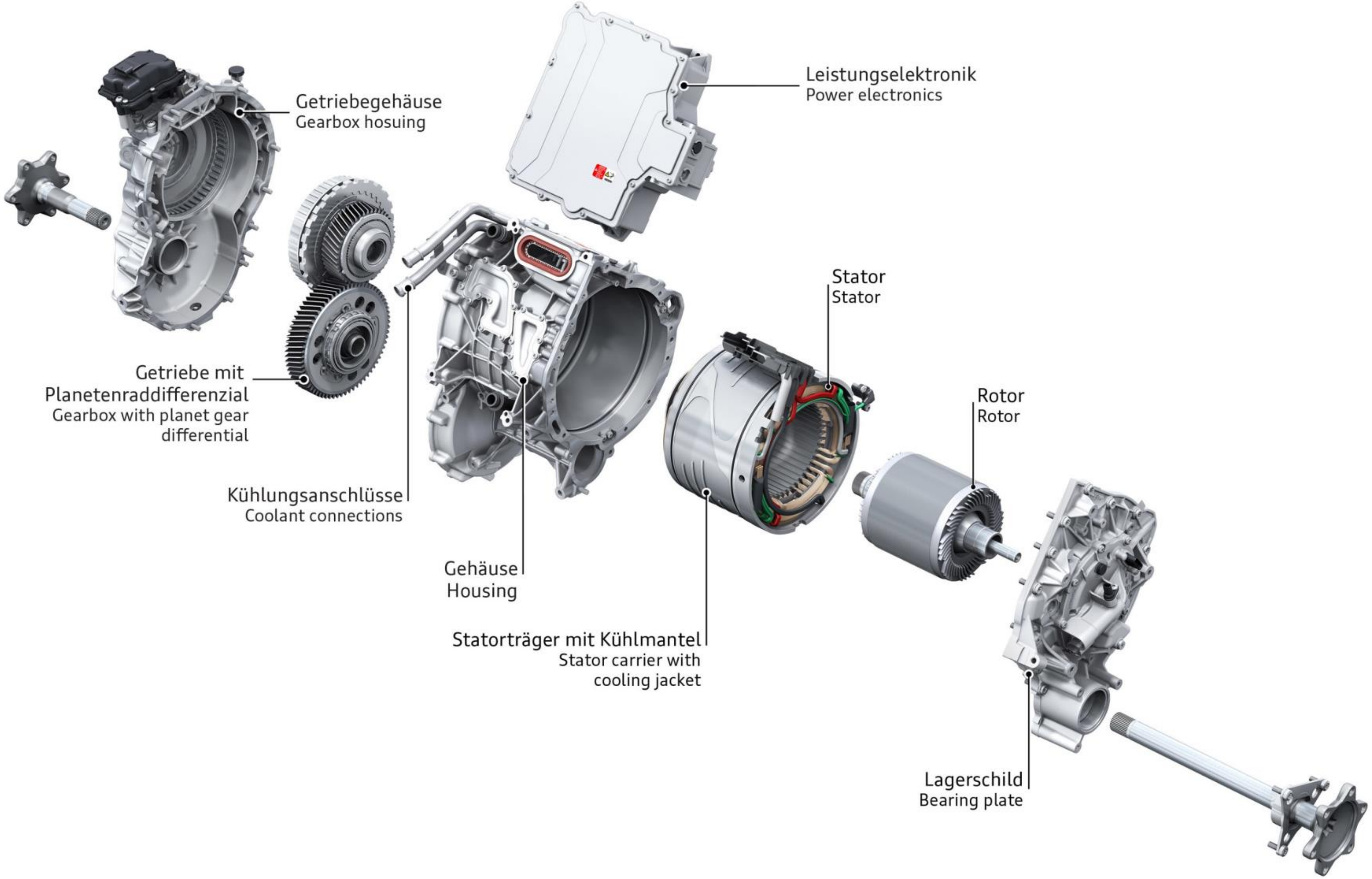
Tribology in e-Mobility

Boris Zhmud

TribNet tribonex

Powertrain of a Battery Electric Vehicle (BEV)



Audi e-tron powertrain, front electric motor (Source: ElectricHasGoneAudi.net)

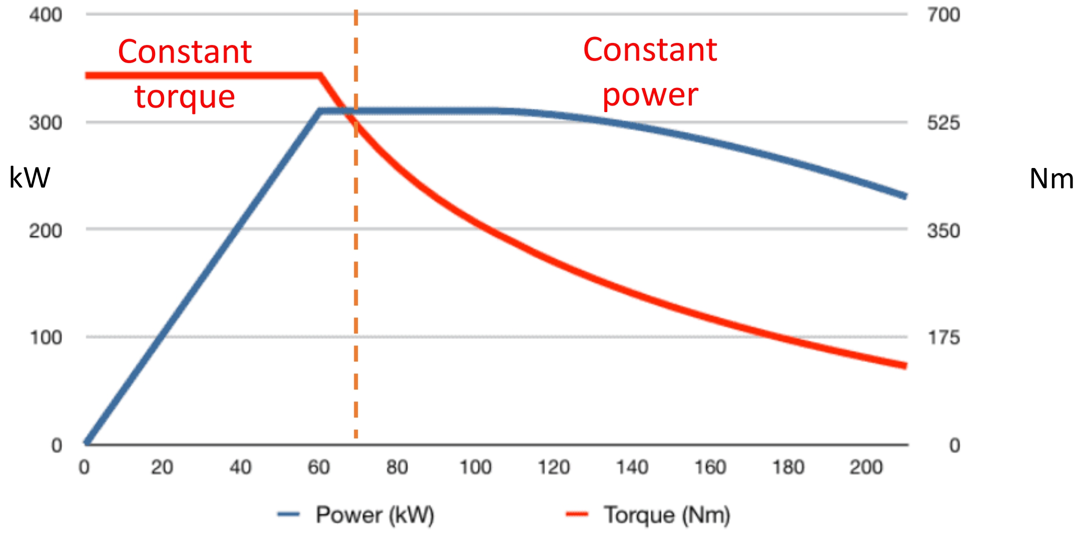
EV Transmission vs ICEV Transmission

Loads and Speeds

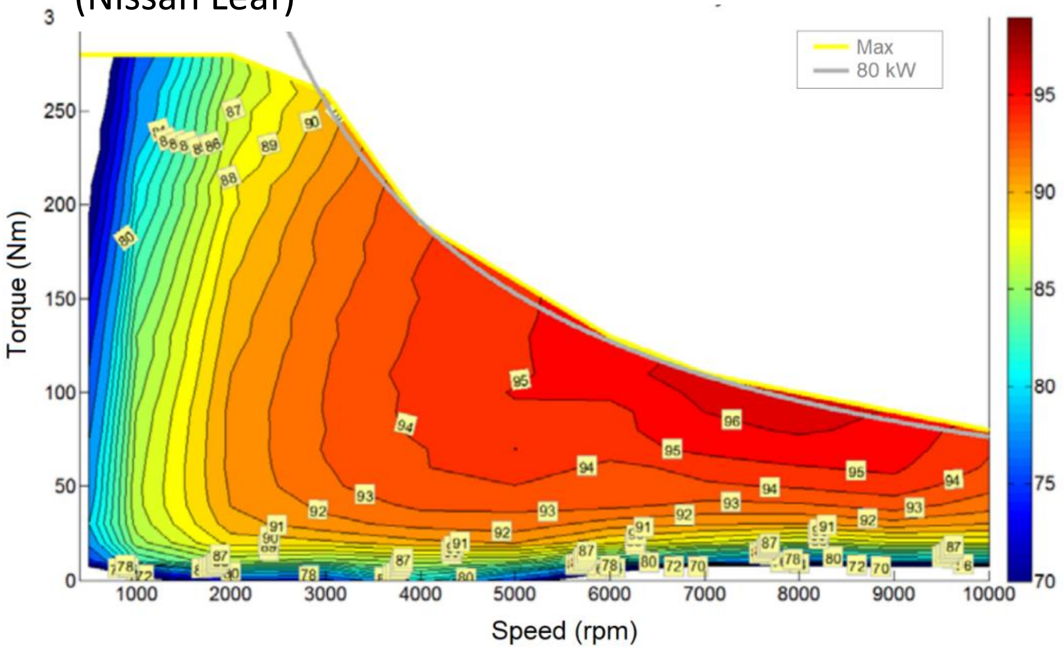
Vehicle wheels won’t rotate over 1000 rpm at legal speeds.
⌀ 29”: 119 rpm at 16 km/h (10 mph); 595 rpm at 80 km/h (50 mph); 833 rpm at 113 km/h (70 mph)

For an ICE: usual working range 1000-6000 rpm with max power close to the redline.
Electric motor may go over 20,000 rpm, instant high torque available at low rpm

Tesla Model S
Torque and power

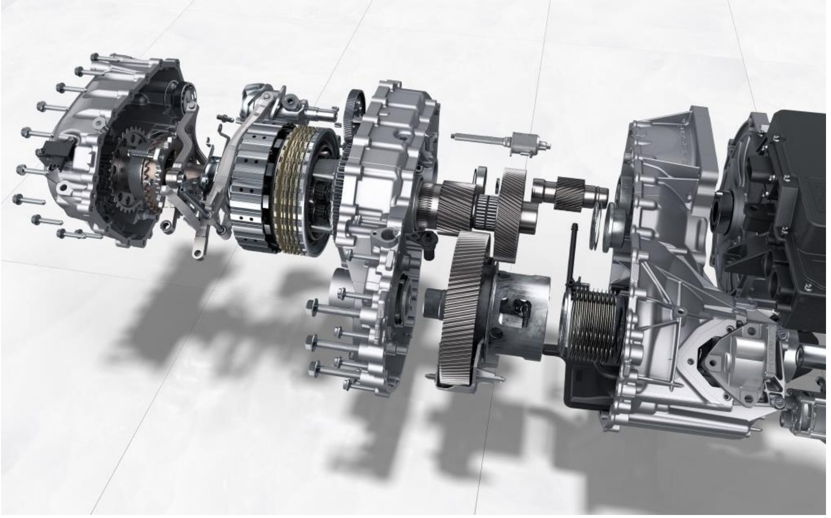


Motor/inverter efficiency map
(Nissan Leaf)



Wide Diversity of Hardware

BorgWarner 1-speed eGearDrive



ZF 2-speed EV transmission

Eaton 4-speed HD EV transmission

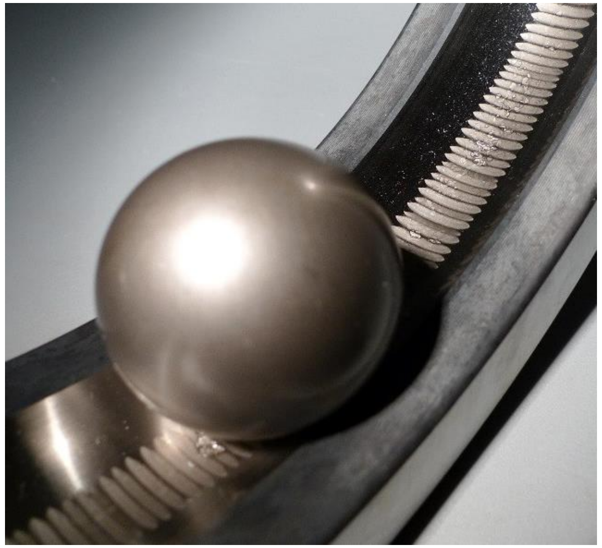
Tribological Problems

- Gear tribology (friction, wear, scuffing, pitting, NVH)
- Bearings
- Seals
- Insulating materials
- Transmission fluids

EV Bearings

Electrically Induced Bearing Damage (EIBD)

