Influence of a DLC Coating on the Temperature and Friction in a Helical Tooth Flank Contact

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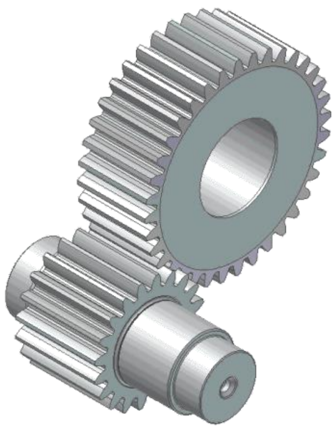
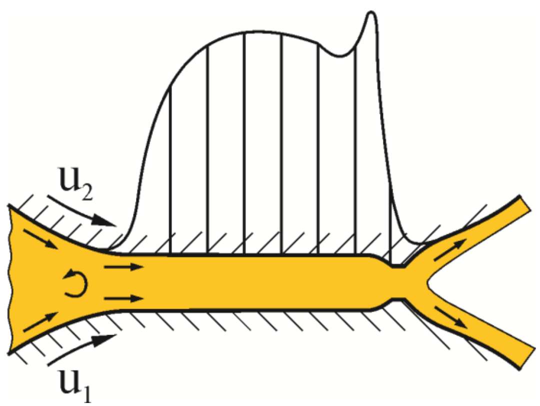
- 3D TEHL Calculation Model
- Calculation Example
- Results
- Summary

Introduction





Tooth flank contact is characterized by

- involute tooth flank profiles including gearing corrections
- gradual meshing
- transient thermal elastohydrodynamic finite line contact
- high pressures
- high shear rates

Contact simulation requires

- transient 3D TEHL calculation model, applied on gearing
- consideration of lubricant rheology including non-Newtonian behavior
- mixed friction approach
- temperature calculation

Content

3D TEHL Calculation Model

Calculation Model

- Elastohydrodynamics
- Real Gear Pair Geometry
- Realistic Load Distribution
- Lubricant Rheology
- Rough Surfaces
- Mixed Friction Conditions
- Temperature Calculation

Generalized Reynolds equation

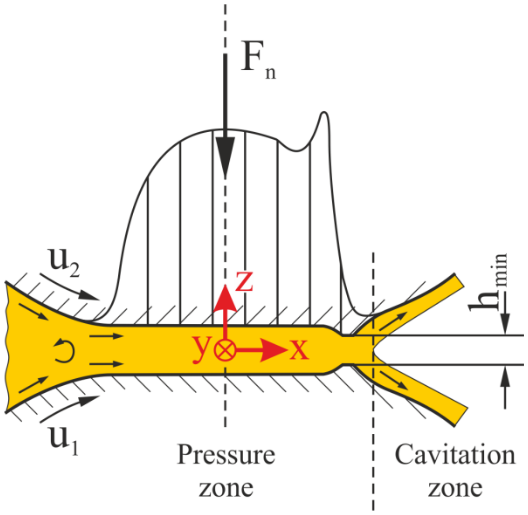
$$\frac{\partial}{\partial x}\left(\Phi_{xx}^{p} G_{1x} \frac{\partial p_h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Phi_{yy}^{p} G_{1y} \frac{\partial p_h}{\partial y}\right) = \frac{\partial}{\partial x}\left(\theta G_{2x} \frac{(u_2 - u_1)}{F_0} + \theta G_3 u_1 + \cdots\right.$$

$$\left.\theta G_3 \Phi_{xx}^{s} \frac{(u_2 - u_1)}{2h}\right) + \frac{\partial}{\partial y}\left(\theta G_{2y} \frac{(v_2 - v_1)}{F_0} + \theta G_3 v_1 + \theta G_3 \Phi_{yy}^{s} \frac{(v_2 - v_1)}{2h}\right) + \frac{\partial}{\partial t}(\theta G_3)$$

with $p_h > p_{cav}$ and $\theta = 1$ in the pressure zone

$p_h = p_{cav}$ and $\theta < 1$ in the cavitation zone

- applicable for any transient three-dimensional elastohydrodynamic contact
- mass-conserving cavitation algorithm
- variable density and viscosity along the x-, y- und z-axes



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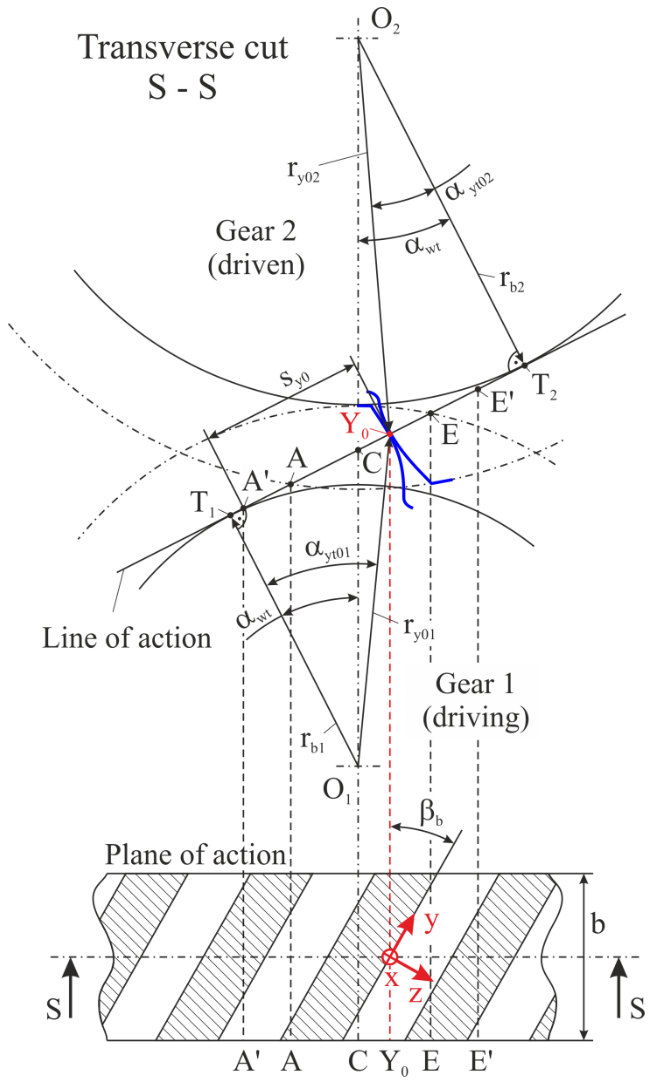
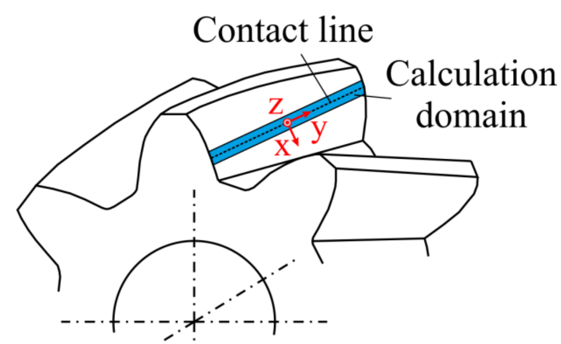


