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Numerical modelling of the thermomechanical beahviour of polymer gears

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Univerza v Ljubljani

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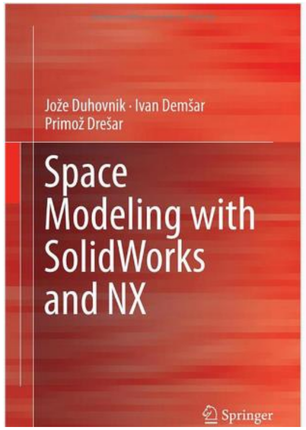
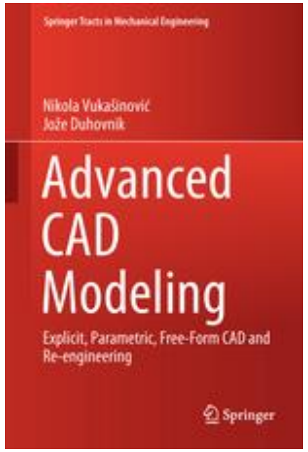
About LECAD Lab

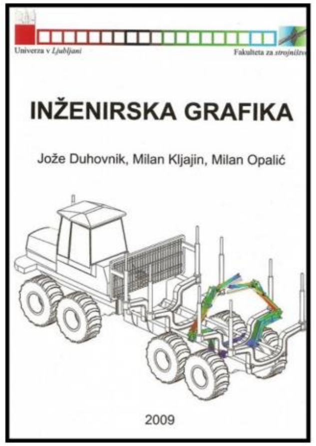
Laboratory for Engineering Design and Supercomputing

- CAD/CAE modelling, PLM,
- HPC based numerical simulations,
- Experimental testing,
- Engineering design methodology,
- Product development,
- Eco-design,
- Industrial design

www.lecad.fs.uni-lj.si







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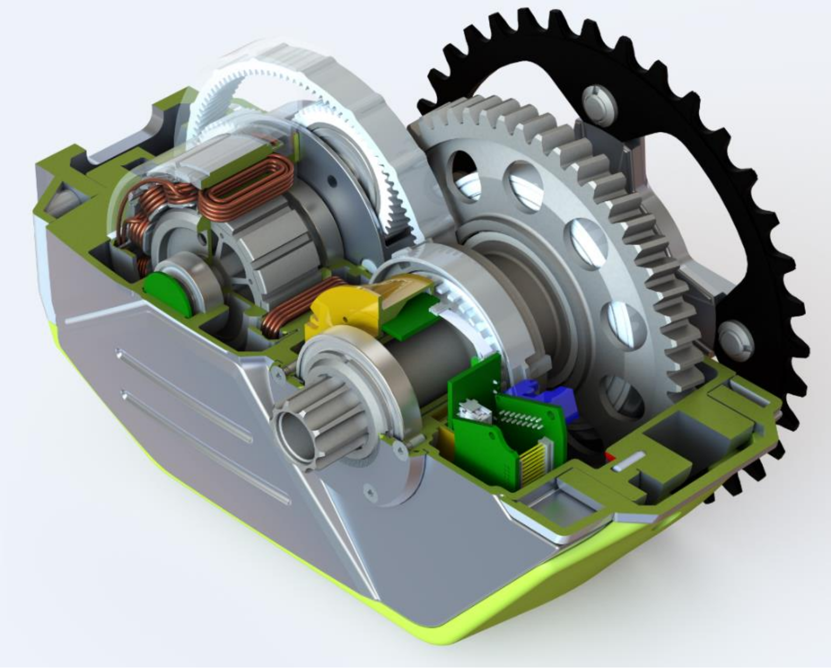
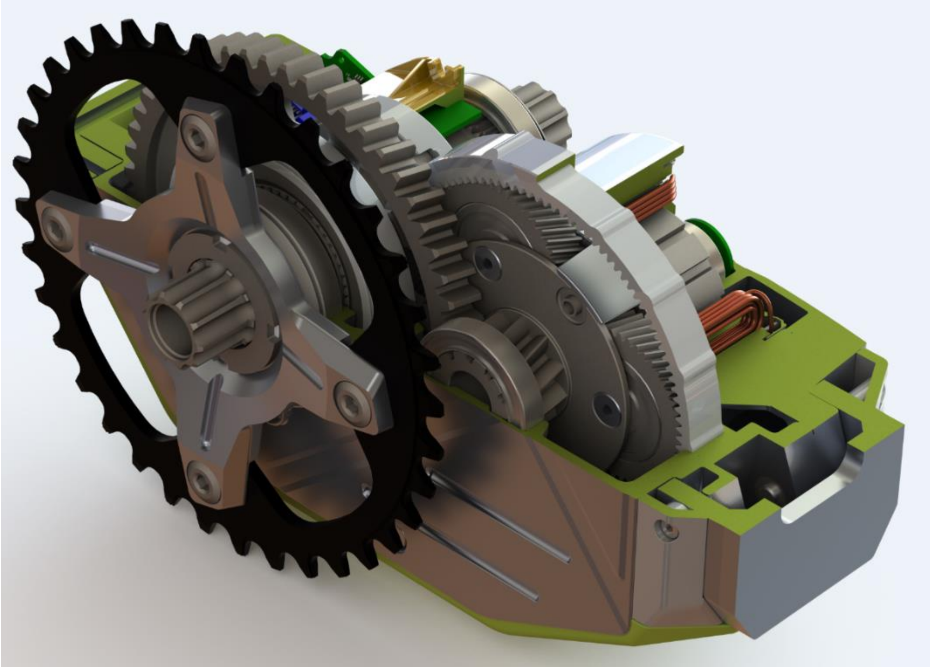
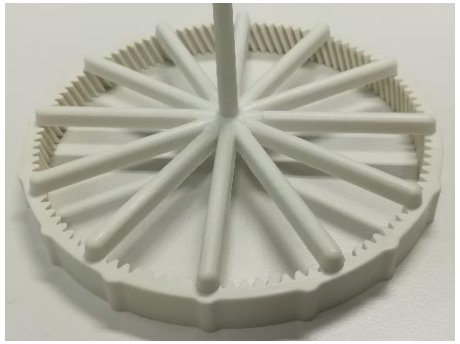
Industrial R&D - Central drive system for pedelec e-bike:

dr. Jože Tavčar, Borut Černe, Damijan Zorko







DOMEL PODKRIŽNIK BMZ THE INNOVATION GROUP

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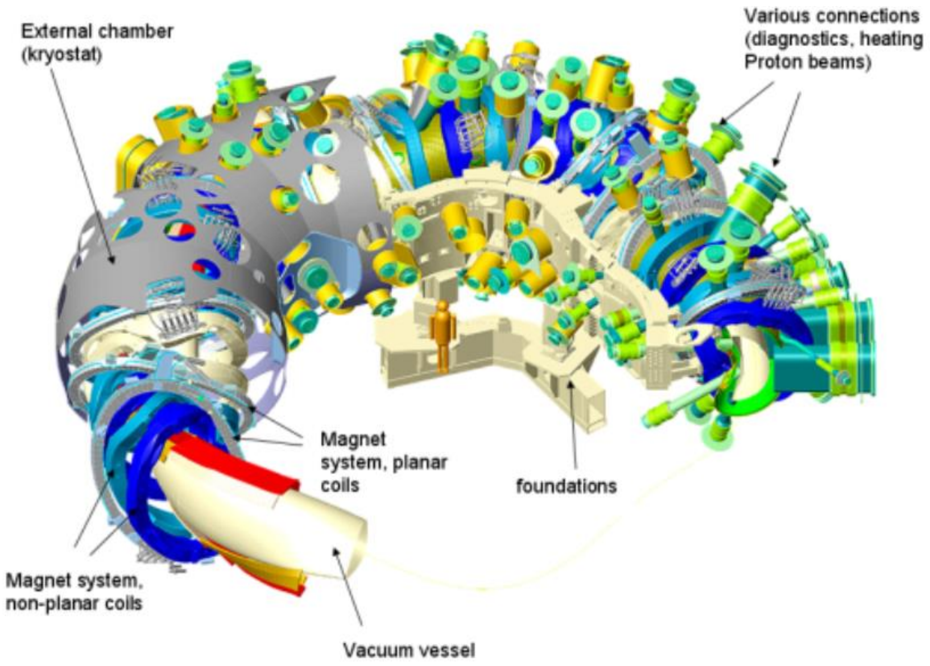
Fusion project, ITER - HPC based numerical modelling and visualization