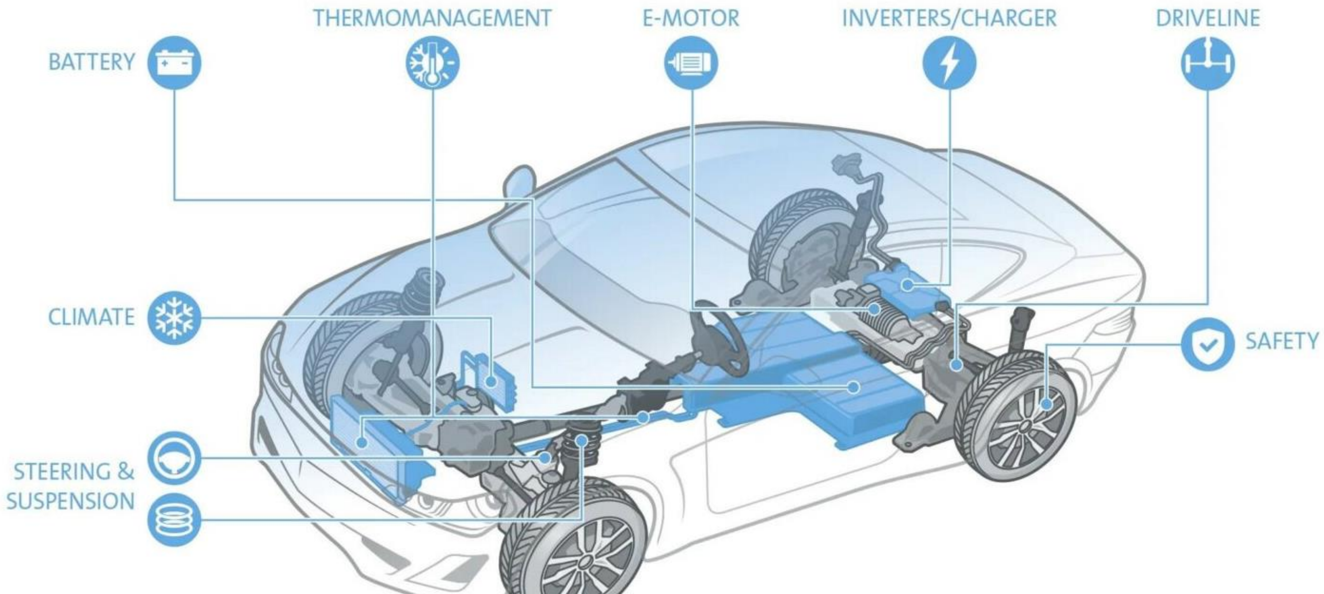
Inverter or
Variable Frequency Drive



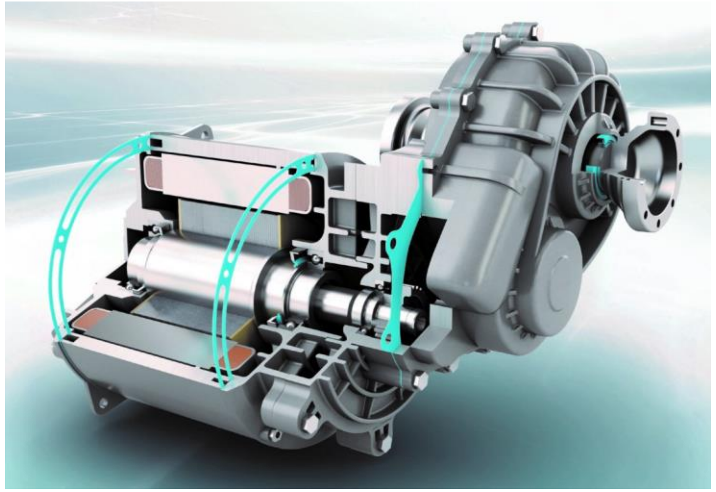
Root cause: Shaft voltage – the voltage difference between the motor shaft and the frame

Remedies: Bearing insulation, Hybrid ceramic bearings, Shaft grounding, Common mode chokes, Conductive greases, etc.

EV Seals



Source: Freudenberg Sealing Technologies



Rapid rotary seals

Low friction (PTFE, FKM, composites)

High speed (surface speeds upto 50 m/s)

Wet, dry or minimum lubrication running

Chemical and thermal stability

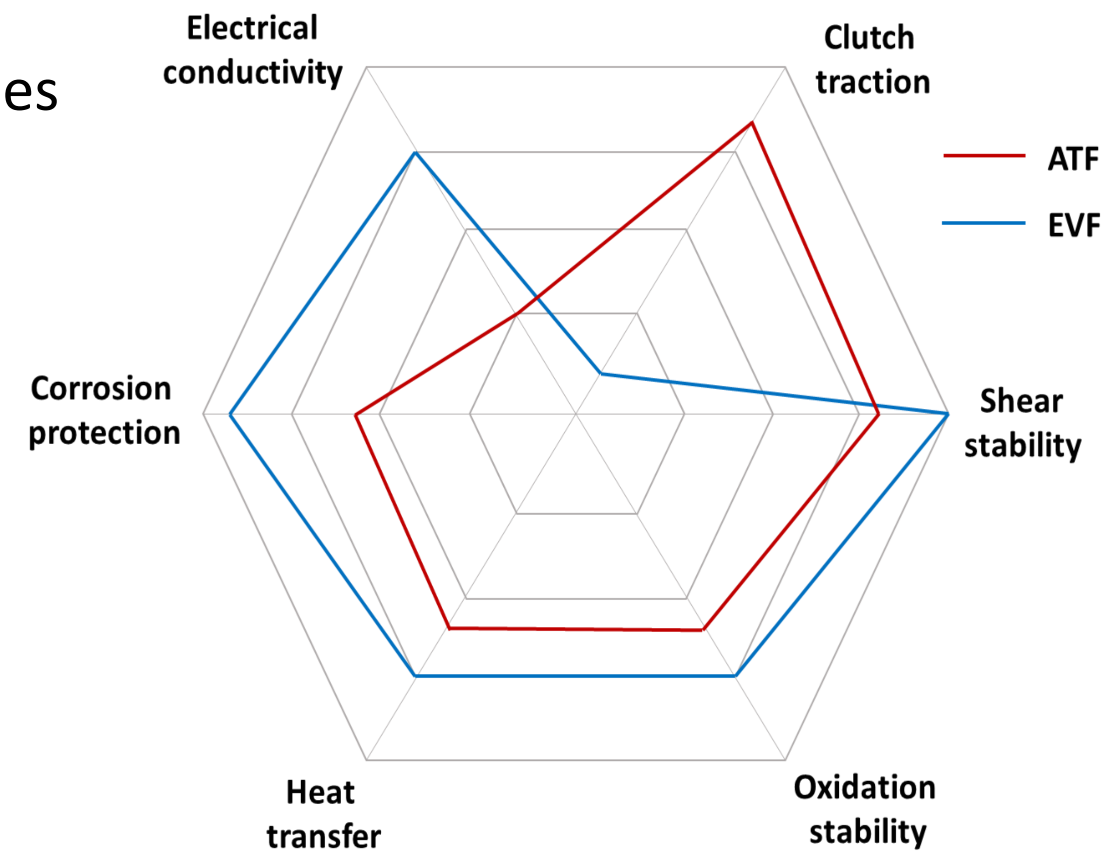
Electric properties (conductive or insulating)

EV Transmission Fluids

Differences from Conventional Transmissions

- Higher input shaft speeds
- Higher torques for budget cars
- Higher amplitude of alternating stresses
- No clutch (for 1-speed gearboxes)
- Presence of electrical circuits
- Higher NVH requirements

But what is "conventional"?
Manual, Automatic, Dual-Clutch, CVT?



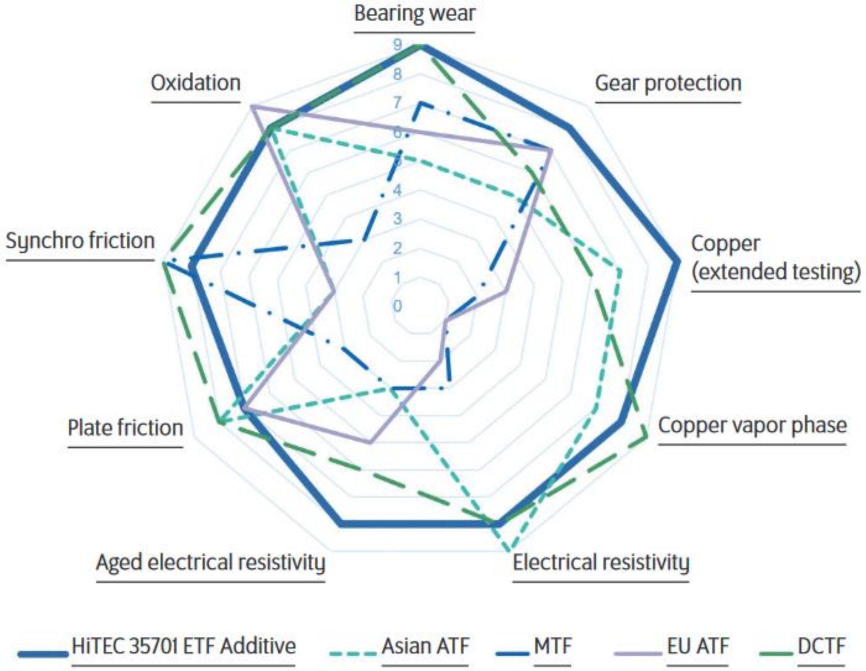
Cat-and-Mouse Development Game

Most e-transmission hardware is developed relying upon the existing transmission fluid technology.
As a result, the existing transmission fluids often are an acceptable choice for this hardware.

Transmission		Manufacturer	FHEV / BEV (Placement)	Total Sales* (millions)	Top Models	Fluid Type (brand name)
EVT		Toyota	FHEV (P23)	17.2	Toyota Prius	**ATF** (Toyota WS)
		Honda	FHEV (P13)	1.2	Honda Accord	**ATF** (Honda DW-1)
AT		Hyundai	FHEV (P2)	0.6	Hyundai Sonata	**ATF** (Hyundai SP-IV)
		ZF Group	FHEV (P2)	0.5	BMW 5-Series	**ATF** (ZF Lifeguard 8)
CVT		Subaru	FHEV (P2)	0.1	Subaru Forester	**CVTF** (Subaru CVTF)
		Jatco	FHEV (P2)	0.1	Nissan X-Trail	**CVTF** (Nissan NS-3)
DCT	Dry	Honda	FHEV (P2)	1.2	Honda Fit	**ATF** (Honda DW-1)
	Wet	VW	FHEV (P2)	0.4	VW Passat	**DCTF** (EG 52529)
RED		Nissan	BEV (P4)	1.6	Nissan Leaf	**ATF** (Nissan Matic-S)
		Tesla Motors	BEV (P4)	1.3	Tesla Model 3	**ATF** (Tesla High Perf.)
		GM	BEV (P4)	0.2	Chevy Bolt	**ATF** (DEXRON® HP)

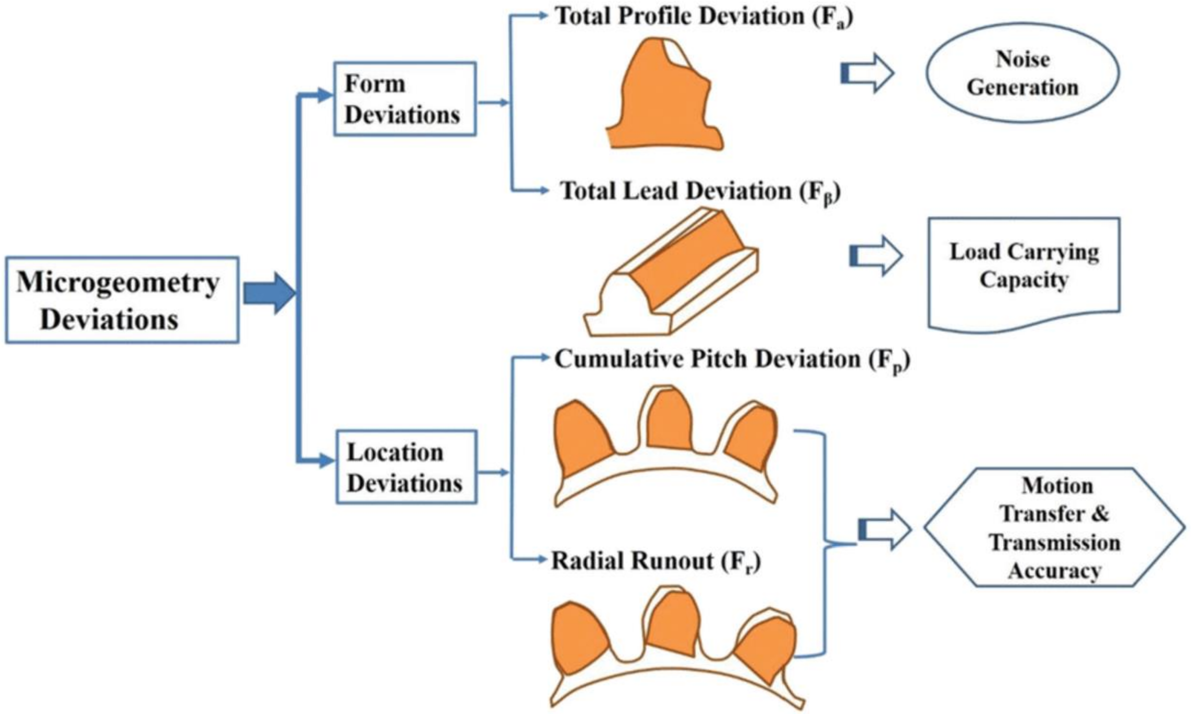
* Cumulative sales of all vehicle models through model year 2020

Infineum



Requirements for High-Speed EV Gears

- ❑ Tight dimensional tolerances, usually ISO 1328 Grade 6 or better
- ❑ The ability to withstand rated torque
- ❑ Higher surface finish quality requirements (NVH, efficiency)

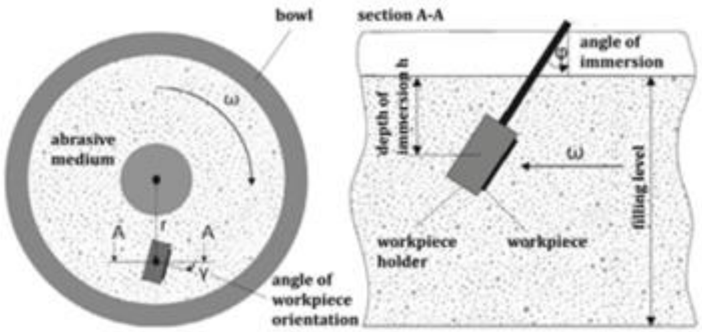


Common deviations and their impact on performance

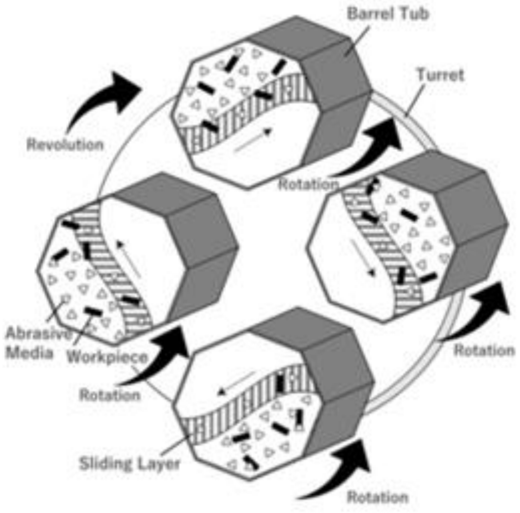
Ref: Kharka et al Int J Adv Manuf Technol 109, 1681–1694 (2020).