- local coordinate system centered in the contact point Y_0 along contact line to consider gear geometry and gearing corrections
- line of action is defined in the center of the plane of action
- meshing takes place from point A’ to point E’
- consideration of realistic load distributions (RIKOR, LVR, FEM, …)



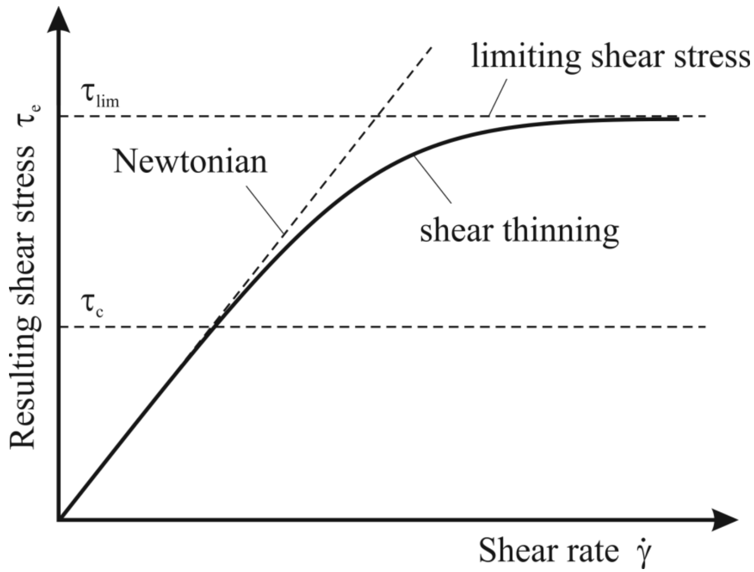
3D TEHL Calculation Model

Calculation Model

- Elastohydrodynamics
- Real Gear Pair Geometry
- Realistic Load Distribution
- **Lubricant Rheology**
- Rough Surfaces
- Mixed Friction Conditions
- Temperature Calculation

Lubricant properties

- consideration of density, viscosity, thermal conductivity and specific heat capacity, dependent on local conditions in the calculation domain (temperature, pressure)
  - ➢ based on high pressure rheometer data
- non-Newtonian flow behavior including shear thinning and limiting shear stress
  - ➢ based on experimental traction data



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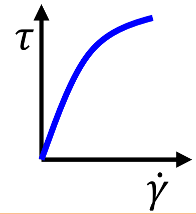
Eyring

$$\dot{\gamma} = \boxed{\frac{\tau_c}{\eta} \cdot \sinh\left(\frac{\tau}{\tau_c}\right)}$$

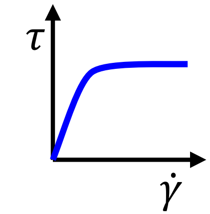


+ specification of critical shear stress τ_c

− ~~shear stress tends towards infinity~~

Bair/Winer (simplified)

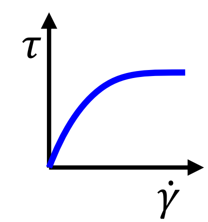
$$\dot{\gamma} = \boxed{\frac{\tau}{\eta}} \cdot \frac{1}{1 - \left(\frac{\tau}{\tau_{lim}}\right)^a}$$



+ specification of limiting shear stress τ_{lim}

− ~~nearly Newtonian behavior to τ_{lim}~~

$$\dot{\gamma} = \frac{\tau_c}{\eta} \cdot \sinh\left(\frac{\tau}{\tau_c}\right) \cdot \frac{1}{1 - \left(\frac{\tau}{\tau_{lim}}\right)^a}$$



➔ limiting shear stress is dependent on local pressure

3D TEHL Calculation Model

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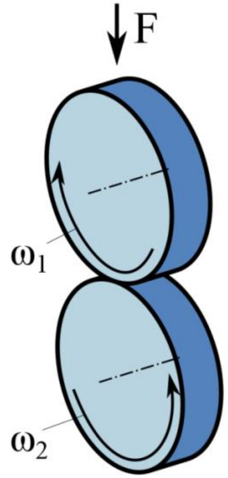
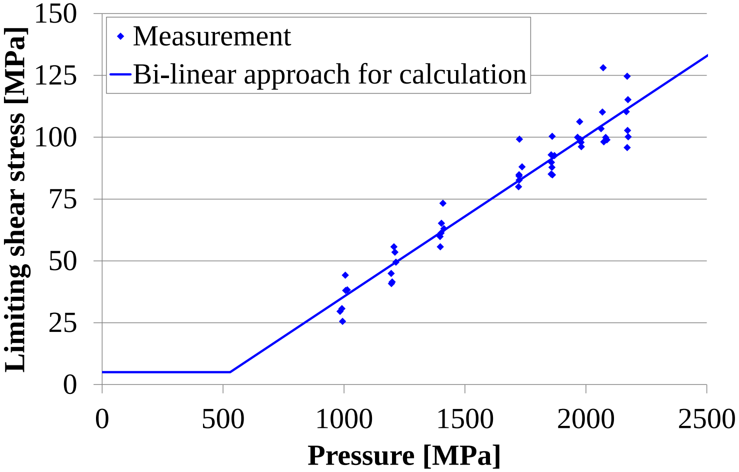
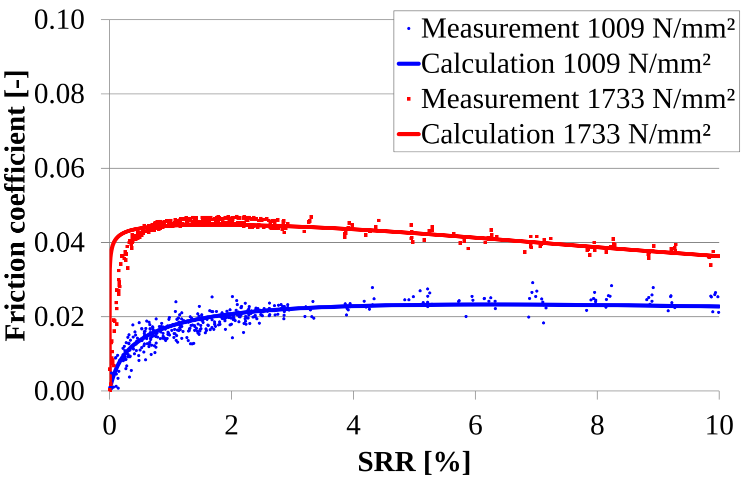
Twin-disk traction measurement – limiting shear stress





