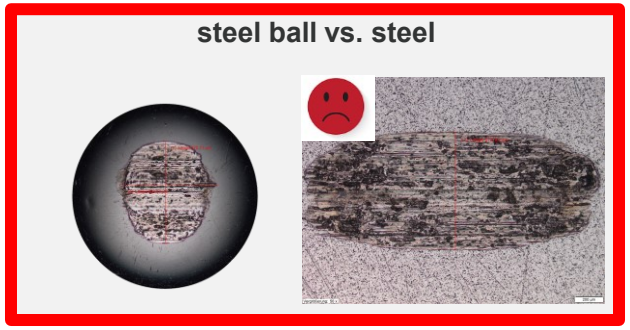


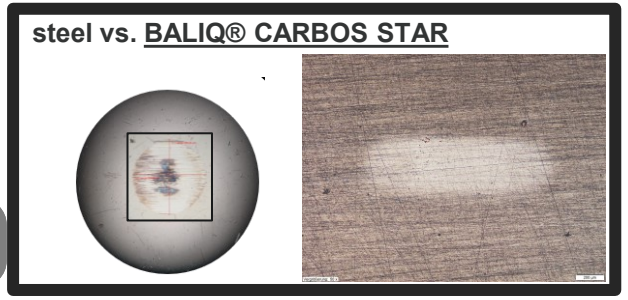
*Material: case hardened 16MnCr5, Roughness Rz 1 µm, Hardness ~58-59 HRC

Diamond Like Carbon coatings for gears
SRV-Tests on flat samples from Dummy Wheel @Pitch

oerlikon balzers