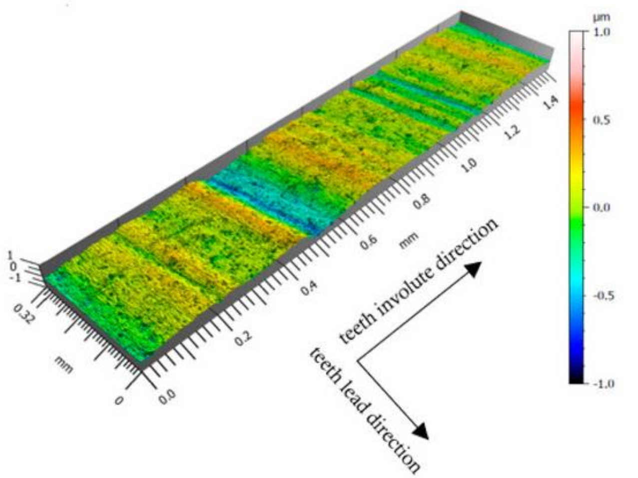
Mass Finishing Processes

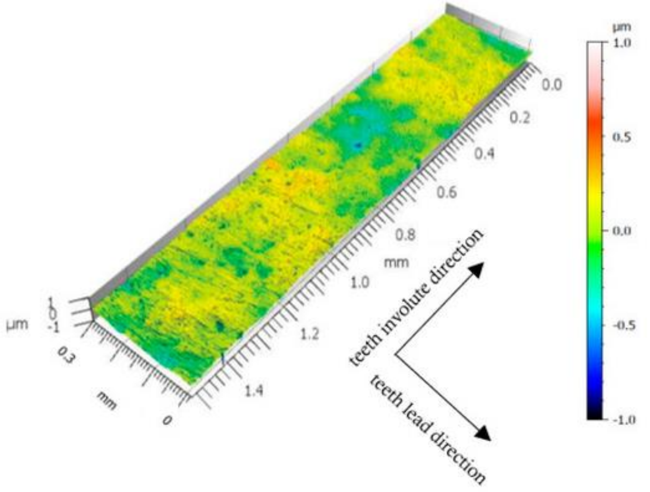
Stream finishing



Centrifugal barrel finishing



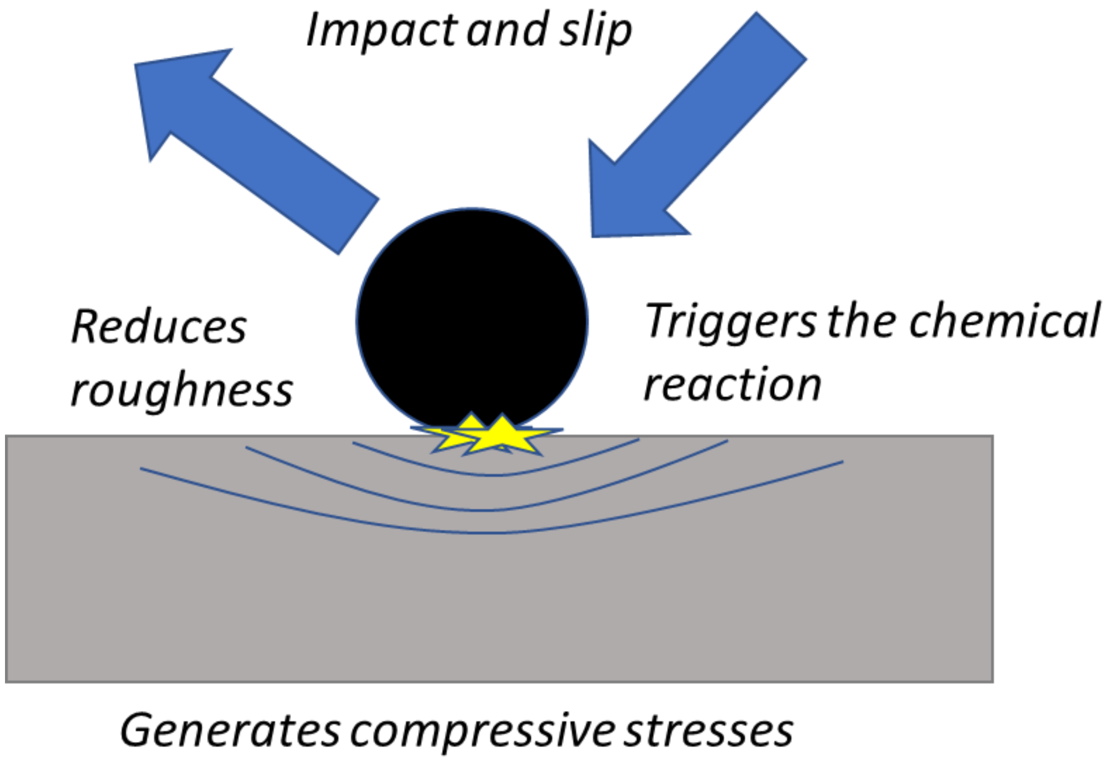


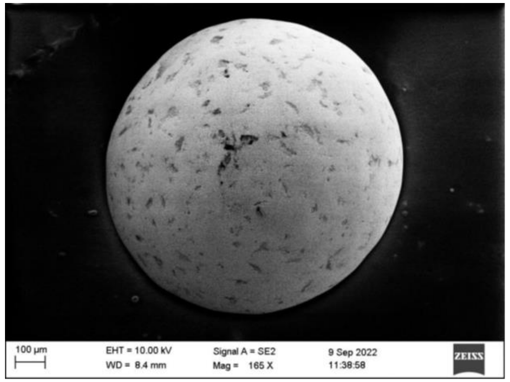


Triboconditioning® CG

A Mechanochemical Mass Finishing Process

Oblique impacts of hard beads burnish the surface:





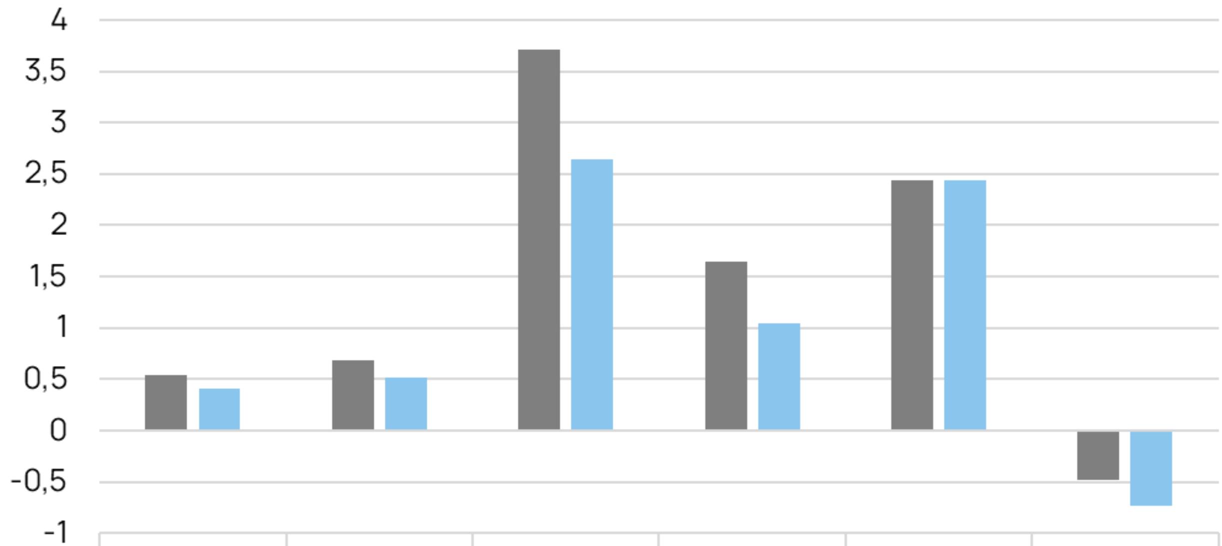
<u>Features shared with mass finishing</u>

- Deburring
- Rounding edges
- Reducing surface roughness
- Eliminating directional anisotropy from grinding

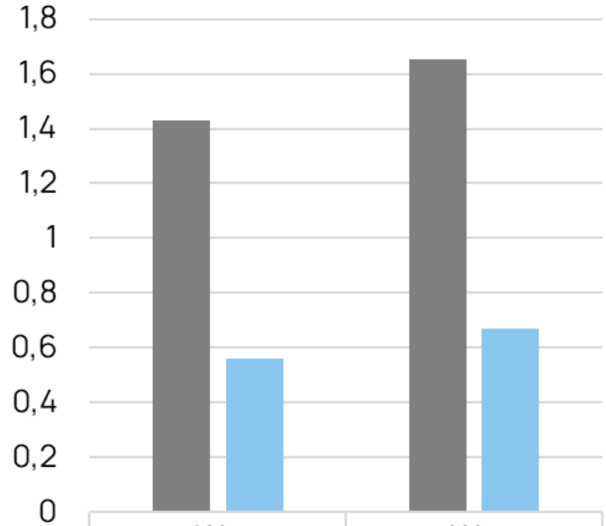
<u>Features unique for Triboconditioning</u>

- Tribofilm priming
- Compressive stress buildup

The Effects on Surface Roughness and Waviness

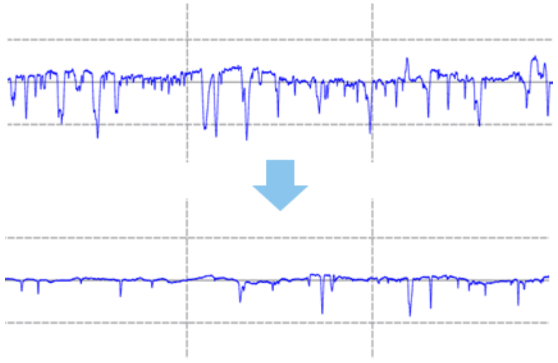


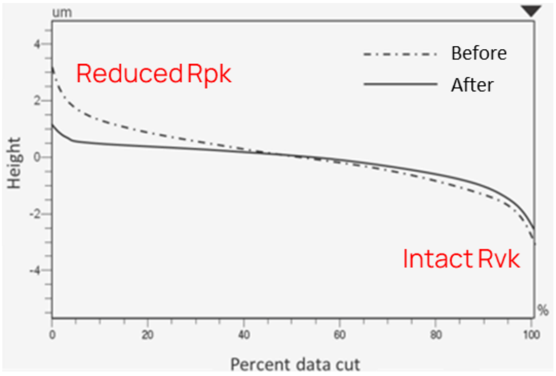
Ra	Rq	Rz	Rp	Rv	Rsk
0,539	0,684	3,712	1,645	2,437	-0,484
0,403	0,515	2,637	1,044	2,434	-0,729



Wa	Wq
1,428	1,652
0,562	0,668

Before treatment
After treatment





Surface roughness profile modification:

- Plateau-like (negative skewness)
- Reduced amplitude roughness
- Reduced gradient roughness

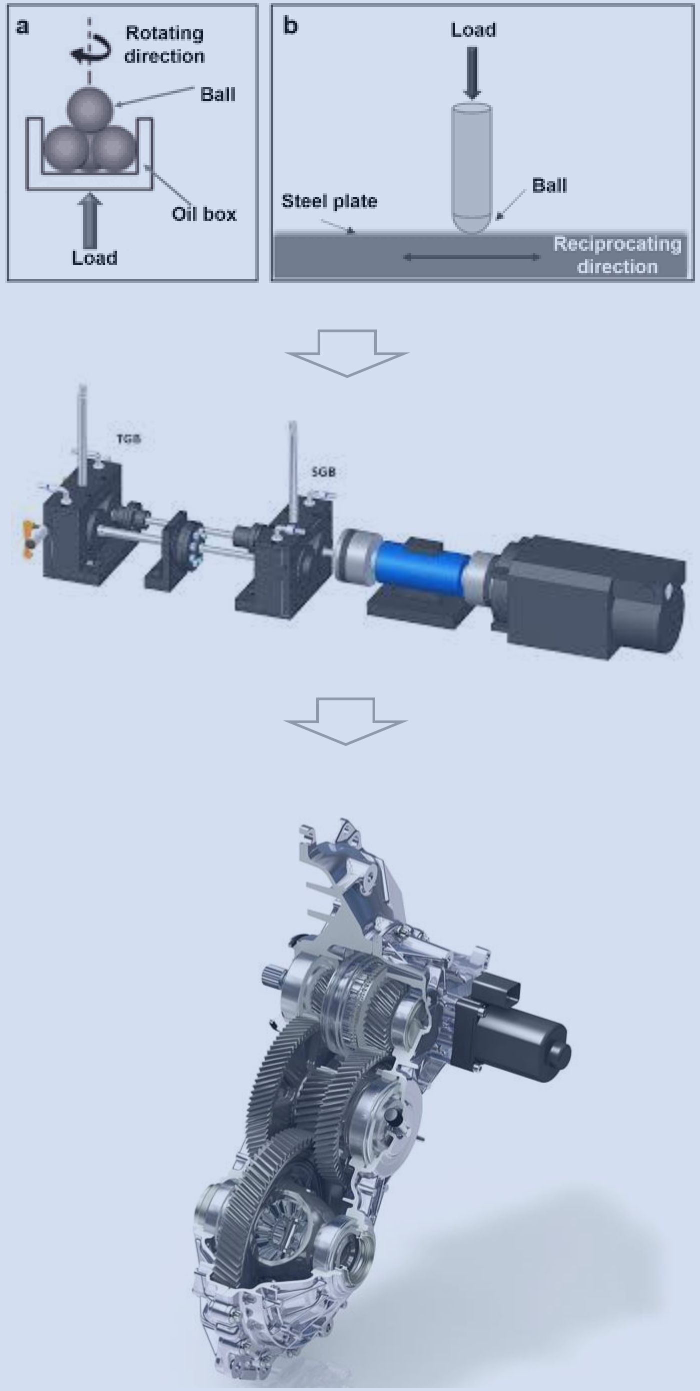
Gear Tribology Simulations

Thermal Elasto-Hydrodynamic Lubrication Model:

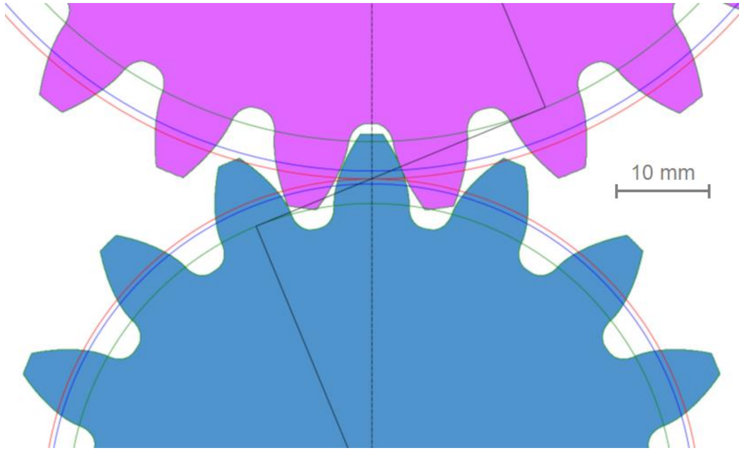
- Reynolds equation
- Roelands equation for viscosity-pressure and -temperature dependence
- Dowson-Higginson for density-pressure and -temperature dependence
- Carreau equation for the shear thinning effect
- Energy conservation and heat transfer equations
- EHD film thickness calculated according to Guilbault contact model

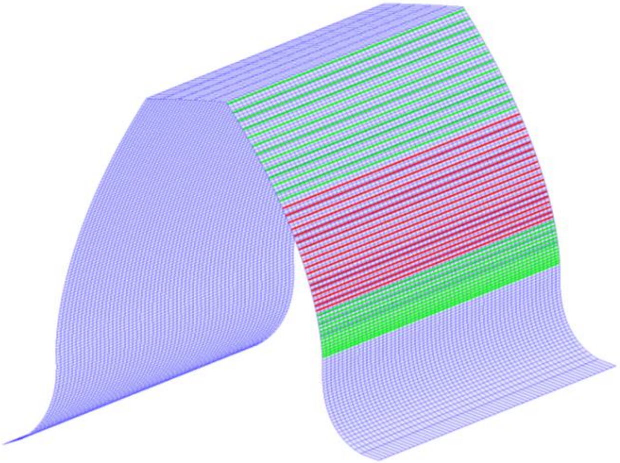
Oil Data --,

		Temp1	Temp2,
Temperature (C)	,	40,	100,
Viscosity (cSt)	,	30.5,	5.8,
Pres.-Visc. Coef. (1/Pa)	,	1.3e-8,	1.1e-8,
Modulus G (MPa)	,	7.0,	0.9,
Slope factor	,	1.0,	1.0,
Specific heat (J/(kg.K))	,	1880,	
Thermal conduct. (W/(m.K))	,	0.14,	
Density (kg/m^3)	,	830,	
At Temp. (C) (density)	,	15,	
Density-Temp. Coef. (1/K)	,	6.4e-4,	
Immersion factor	,	0.5,	
Oil volume (m3)	,	0.005,	
Sump Temperature (C)	,	60,	



Example 1: FZG Spur Gears



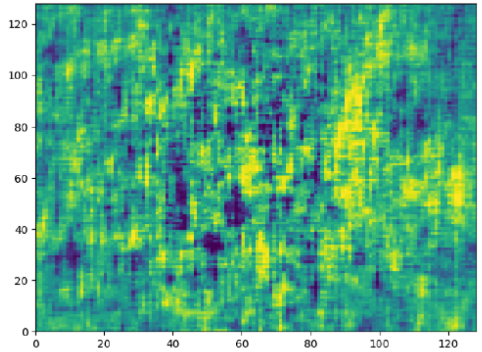


Input parameters: FZG type C gears with tip relief

Type:(E = external-external) (W = external-worm),			E,
		Gear1	Gear2,
Number of Teeth	,	16,	24,
Tip Diameter (mm)	,	83.2,	117.4,
Addendum Coefficient	,	1,	1,
Dedendum Coefficient	,	1.25,	1.25,
Profile Shift Coefficient	,	0.27,	0.05,
Cutter Fillet Coefficient	,	0.38,	0.38,
Face Width (mm)	,	20,	20,
Tip Relief Length (mm)	,	4,	3,
Tip Relief Magnitude (mm)	,	0.02,	0.02,
Root Relief Length (mm)	,	0,	0,
Root Relief Magnitude (mm)	,	0,	0,
Face Relief Length (mm)	,	0,	0,
Face Relief Magnitude (mm)	,	0,	0,
Face Slope Modification (mm)	,	0,	0,
Face crown Magnitude (mm)	,	0,	0,
Tip Bias at W = 0 (mm)	,	0,	0,
Tip Bias at W = Fw (mm)	,	0,	0,
Root Bias at W = 0 (mm)	,	0,	0,
Root Bias at W = Fw (mm)	,	0,	0,
Material Properties --,			
Elastic Module (MPa)	,	206000,	206000,
Poisson Ratio	,	0.3,	0.3,
Density (Kg/m3)	,	7850,	7850,
Specific Heat (J/(kg.K))	,	460,	460,
Thermal Conduct. (W/(m.K))	,	47,	47,
Bulk Temperature (C)	,	60,	60,
Surface Roughness (micron) ------------------------------------,			
Root Mean Square	,	0.13,	0.13,
Skewness	,	-1.5,	-1.5,
Kurtosis	,	5.0,	5.0,
Autocorrelation X	,	100,	100,
Autocorrelation Y	,	100,	100,

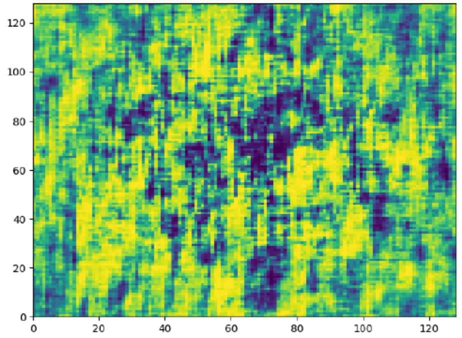
Ground gears

Ra = 0.3 micron
Skewness = -0.5
Kurtosis = 3.5

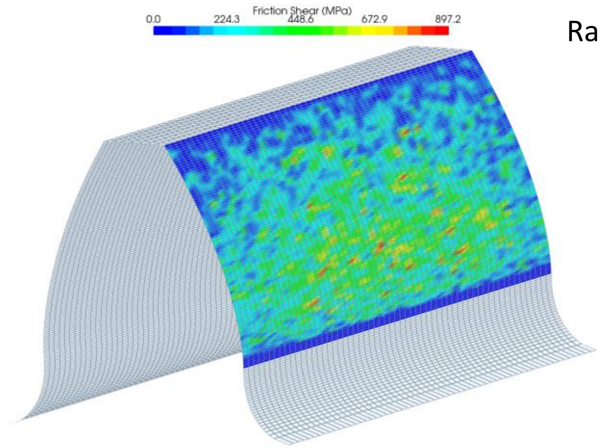


TCG-treated gears

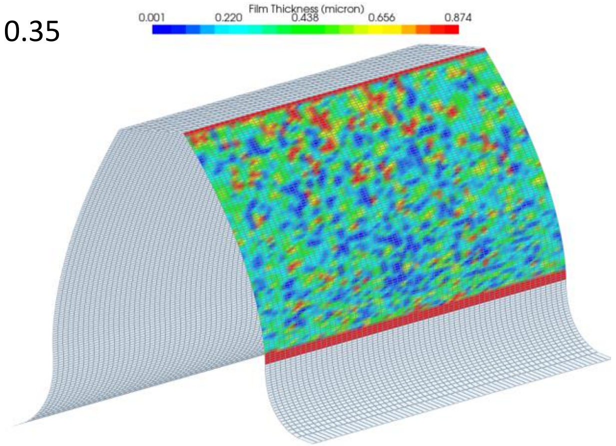
Ra = 0.1 micron
Skewness = -1.5
Kurtosis = 2.5

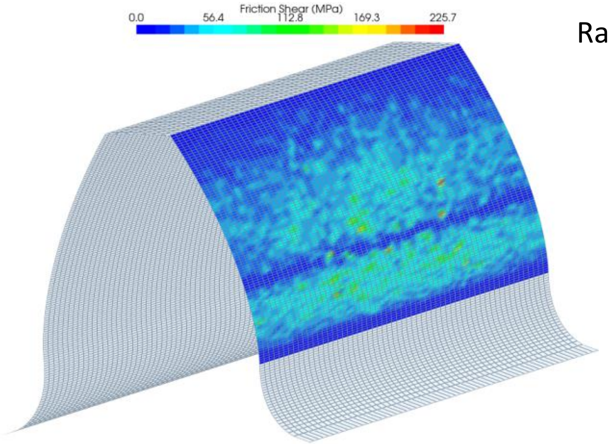


Predicted Performance Benefits

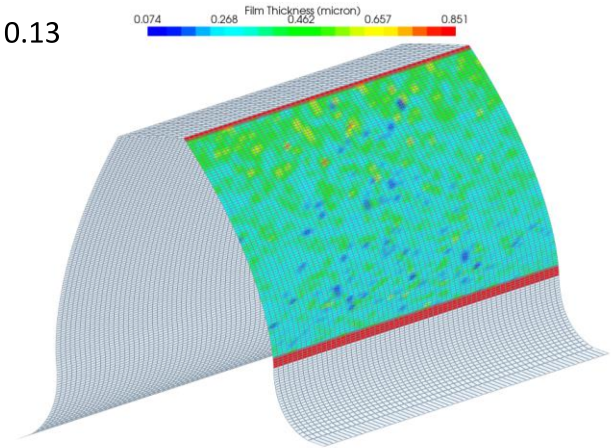


Ra = 0.35

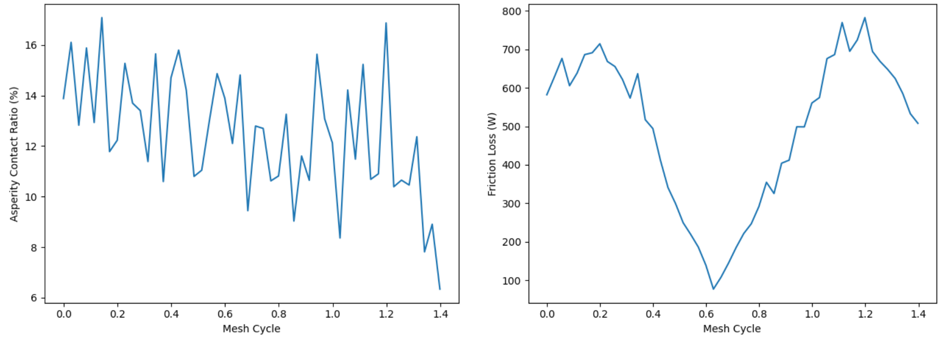




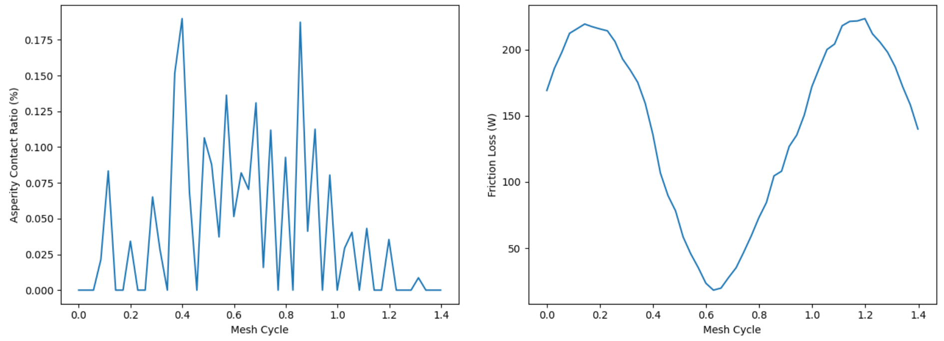
Ra = 0.13



Ra = 0.35



Ra = 0.13



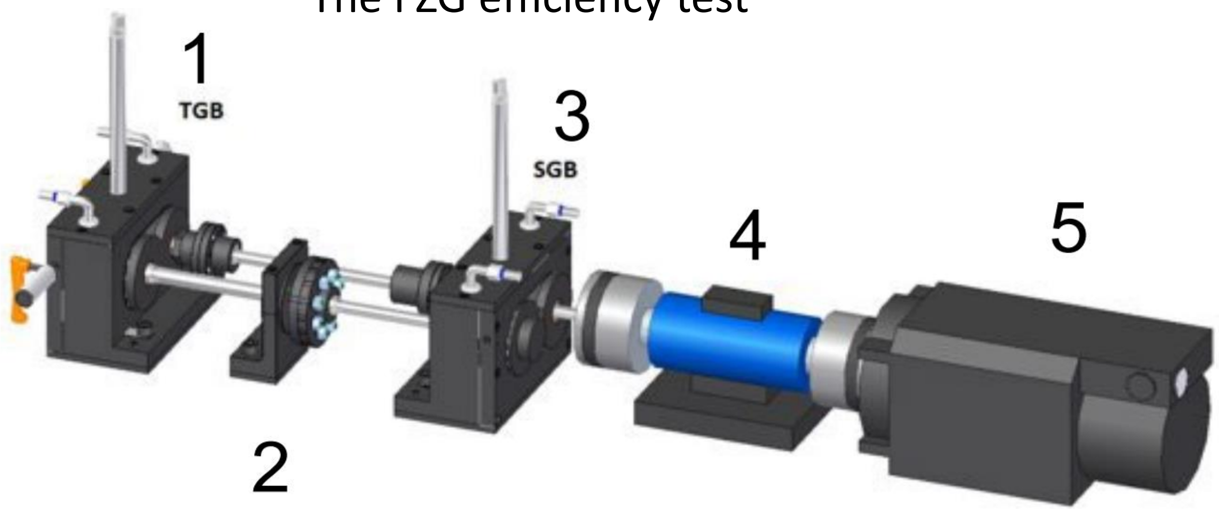
- ✓ Reduced friction shear stress
- ✓ Improved lubricant film integrity