Comparison of measured and calculated traction curves



Measurement data: IMKT, University Hannover, Germany

3D TEHL Calculation Model

Calculation Model

- Elastohydrodynamics
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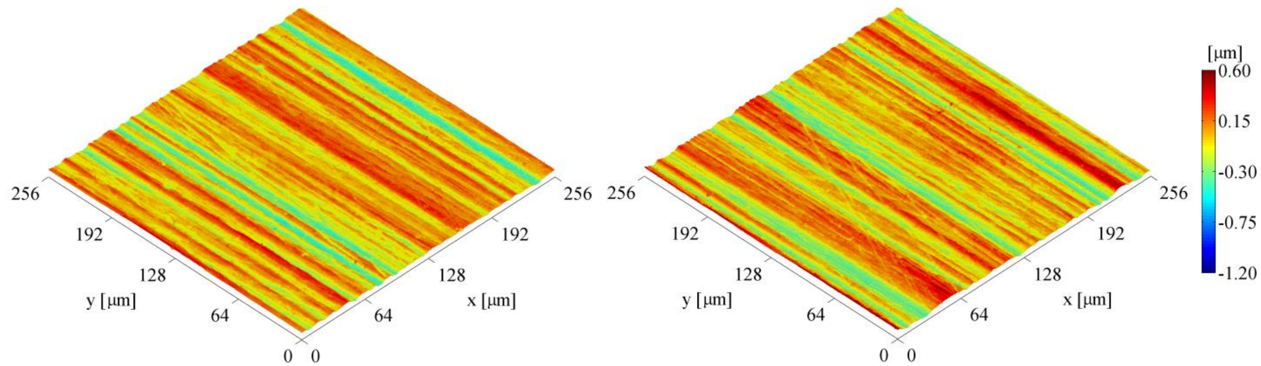
- Realistic Load Distribution
- Lubricant Rheology
- **Rough Surfaces**
- **Mixed Friction Conditions**
- Temperature Calculation

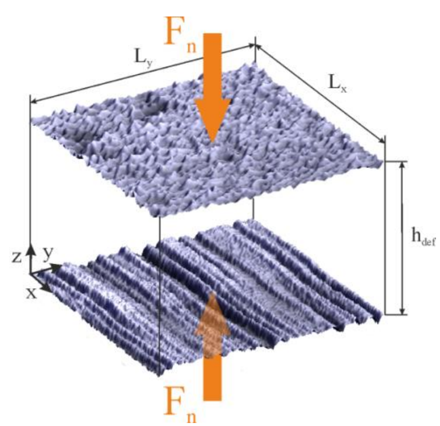
Measurement of real surface topographies of gear 1 and 2

Gear 1 **Gear 2**

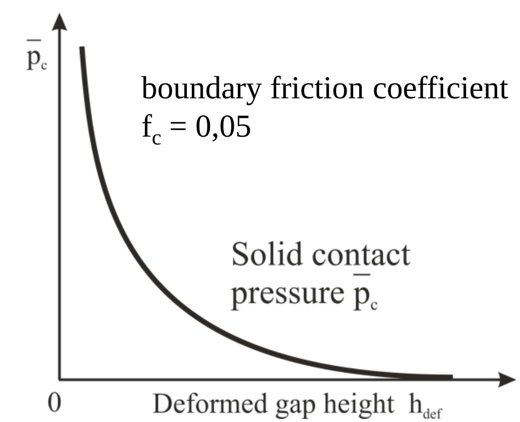


Calculation of characteristic mixed friction maps

Discrete solid contact model



Characteristic map



3D TEHL Calculation Model

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- Elastohydrodynamics
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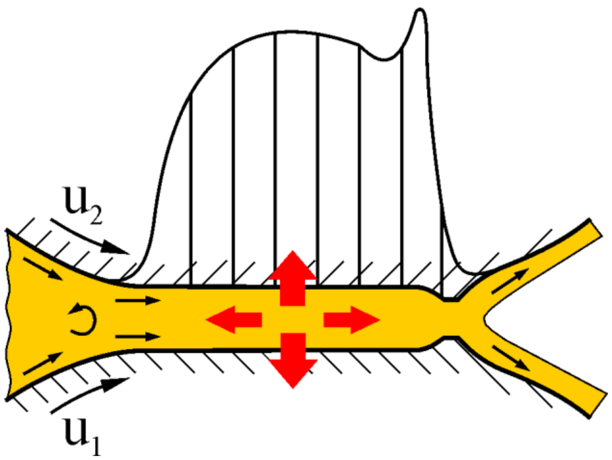
- Rough Surfaces
- Mixed Friction Conditions
- **Temperature Calculation**

- consideration of compression, expansion, shear, convection and heat conduction by gap height resolved solution of the energy equation for the fluid
- coupling with Fourier heat equation for tooth flanks
  - definition of depth-dependent thermo-physical material properties allows the calculation of complex multi-layer coatings
- consideration of additional heat sources as a result of boundary friction in the transitional condition