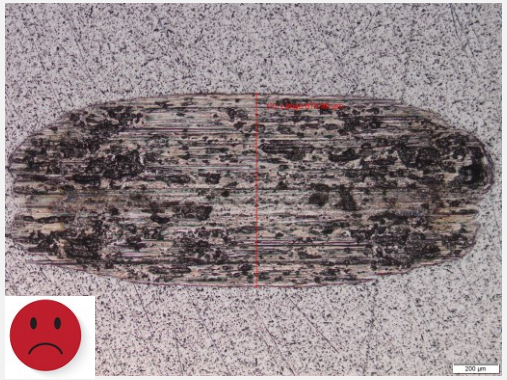
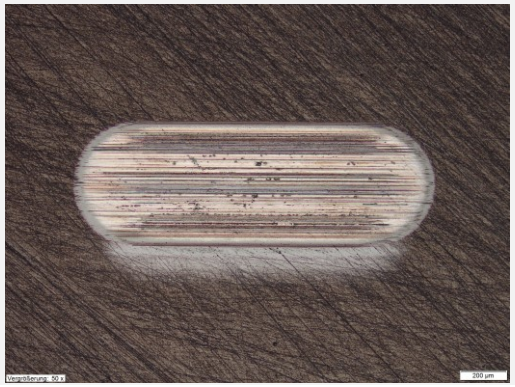
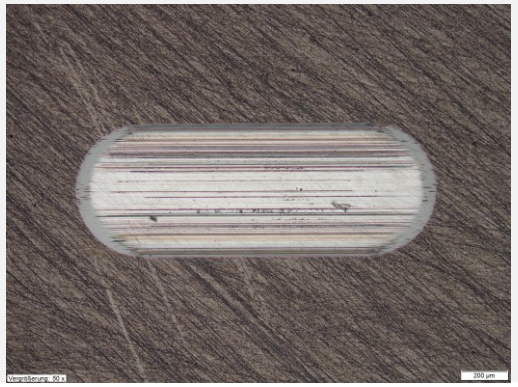
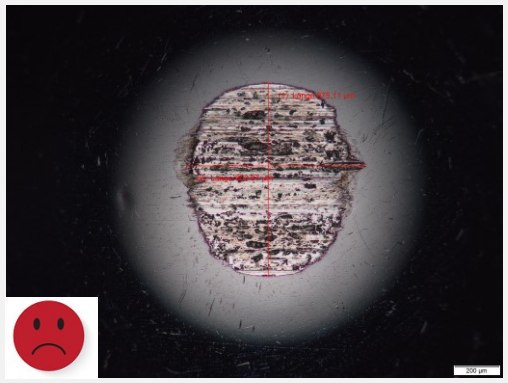
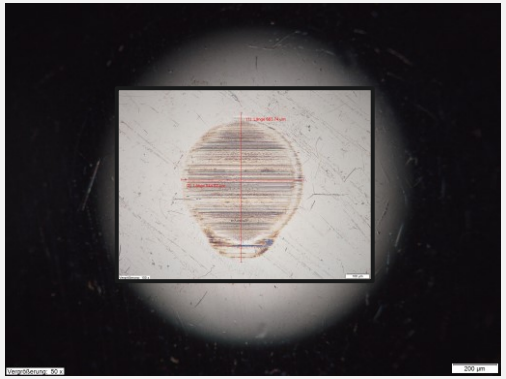
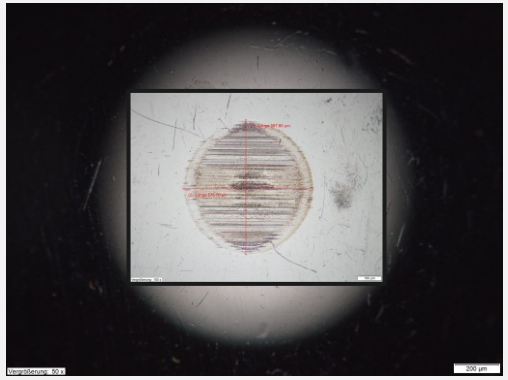
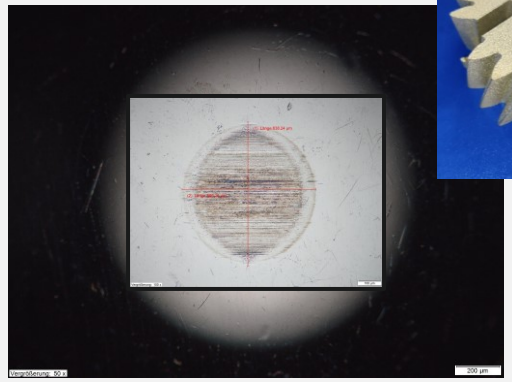