→

- ✓ Improved efficiency
- ✓ Lower wear

From Simulations to Testing

The FZG efficiency test



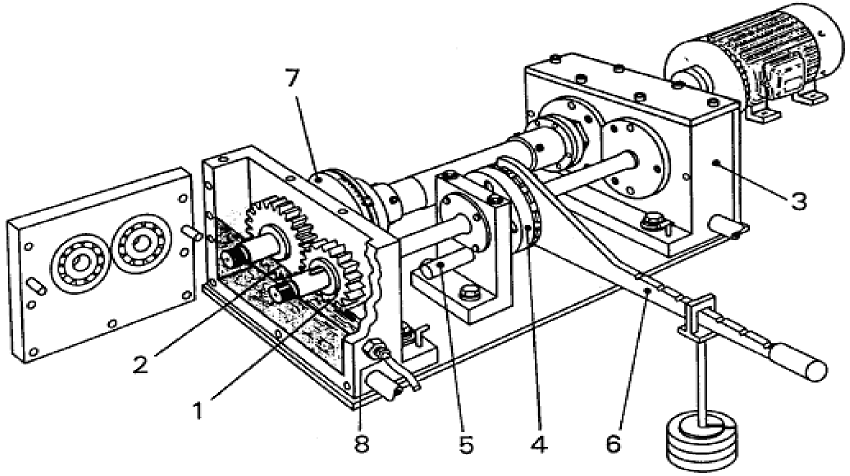
1 - test gearbox,
2 - load clutch,
3 - slave gearbox,
4 - torque and speed sensor,
5 - motor

Choose the right test:
A/8.3/90
A10/16.6R/120
C/0.05/90:120/12

Standard Load Stages for FZG Scuffing Test

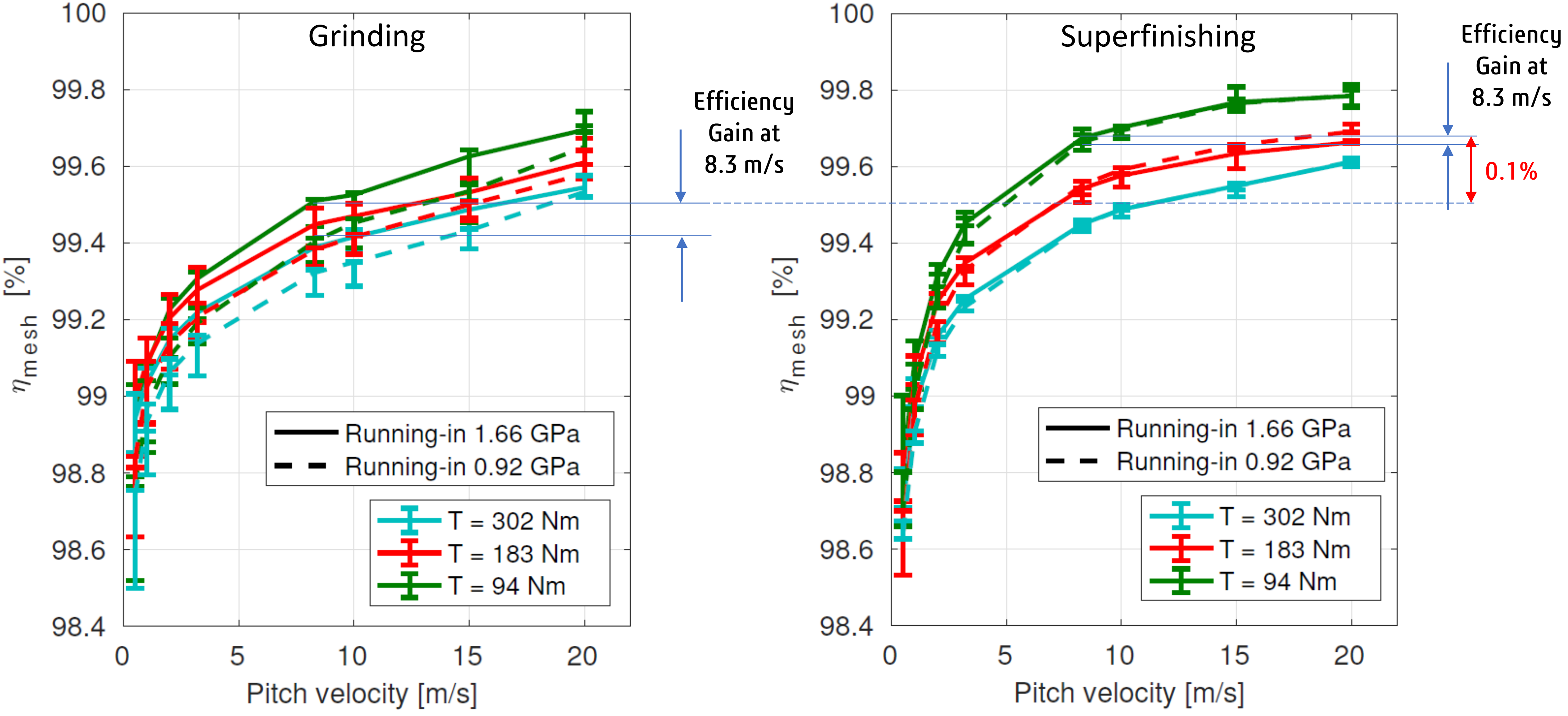
Load Stage	Torque on Pinion (N·m)	Tooth Normal Force (N)	Hertzian Contact Pressure (N/mm²)	Total Work Trans-mitted (kW·h)
1	3.3	99	146	0.19
2	13.7	407	295	0.97
3	35.3	1044	474	2.96
4	60.8	1799	621	6.43
5	94.1	2786	773	11.8
6	135.5	4007	929	19.5
7	183.4	5435	1080	29.9
8	239.3	7080	1232	43.5
9	302.0	8949	1386	60.8
10	372.6	11029	1539	82.0
11	450.1	13342	1691	107.0
12	534.5	15826	1841	138.1

FZG scuffing test (ASTM D 5182)



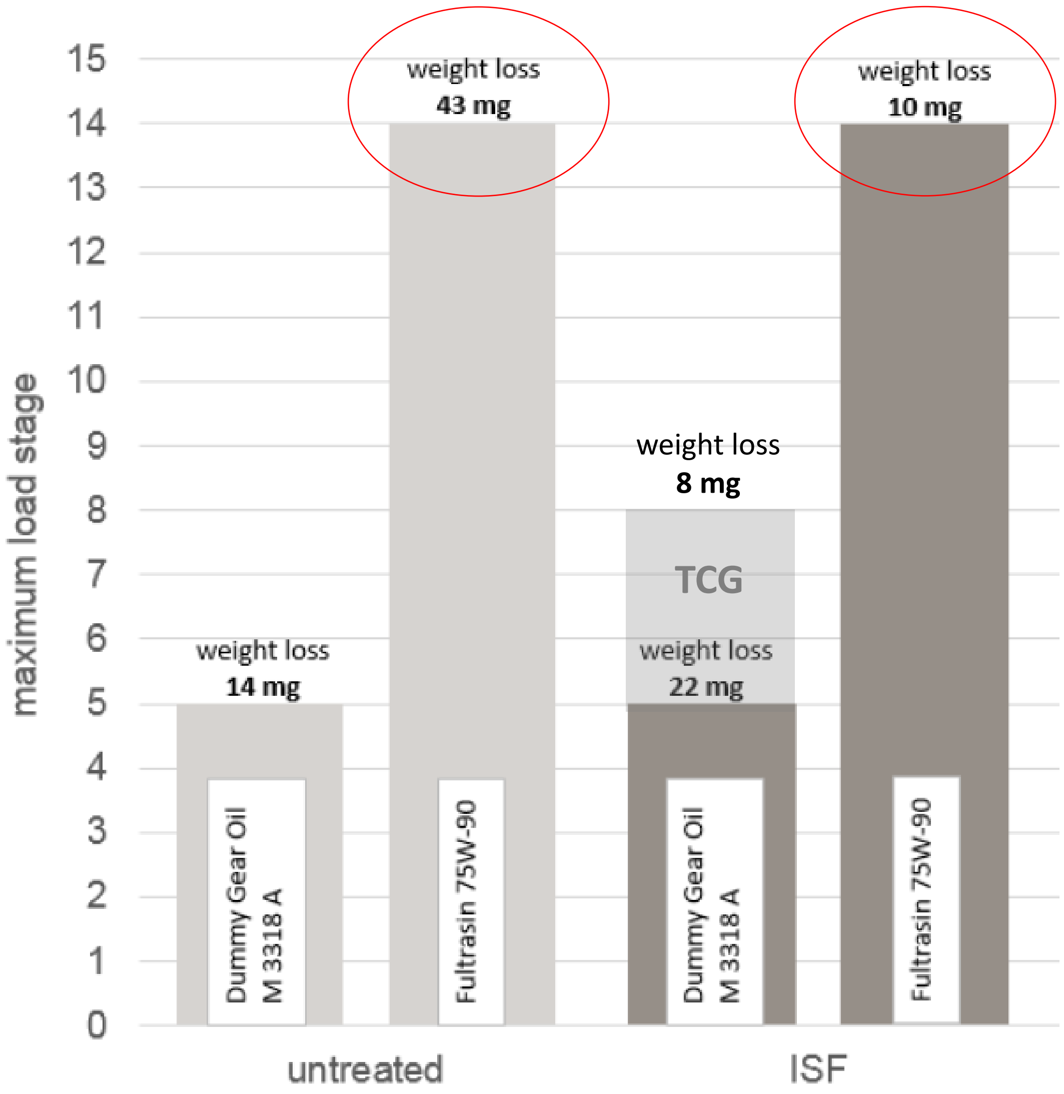
1 Test Pinion
2 Test Wheel
3 Slave Gear
4 Load Clutch
5 Locking Pin
6 Load Lever and Weights
7 Torque Measuring Clutch
8 Temperature Sensor

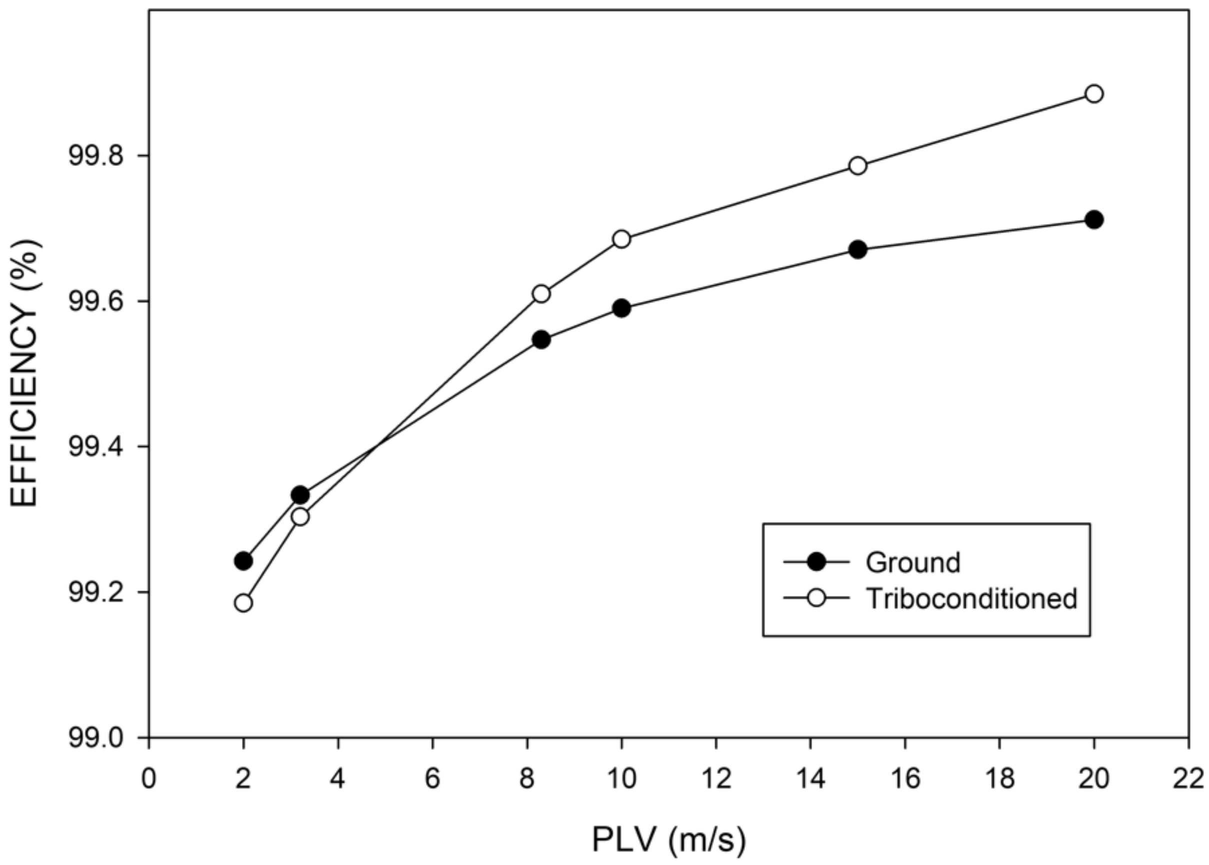
Effect of Surface Finish on Running-in and Efficiency