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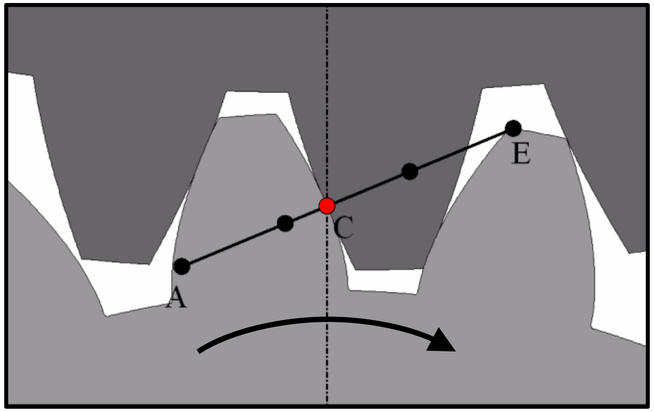
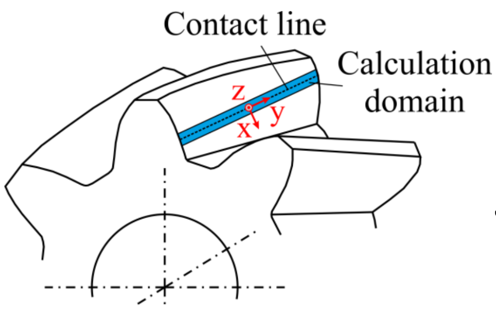
Calculation Example
Geometry data and operating parameters

Geometry data

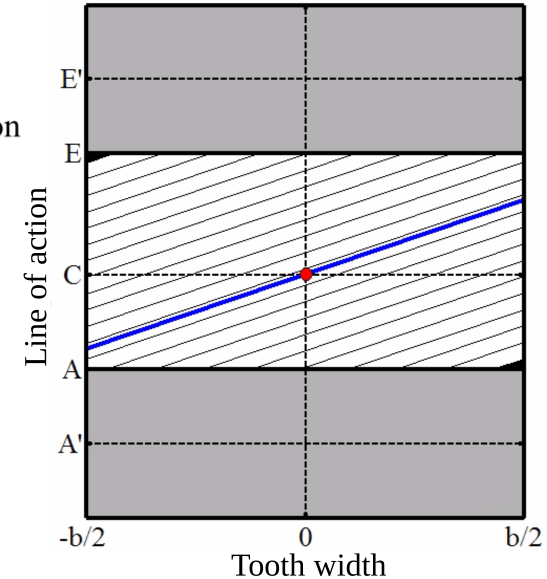
- normal modulus: $m_n = 3$ mm
- normal pressure angle: $\alpha_n = 20°$
- helix angle: $\beta = 20°$
- number of teeth: $z_1 = 24$, $z_2 = 61$
- center distance: $a = 137$ mm
- addendum modification: $x_1 = 0.3125$, $x_2 = 0.1404$
- width of gear: $b_1 = b_2 = 27.5$ mm
- crowning: 8 µm
- tip relief: 10 µm / 1.5 mm

Meshing (center of plane of action)





Plane of action

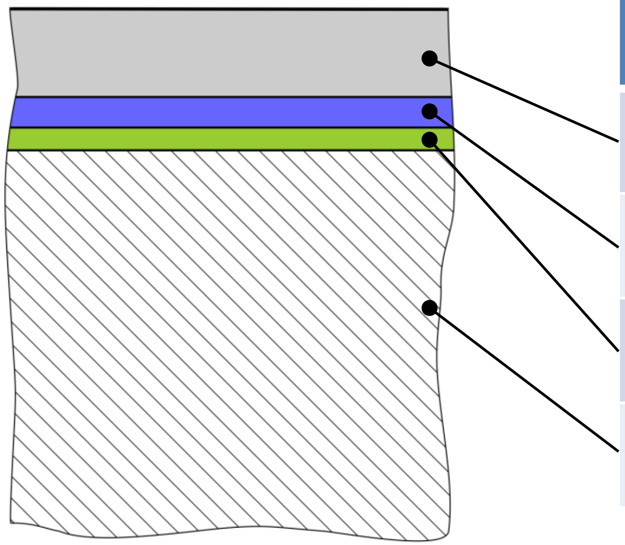


Operating parameters

- torque: $T_1 = 200$ Nm
- speed: $n_1 = 1485$ min^{-1}
- power: P = 31.102 kW
- lubricant: ISO VG 150
- temperature (bulk, oil): 60 °C

Calculation Example
Coating

Tooth flank coating structure



Layer	Thickness [µm]	Density [kg/m³]	Heat conductivity [W/(m K)]	Specific heat capacity [J/(kg K)]
DLC coating a-C:H	2.7	1860	0.566	700
Tungsten carbide layer	0.82	15800	58	283
Chrome layer	0.53	7190	90	447
Substrate Steel 16MnCr5	-	7760	44	431

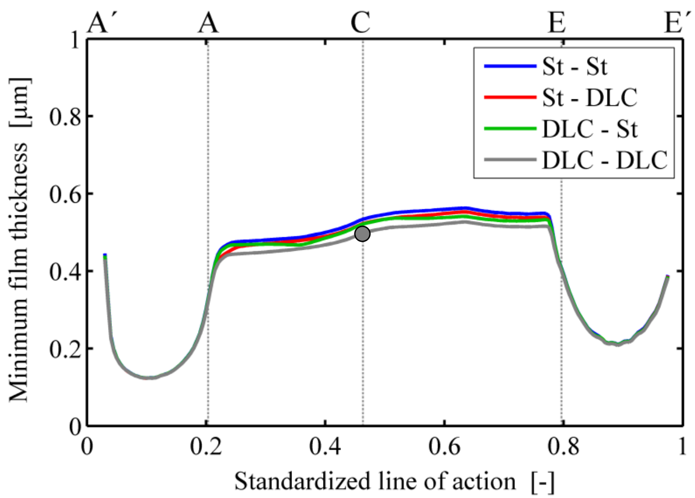
Overview of calculation examples

Notation	Gear 1	Gear 2
St-St	uncoated steel	uncoated steel
St-DLC	uncoated steel	DLC coated steel
DLC-St	DLC coated steel	uncoated steel
DLC-DLC	DLC coated steel	DLC coated steel