~180.000x stressed @ pitch

! No galling ! with GEAR OPTIMIZED BALINIT® C

Diamond Like Carbon coatings for gears
GEAR OPTIMIZED BALINIT® C on gear wheel

oerlikon balzers

steel	Dedendum GEAR OPTIMIZED BALINIT® C	Pitch GEAR OPTIMIZED BALINIT® C	Addendum GEAR OPTIMIZED BALINIT® C
			
			

! No galling ! with GEAR OPTIMIZED BALINIT® C

#4834-1070

Diamond Like Carbon coatings for gears

GEAR OPTIMIZED BALIQ® CARBOS STAR on gear wheel

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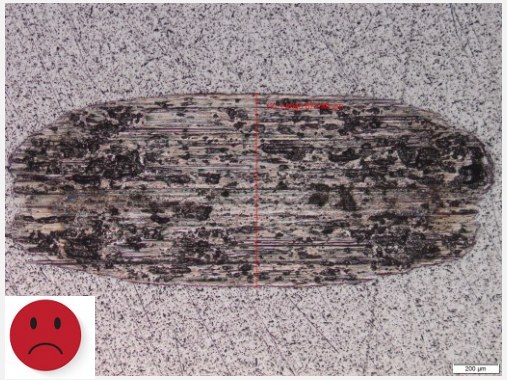
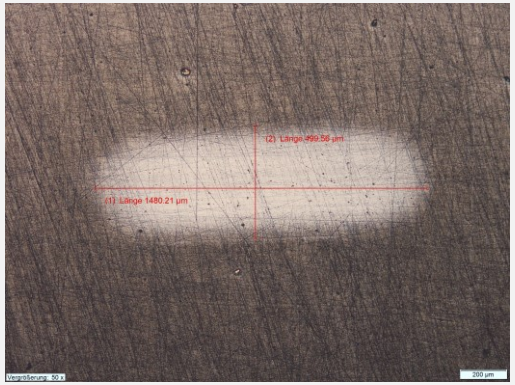
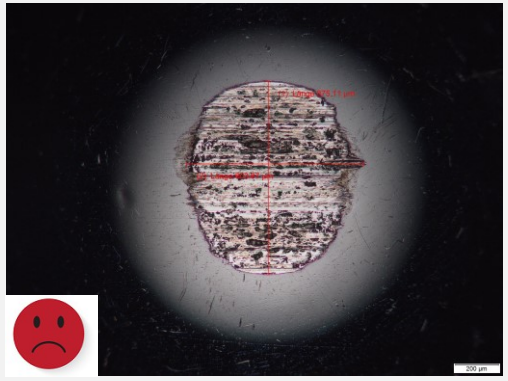
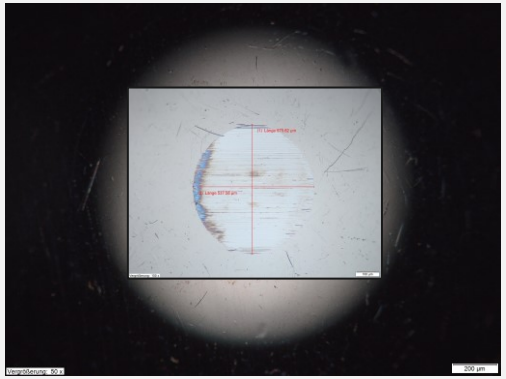
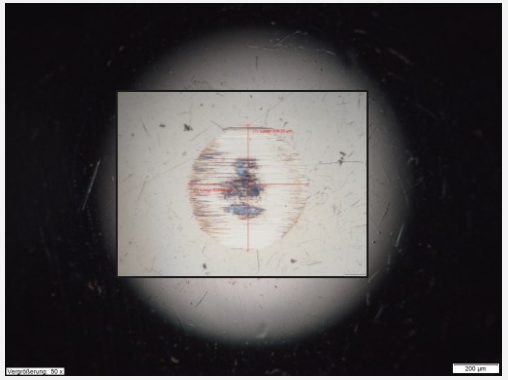
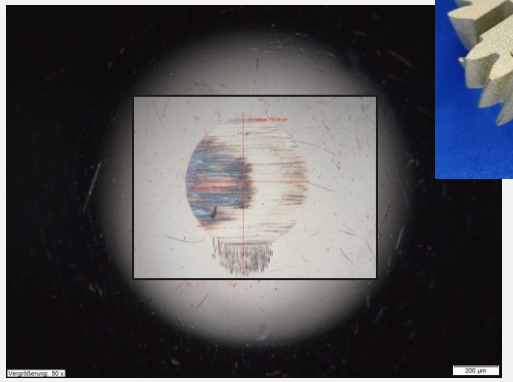
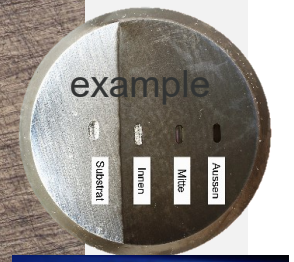
steel	Dedendum GEAR OPTIMIZED BALIQ® CARBOS STAR	Pitch GEAR OPTIMIZED BALIQ® CARBOS STAR	Addendum GEAR OPTIMIZED BALIQ® CARBOS STAR
			
			



! No galling & almost no wear ! with GEAR OPTIMIZED BALIQ® CARBOS STAR

A242414_#3326-1365 & #3403_1365

Diamond Like Carbon coatings for gears
SRV-Tests on flat samples from Dummy Wheel @Pitch