Ref: Mario Sosa, PhD Thesis, KTH, Stockholm, 2017

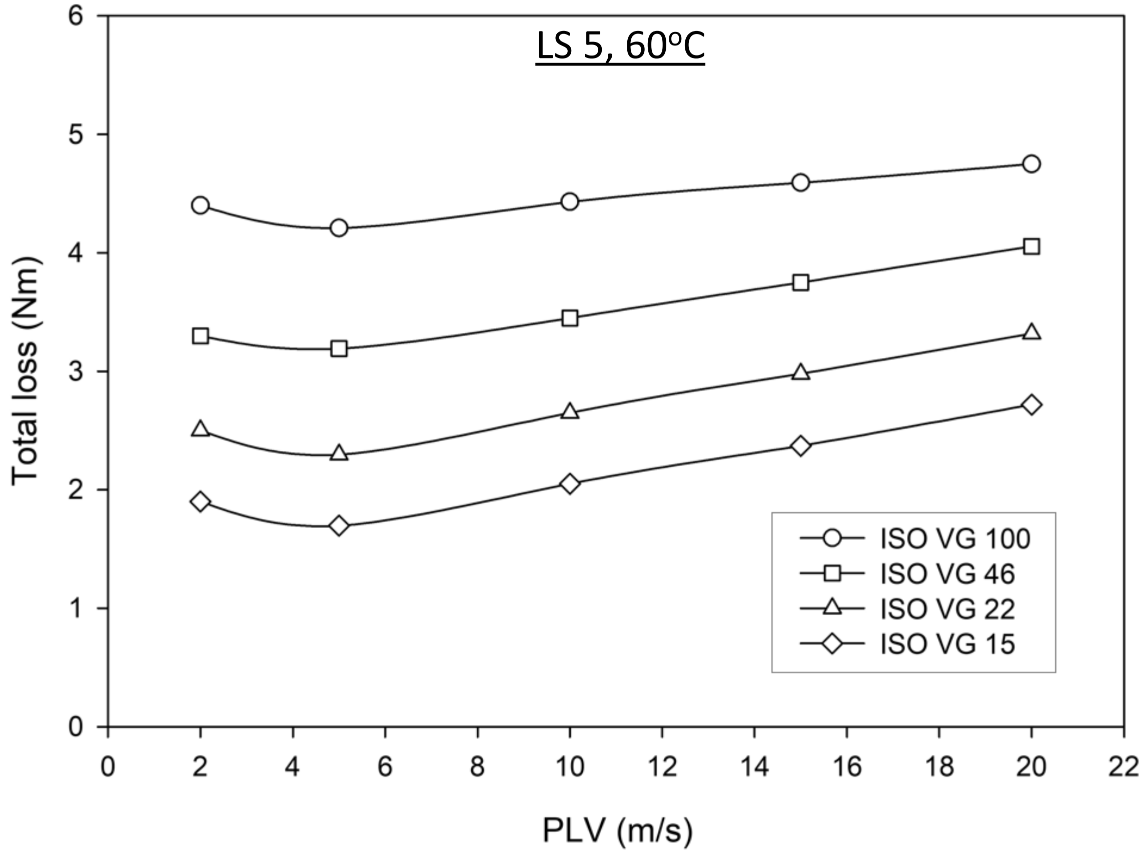
FZG Test Results: Scuffing, Wear, and Efficiency

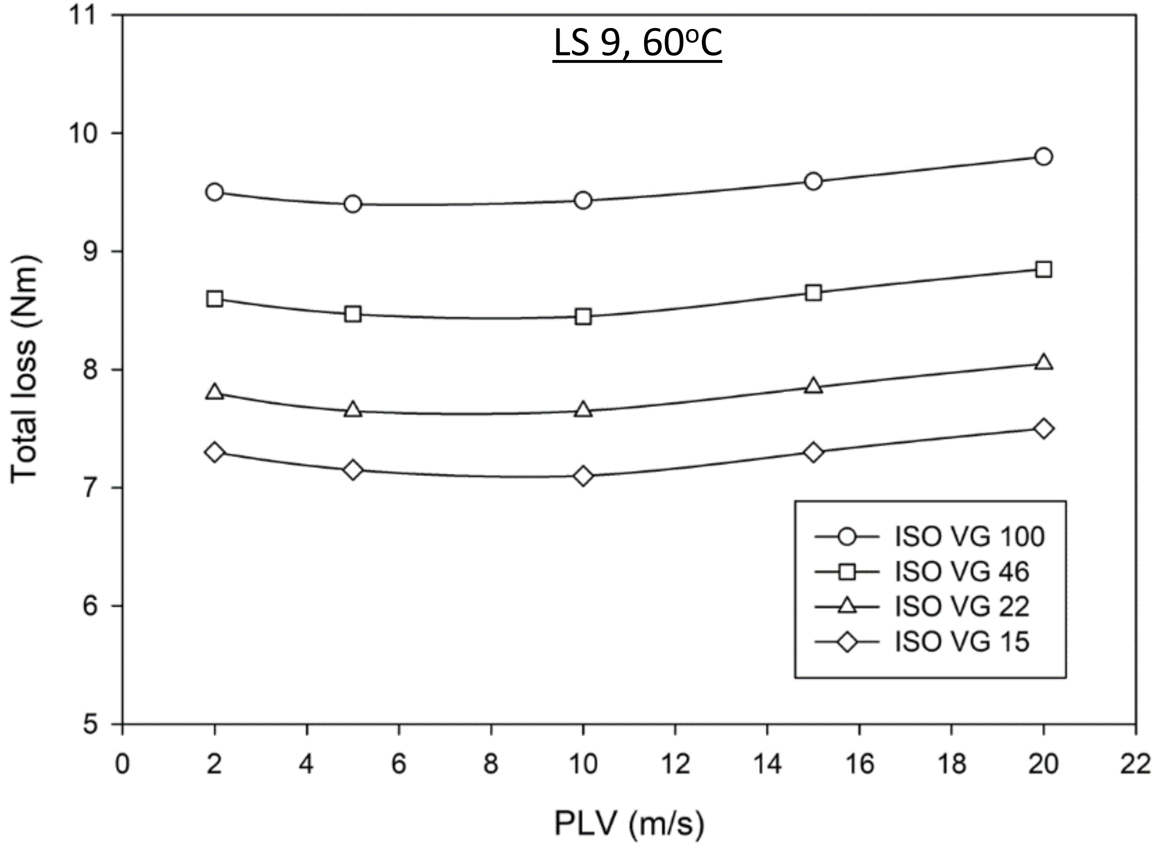




NOTE: Scuffing resistance, wear, and efficiency do not necessarily correlate to each other

Gear Oil Viscosity and Gearbox Losses





Viscosity grade	KV40, cSt	KV100, cSt	Density, g cm-3
ISO VG 100	98.1	11.2	0.87
ISO VG 46	46.2	7.0	0.85
ISO VG 22	23.4	5.0	0.83
ISO VG 15	14.5	3.5	0.82

- High-speed gears call for lower viscosity
- Water-based transmission fluids in development
- Challenge with high-torque at the start

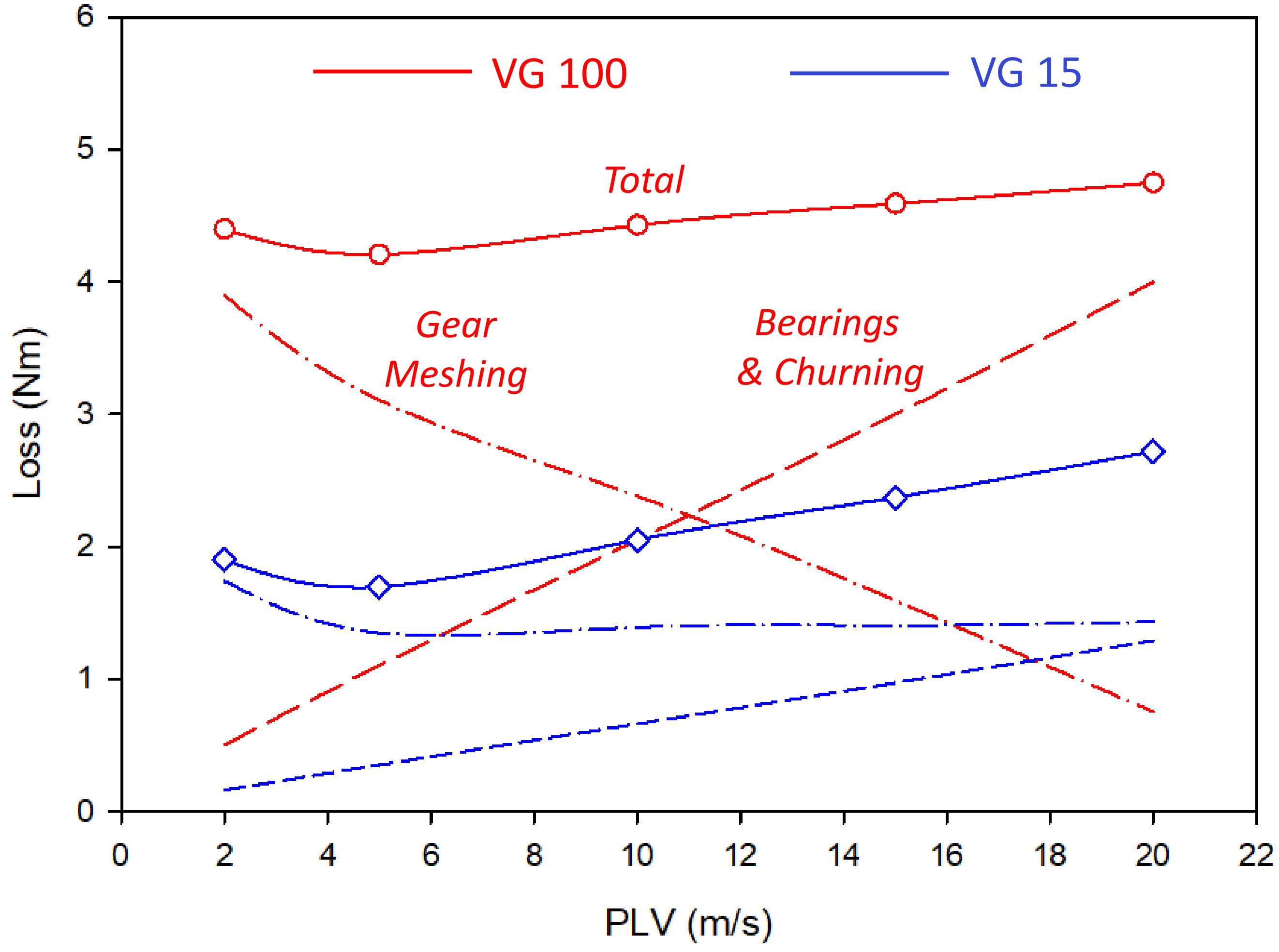
Partitioning Friction Losses

Total loss is a sum of

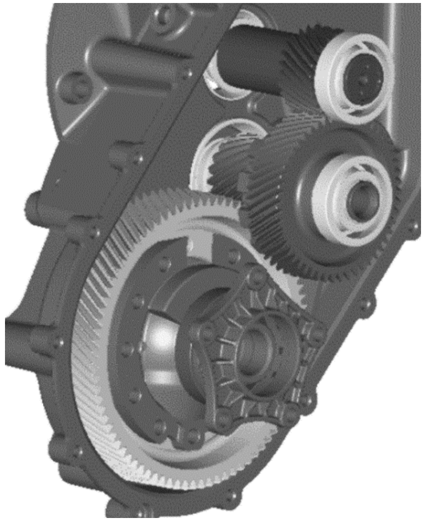
- Gear meshing losses
- Bearings / seals losses
- Churning losses