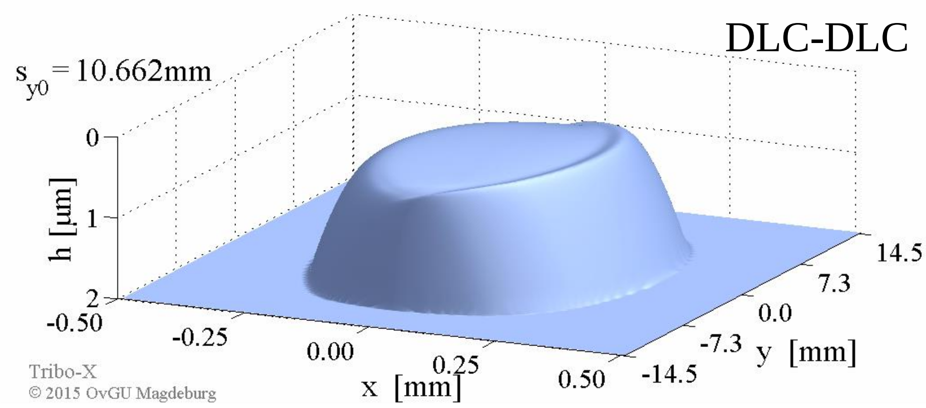
Content

Results

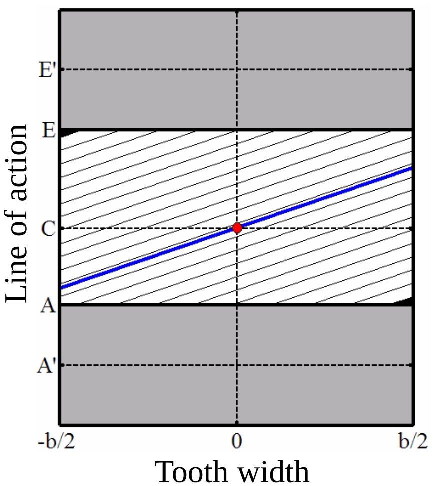
Minimum film thickness



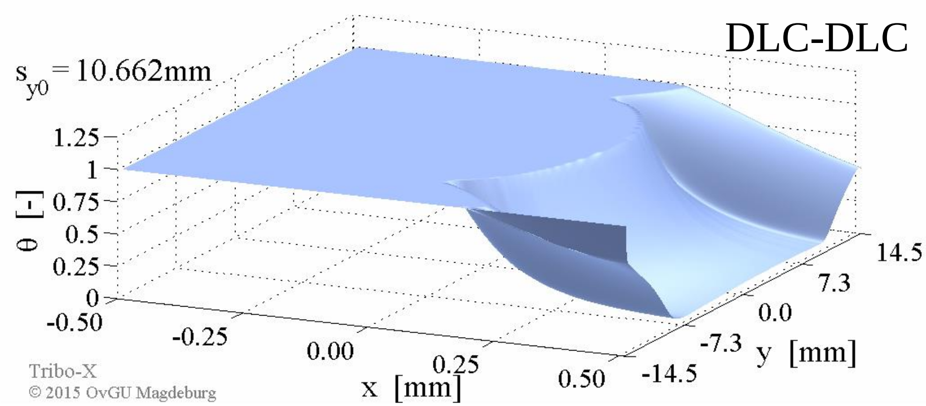
Film thickness



Plane of action

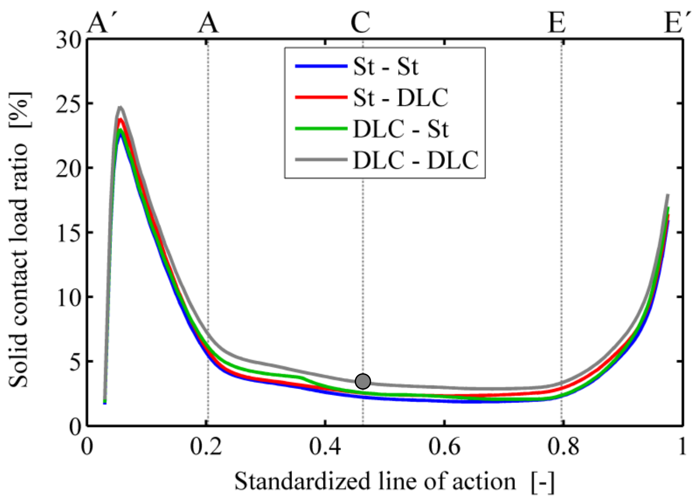


Gap fill factor (cavitation)