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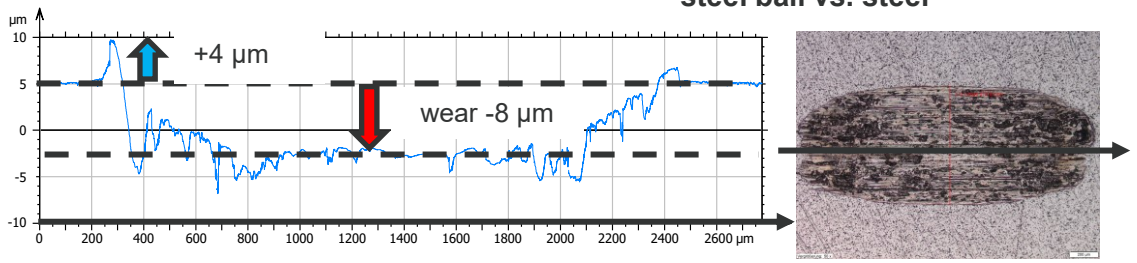
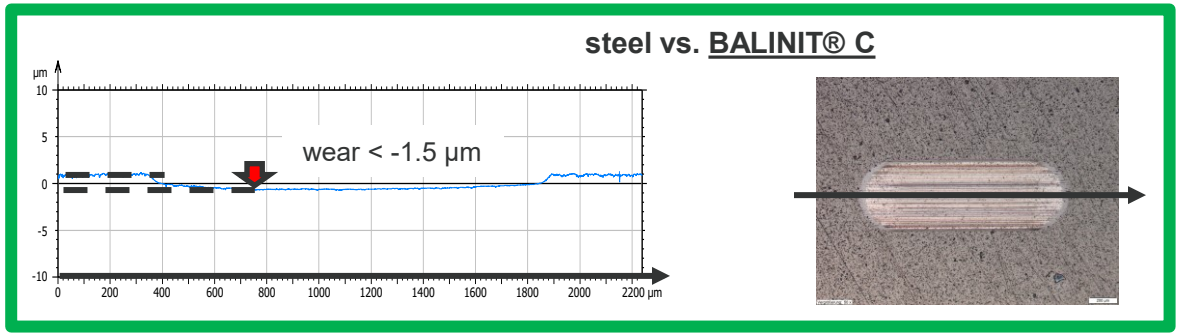
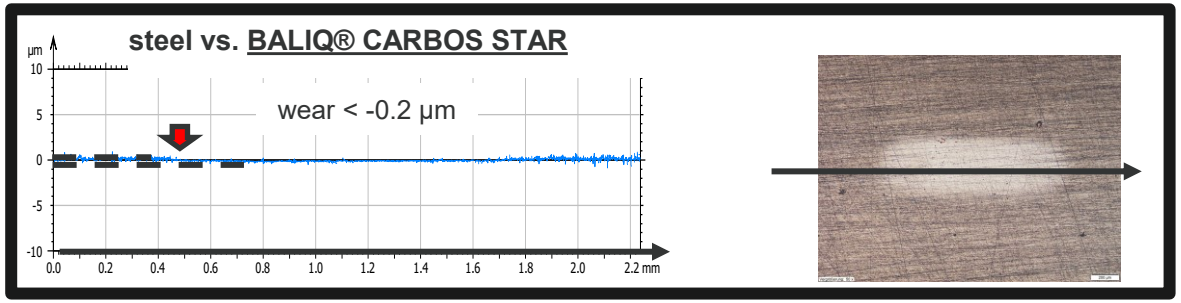
steel ball vs. steel



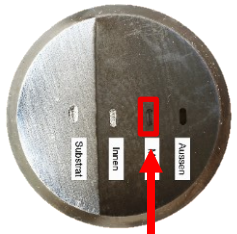
steel vs. BALINIT® C



steel vs. BALIQ® CARBOS STAR

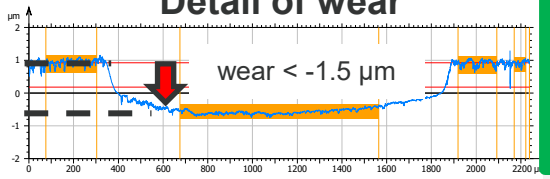


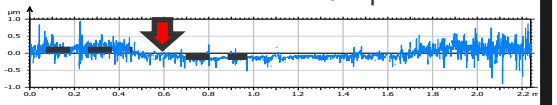
Profile



Coating thickness @Pitch = 2.25 µm

Detail of wear





steel ball vs. steel

steel vs. BALINIT® C

steel vs. BALIQ® CARBOS STAR

With GEAR OPTIMIZED BALINIT® C and BALIQ® CARBOS STAR the wear depth is still inside the coating