One can accurately measure only the total loss, as well as the loss at zero load

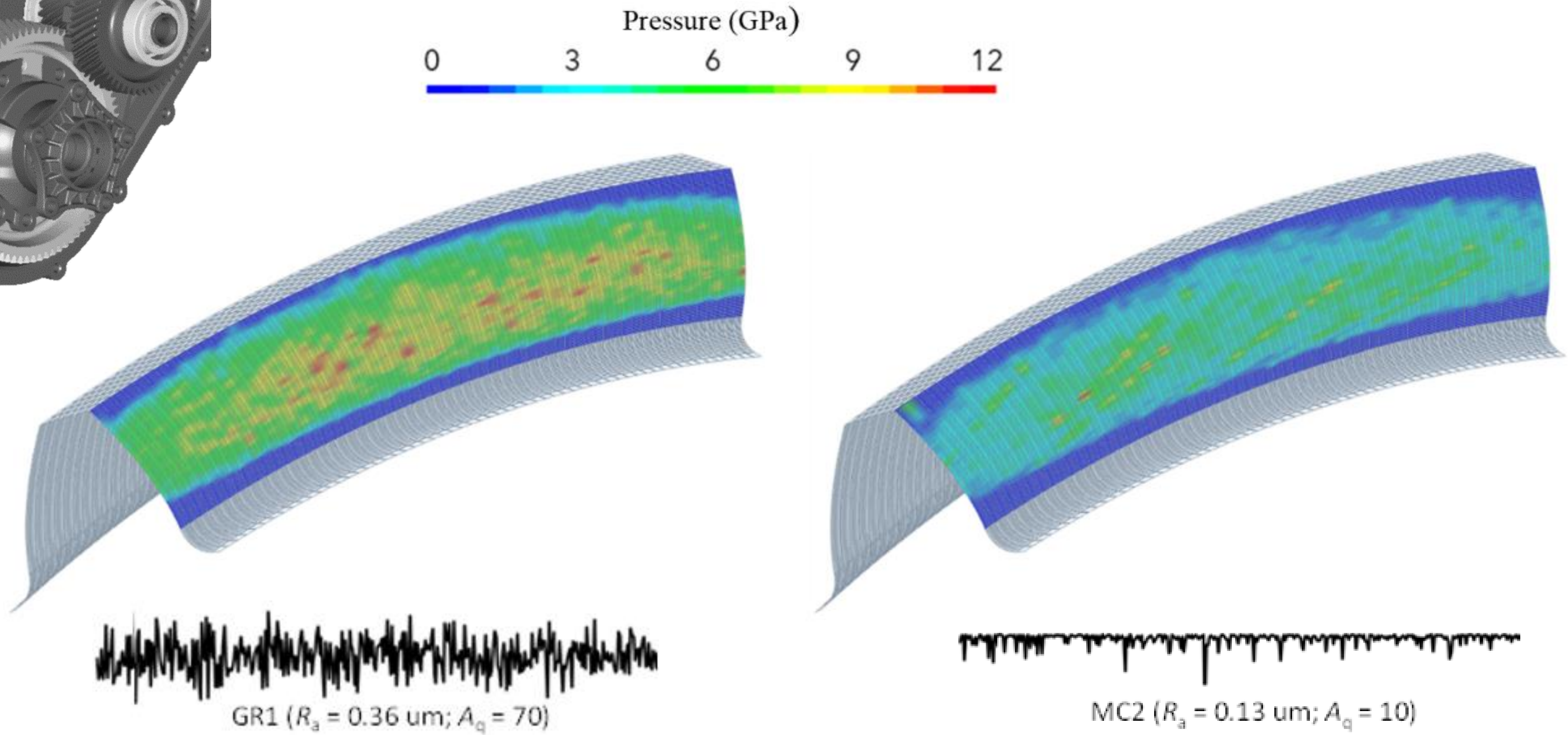
For energy efficiency, the total loss only is of importance



Example 2: Helical Gears



Contact pressure maps for different surface finishes

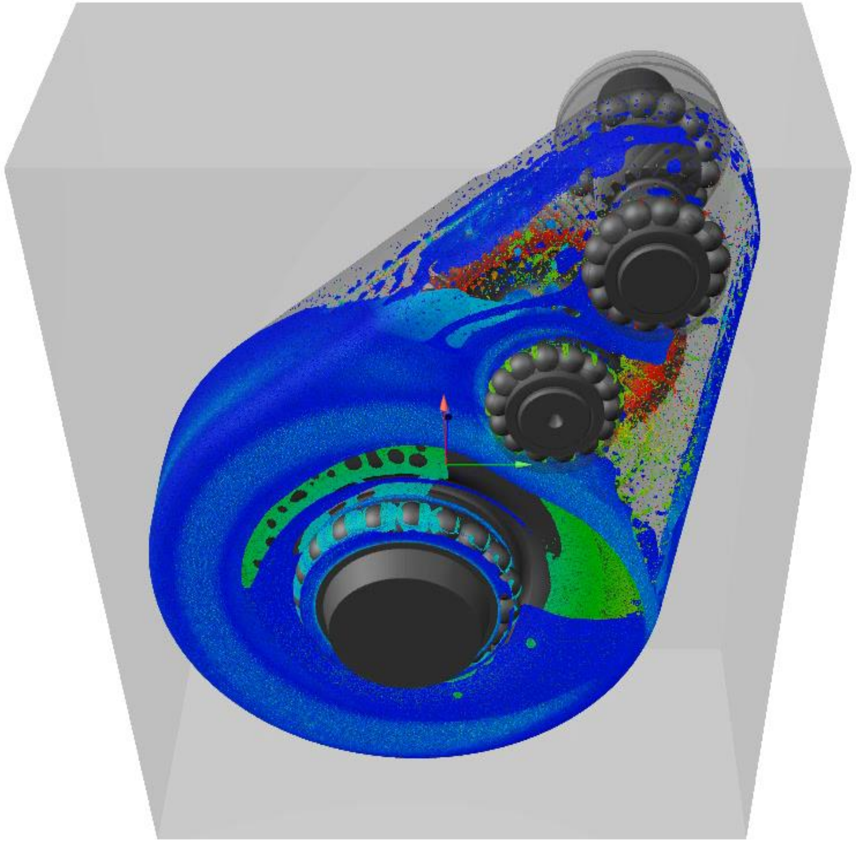


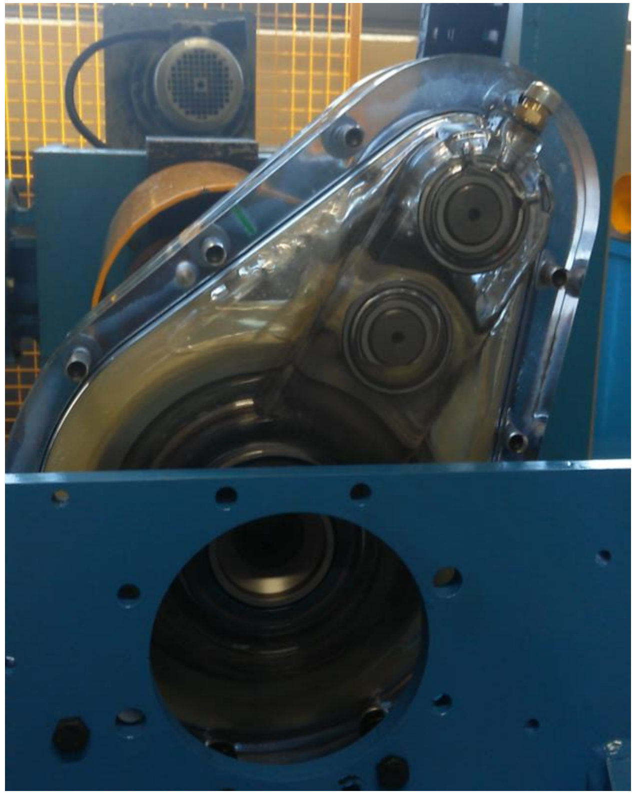
From TEHD “Micro” to CFD “Macro” Simulations

Two speed reduction gear-box

“We will use simulation if it can deliver **reliable results in a few days**, during the design process. We need to predict and optimize gears lubrication **before the prototype**”

Comer Industries Engineering Manager, 2016





Courtesy E. Fava, Comer Industries

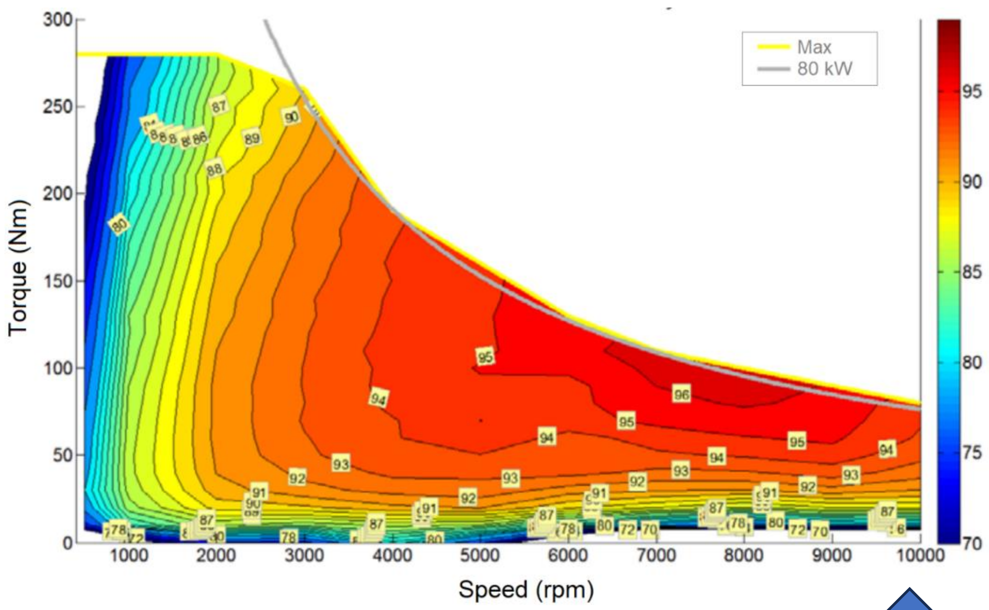
Particleworks EUROPE

Analysis of Two Limiting Cases

LSHL
(low speed high load)

LSHL

Maximum Contact Pressure (MPa):	5038.70
Average Asperity Contact Ratio (%):	18.35
Average Flash Temperature (C):	167.16
Average Friction Loss (W):	241.30
Churning Loss (W):	22.39
Efficiency (%):	99.16
Wear Probability (%):	95.00
Scuffing Probability (%):	5.00



HSLL

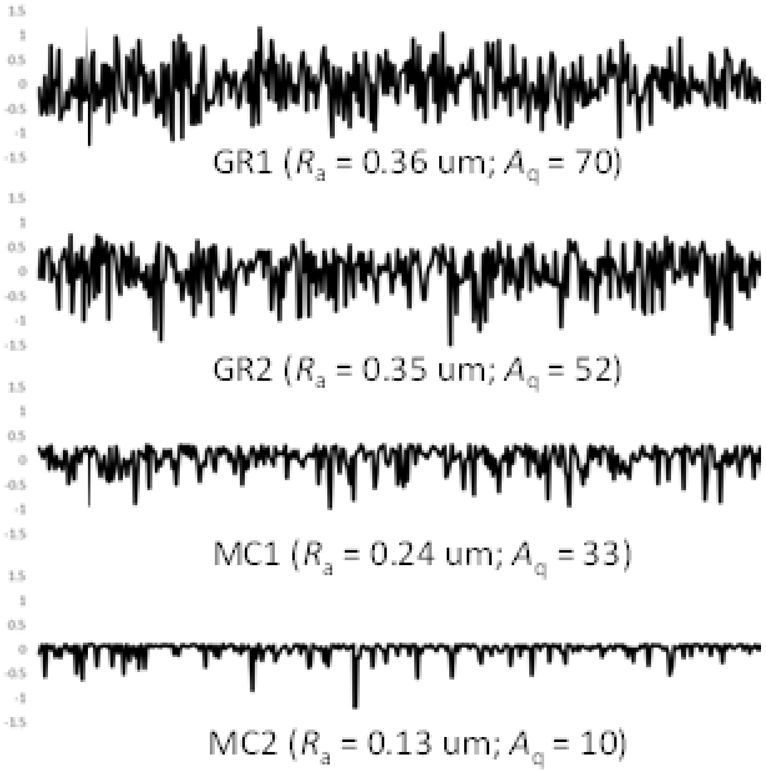
Maximum Contact Pressure (MPa):	3796.54
Average Flash Temperature (C):	253.01
Average Friction Loss (W):	247.76
Churning Loss (W):	613.37
Efficiency (%):	99.18
Wear Probability (%):	95.00
Scuffing Probability (%):	74.00