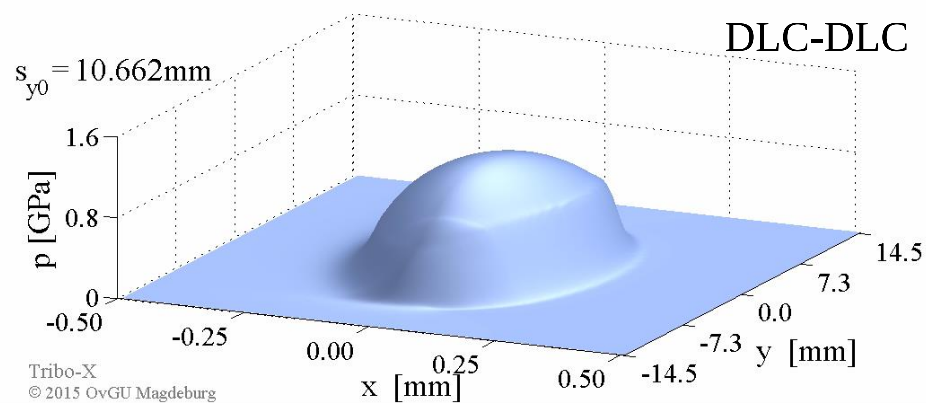


Results

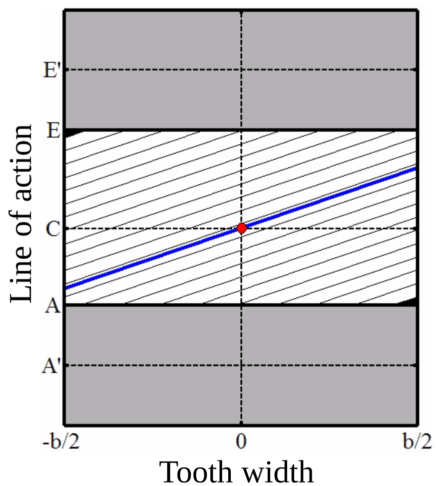
Solid contact load ratio



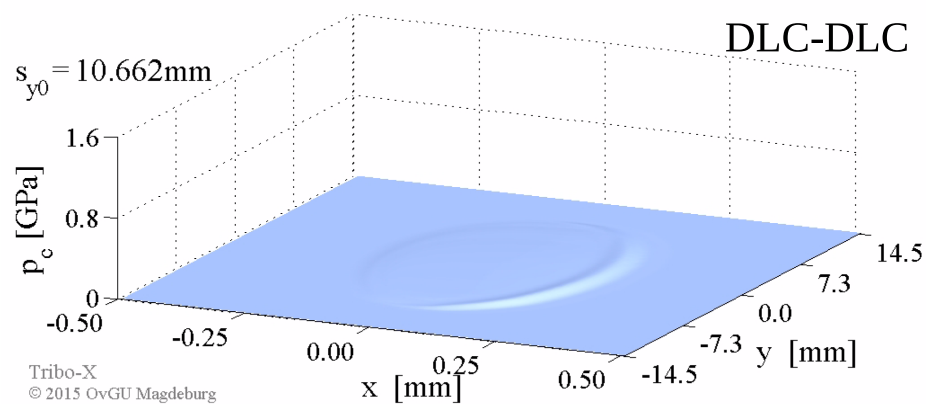
Total pressure



Plane of action

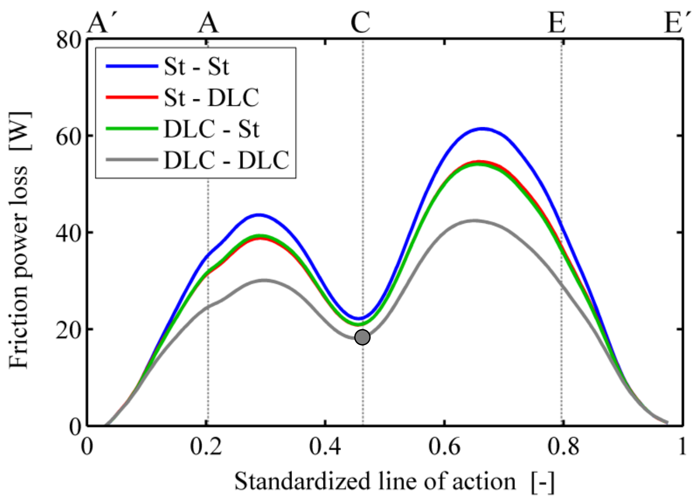


Solid contact pressure

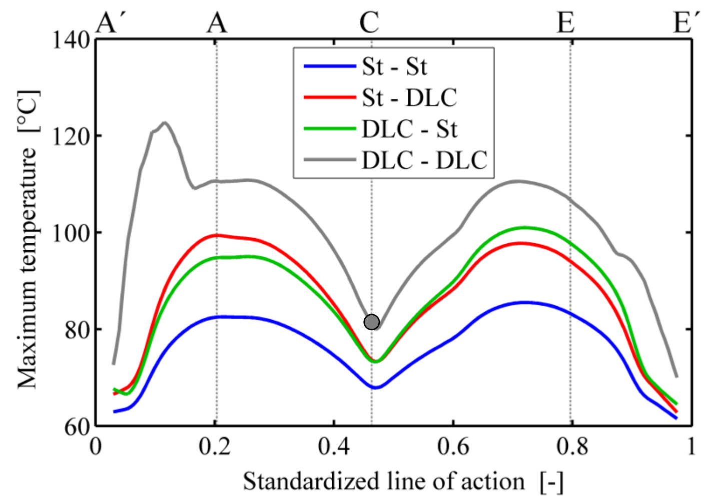


Results

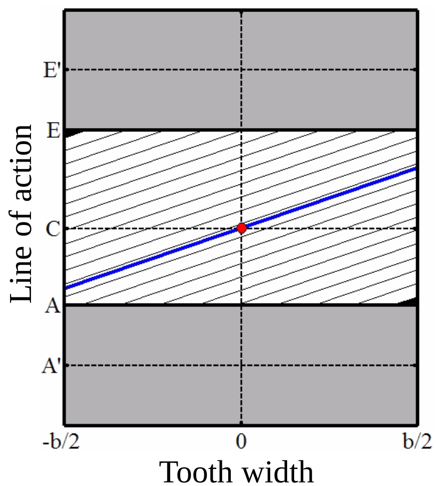
Friction power loss



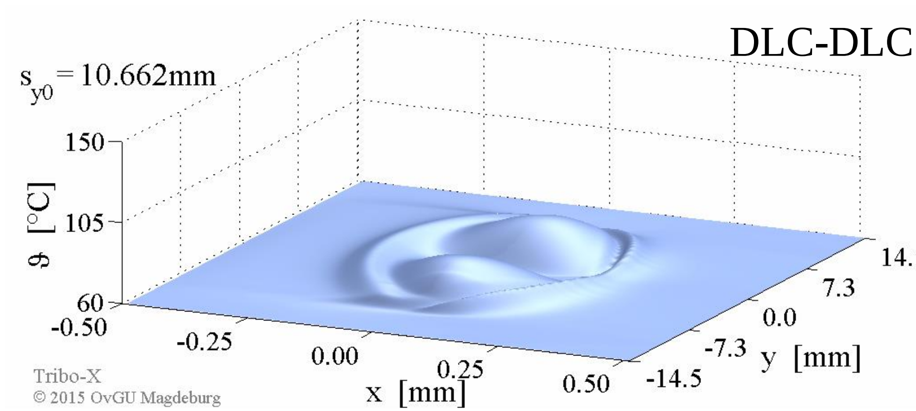
Maximum temperature



Plane of action

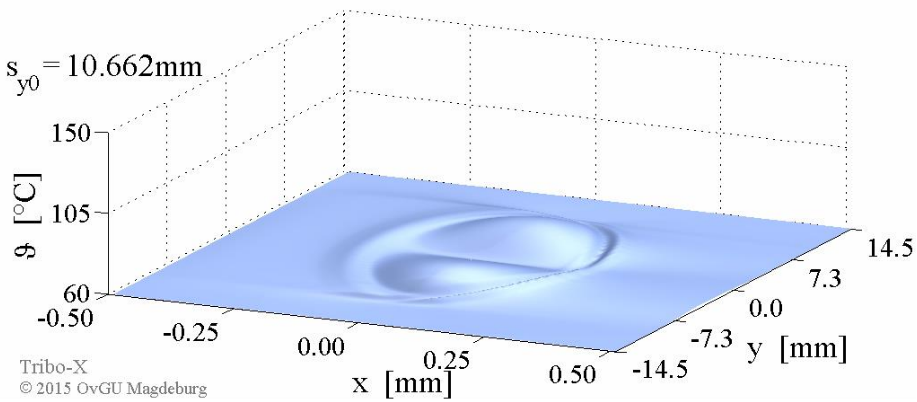


Temperature (mid lubricating gap)