Know-How
DLC coatings for gears

Diamond Like Carbon coatings for gears
Valuable Know-How

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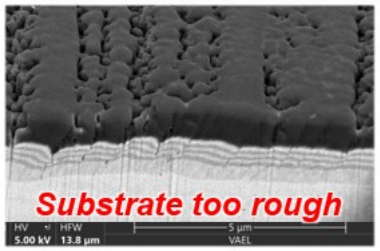
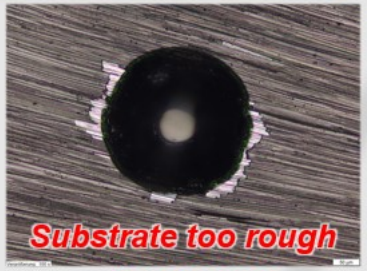
Surface Topography



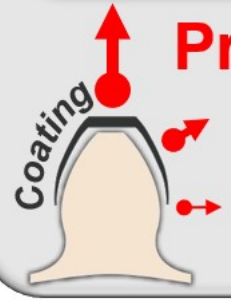
coating growth quality

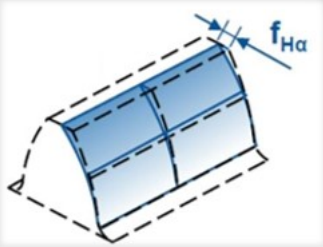


Spallation

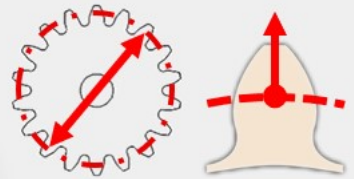
Coating Thickness Distribution

Profile

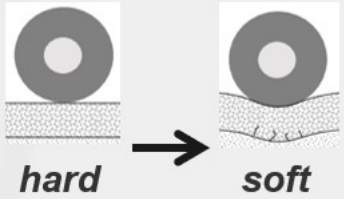




Coating Process Temperature

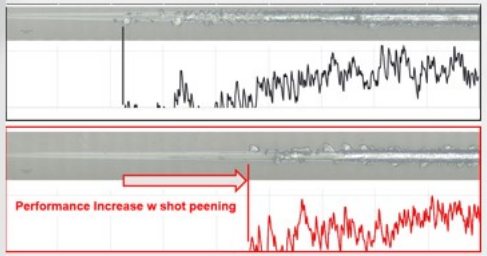


Diameter



Direct: Substrate Hardness

Indirect: Durability



Direct: Intrinsic Stress

Indirect: Durability

Know-How

Summary

Diamond Like Carbon coatings for gears
Summary & Outlook

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Summary:

- **Digital Twin of substrate and coating helps to explain the wear mechanism**
  - **typical continuous wear (von Mises stress < yield strength)**
  - **excessive wear (von Mises stress > yield strength)**
- **TEHL Simulations help to explain the wear behaviour of coated gears**

STANDARD PERFORMANCE:

- **BALINIT® C (WC/C) < 165°C Substrate Temperature**
  - Rz < 2 µm, (~Ra < 0.3 µm) necessary, e.g. honing

HIGH PERFORMANCE:

- **BALIQ® CARBOS STAR (a-C) < 165°C Substrate Temperature**
  - Rz < 1 µm, (~Ra < 0.2 µm) necessary, e.g. polish honing

Outlook 2025:

- **BALIQ® CARBOS STAR (a-C) gear performance and efficiency tests together with different customers**
- **Testing different coating combinations (coating #1 @pinion, coating #2 @wheel)**

THANK YOU.

Contact us

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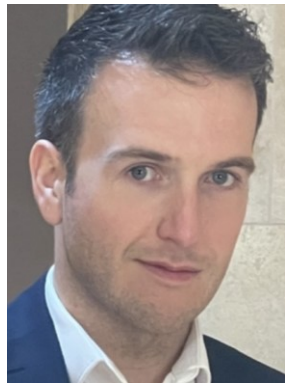

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