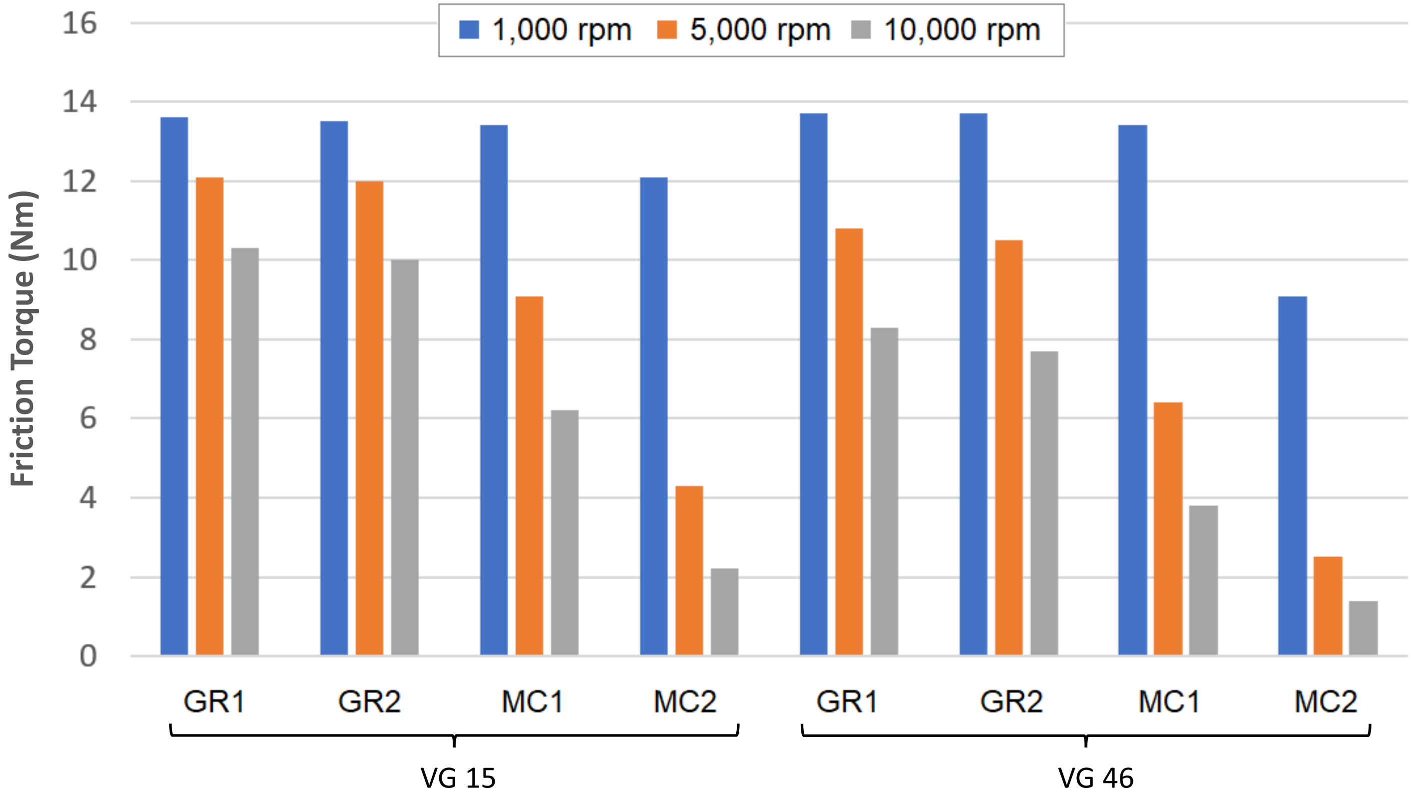
HSLL
(high speed low load)

Improve cooling at high speed! How? Lower viscosity, OSP, PAG/water…

Roughness, Speed, Velocity, Load

The Hersey number (Lubricant film thickness): Viscosity (Pa s) x Velocity (m/s) / Load (N/m2)
The Lambda ratio: lubricant film thickness / Composite roughness





- With decreasing viscosity, gear friction increases, but losses in bearings decrease
- Differences in base oil lubricity

Choosing Right Base Oil and Additives

Is the gearbox heavily loaded so that there's a risk of scuffing?

Remedy:
- Switch to a higher viscosity lubricant
- Deploy active sulfur carriers (sulfurized olefins, sulfurized fatty acid esters), aminophosphates

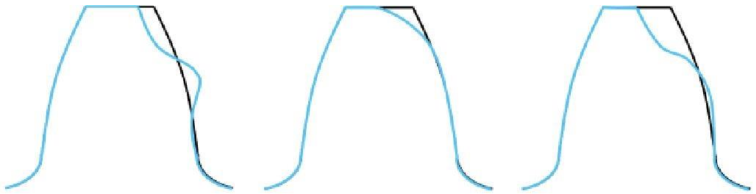
Is gearbox overheating under high speed operation?

Remedy:
- Switch to lower viscosity / higher thermal conductivity lubricant
- Add spray/jet lubrication
- Add heat exchangers

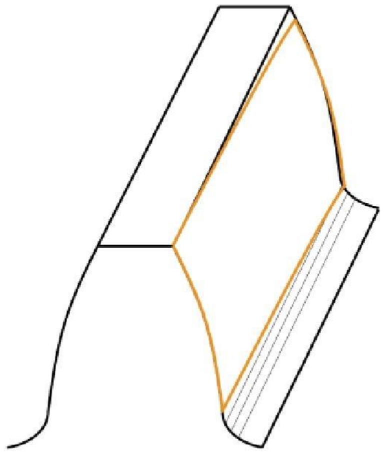
Additives do NOT add

Gear Accuracy and Surface Finish: Finding Balance

Gear accuracy + Mounting accuracy + Lubrication



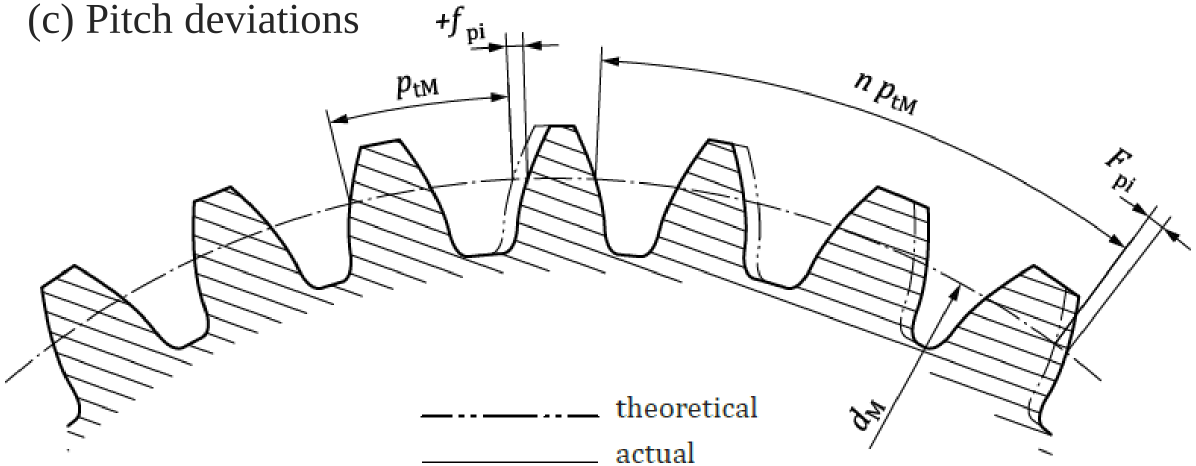
(a) Profile errors, characterised by a deviation from the nominal profile. These increase noise.



(b) Lead errors, a linear deviation along the face of the tooth. This affects load-carrying capacity.

ISO 1328

(c) Pitch deviations



- Individual single pitch deviation
- Individual cumulative pitch deviation

For cylindrical gears with diameter 5 to 12 cm:

- Highest accuracy: Single pitch deviation down to 1 um
- Lowest accuracy: Single pitch deviation upto 100 um

High accuracy gears require superfinishing.
Low accuracy gears benefit little from superfinishing.

Does Reducing Gear Friction Improve Range?

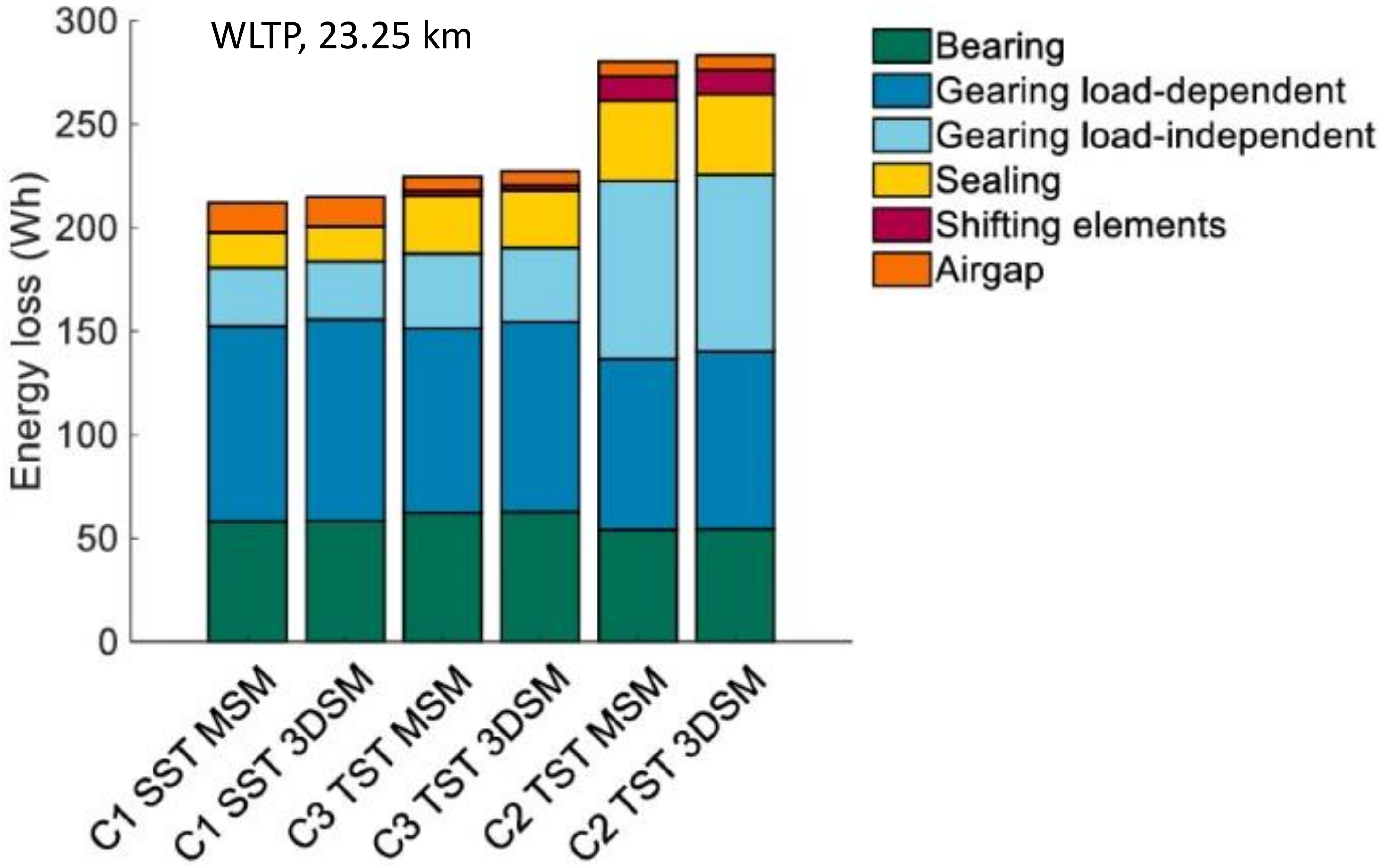
The average BEV consumes 200 Wh/km (WLTP)

Energy loss in transmission is around 10 Wh/km.

Even if you manage to halve the transmission losses, the range extension will be just 2-3%.

Say, instead of 300 km, you may be able to drive max 310 km ☺

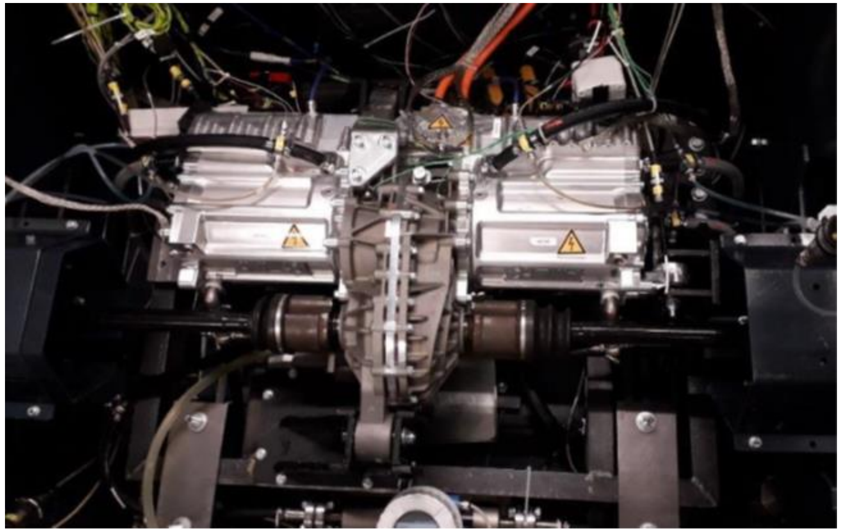
Reducing gearbox temperature, improving driving comfort, and ensuring trouble-free operation is far more important than the range!



Ref.: Hengst, J., Werra, M. & Küçükay, F. Evaluation of Transmission Losses of Various Battery Electric Vehicles. Automot. Innov. 5, 388–399 (2022)

Tested by AVL in a High Speed Electric Drive Unit

Testing of new E-drive solution in test bench as well as on-road integrated in Tesla Model S test car successfully verified the capability of withstanding full drive cycles and challenging 30,000 rpm operational speeds



tribonex

Conclusions

A total system approach is essential for understanding electric powertrain tribology

Hardware design and lubricant/coolant properties must be carefully matched

Ultralow viscosity synthetic fluids appear to be a better fit for high-speed EV reduction transmissions than conventional ATFs.

High-speed gear drives pose higher demands on gear accuracy and surface finish quality.

Mechanochemical surface finishing opens new ways to optimizing tribology for high-speed EV drives (gears, bearings, seals)