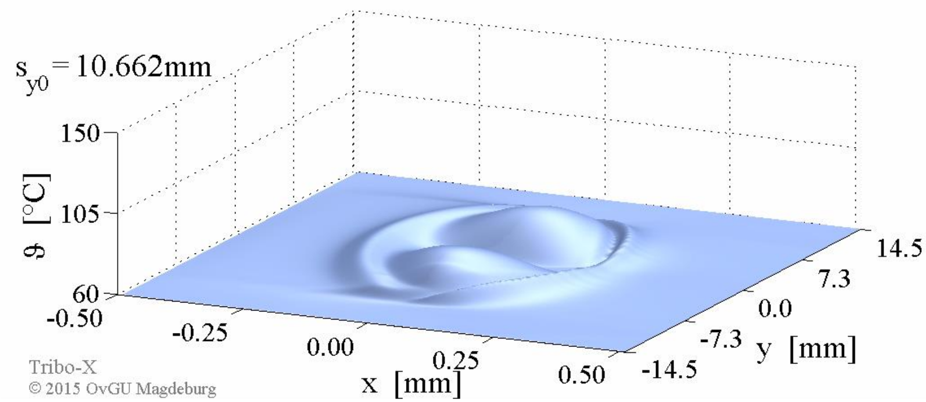


Results
Temperature (mid lubricating gap)

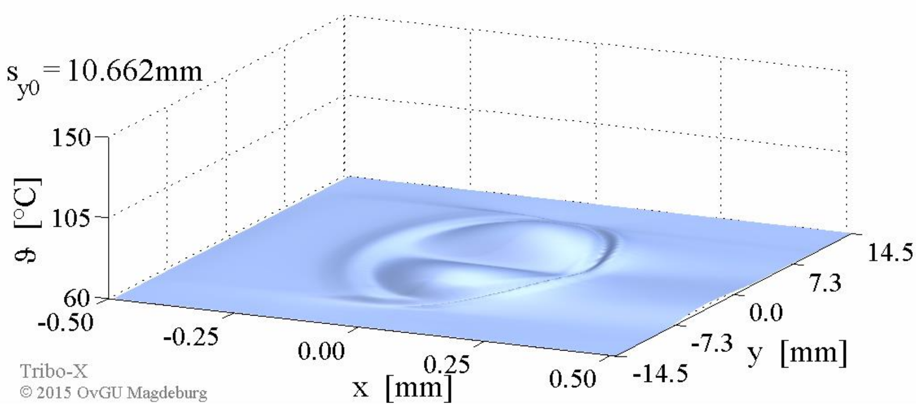
DLC-St



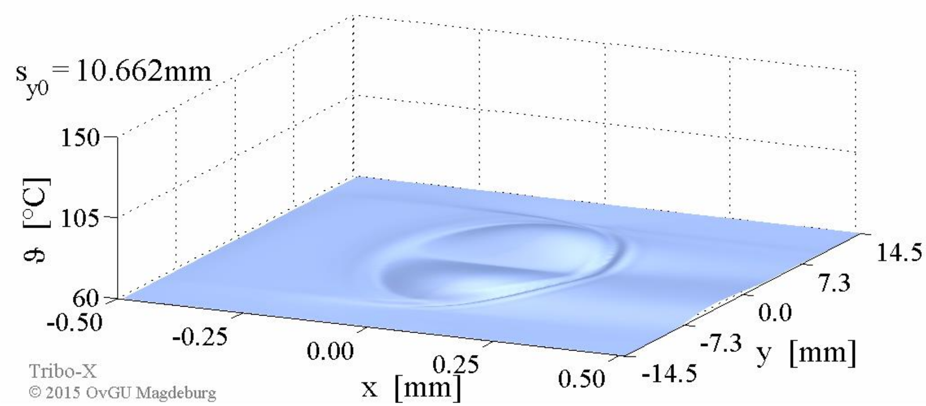
DLC-DLC



St-DLC

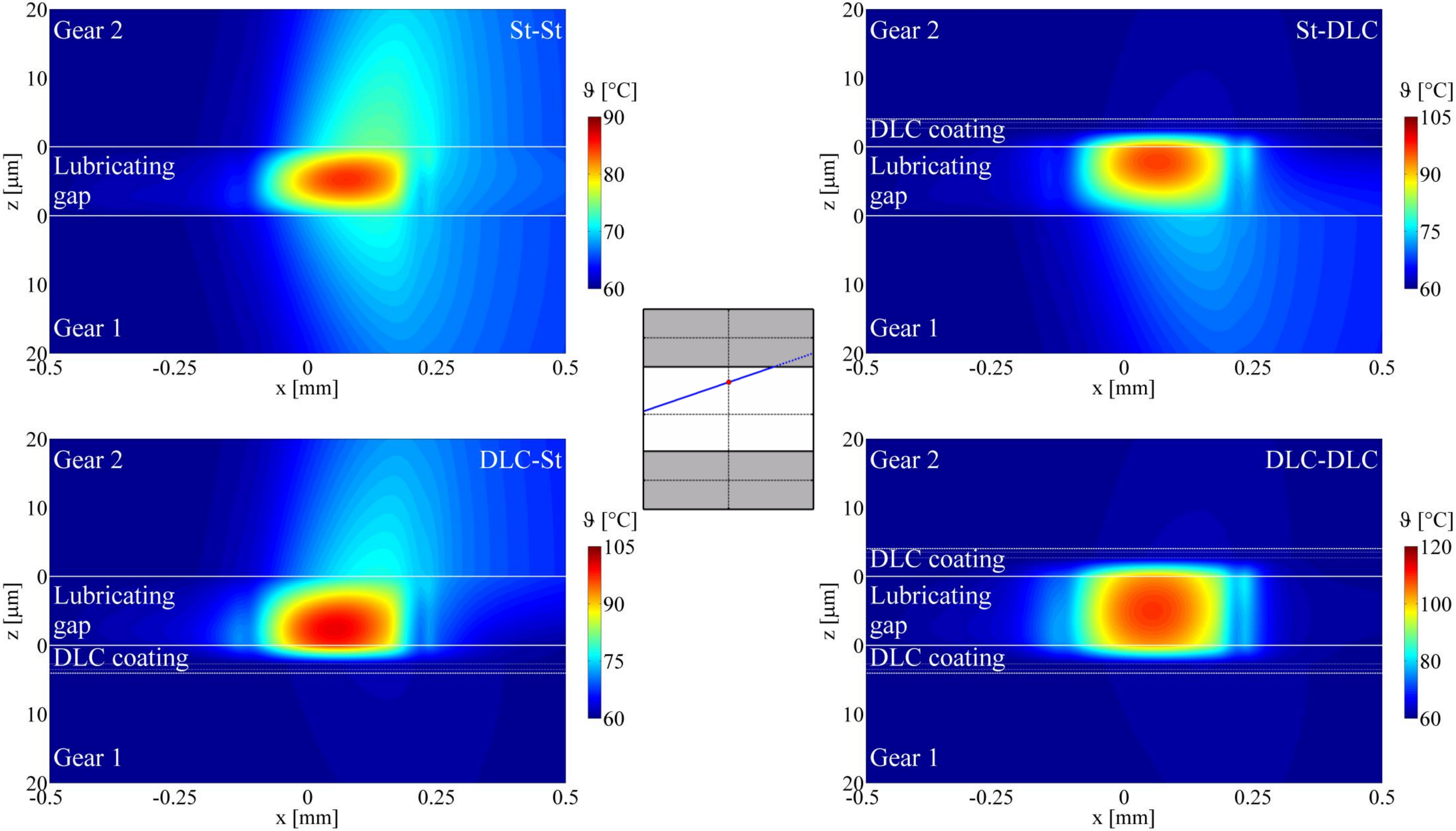


St-St

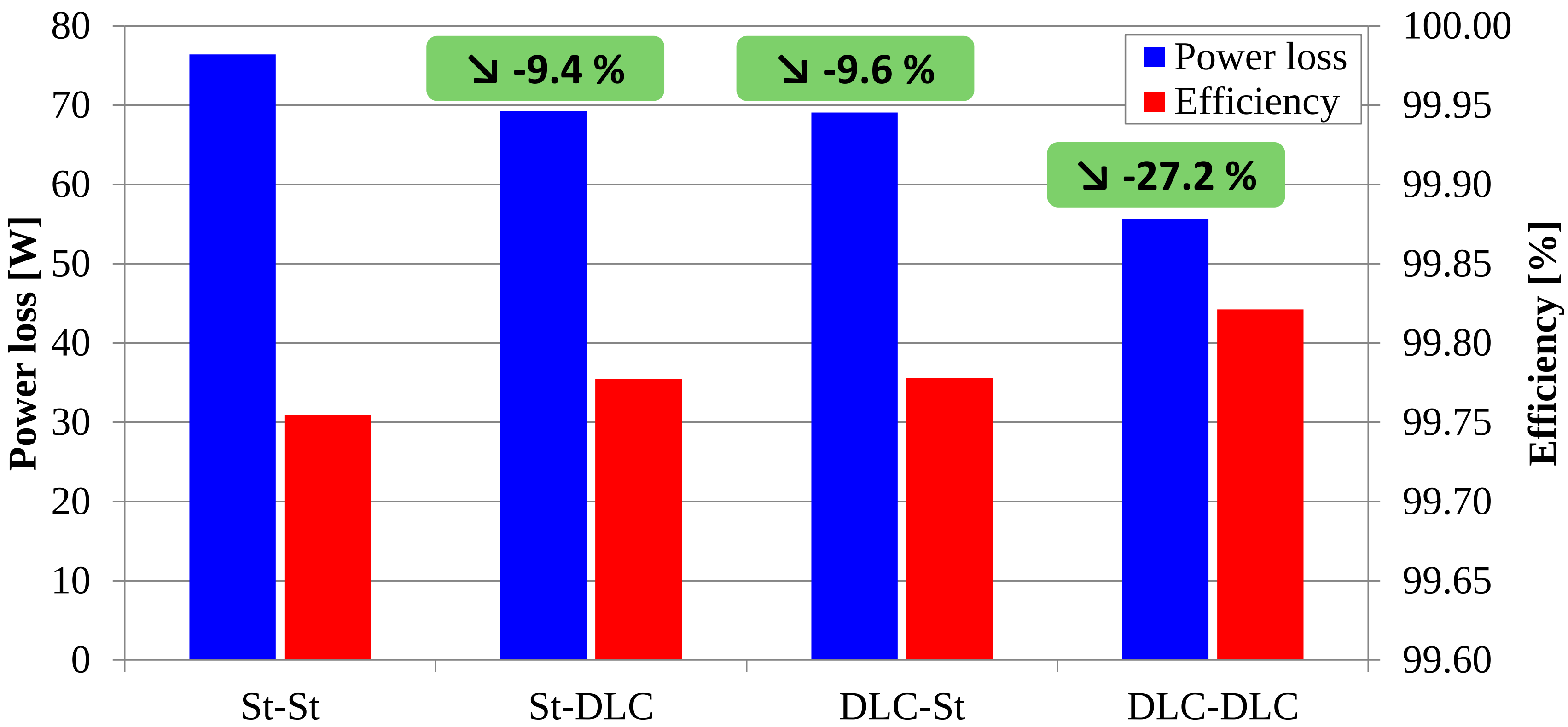


Results

Temperature distributions in sectional planes (center of gear, along line of action)



Results
Power loss and efficiency



Causal chain

DLC coating insulation effect → temperature increase → viscosity decrease → friction decrease

Content

Summary

- A calculation model for **transient thermal elastohydrodynamic simulation** was introduced.
  - ➢ applied on tooth flank contact of a helical gear pair
- Multi-layer **DLC coating** and realistic **rheological behavior** of the fluid were taken into account.
- DLC coated tooth flanks **reduced power loss** as a result of reduced hydrodynamic friction due to **higher temperatures**.
  - ➢ DLC coating on both gears led to highest temperatures and lowest power loss
- Higher temperatures in DLC coated contacts could be attributed to the **insulating effect** of the coating due to poorer thermal conductivity.
- Power loss results are **limited to mild mixed friction conditions**.
  - ➢ boundary friction coefficient of DLC coating may be different

Contact & Acknowledgments

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