- dr. Leon Kos, dr. Janez Povh, dipl. ing. str. Matic Brank



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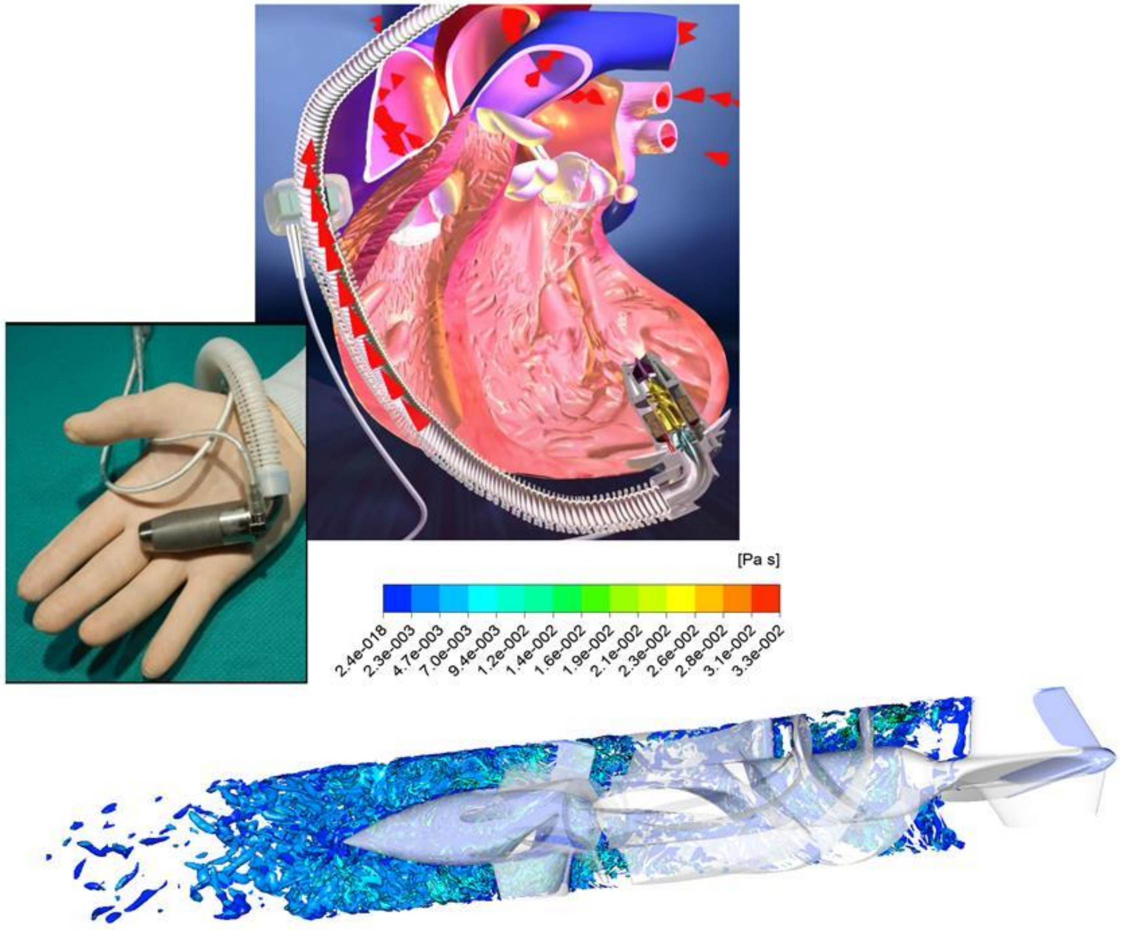
Analyses of the blod flow in an LVAD heart pump, PhD work project :

- dr. Primož Drešar

Goal:

- Apply and compare advanced turbulence models to accurately predict the flow induced stresses on blood cells



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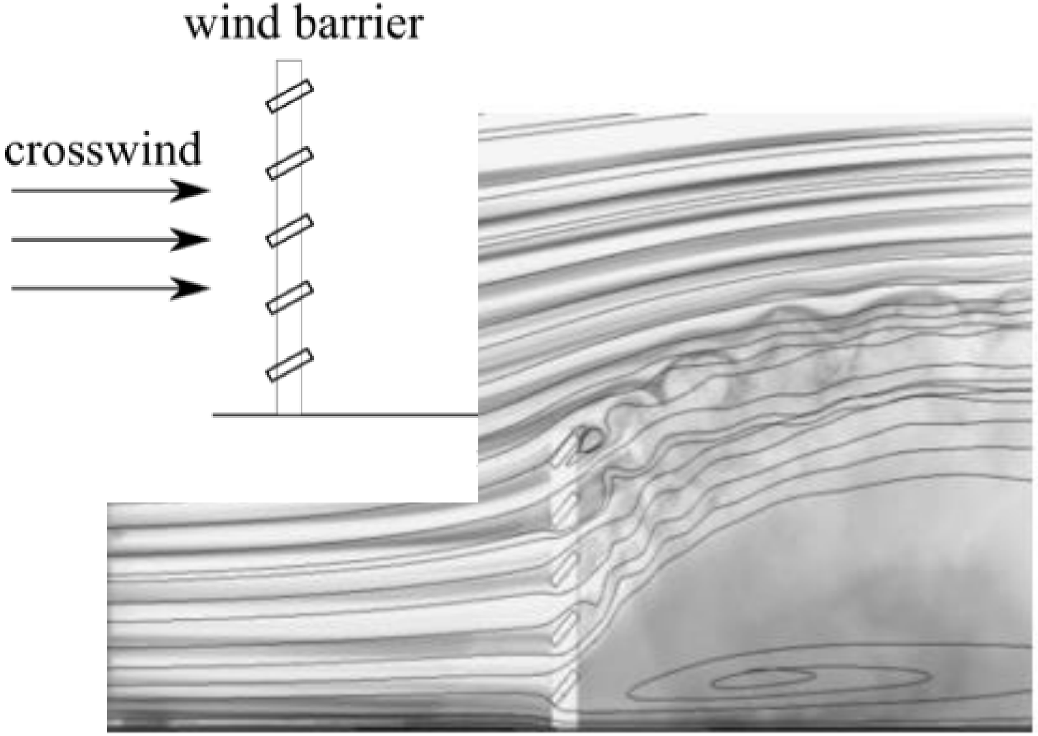
Leg prosthesis, PhD work project

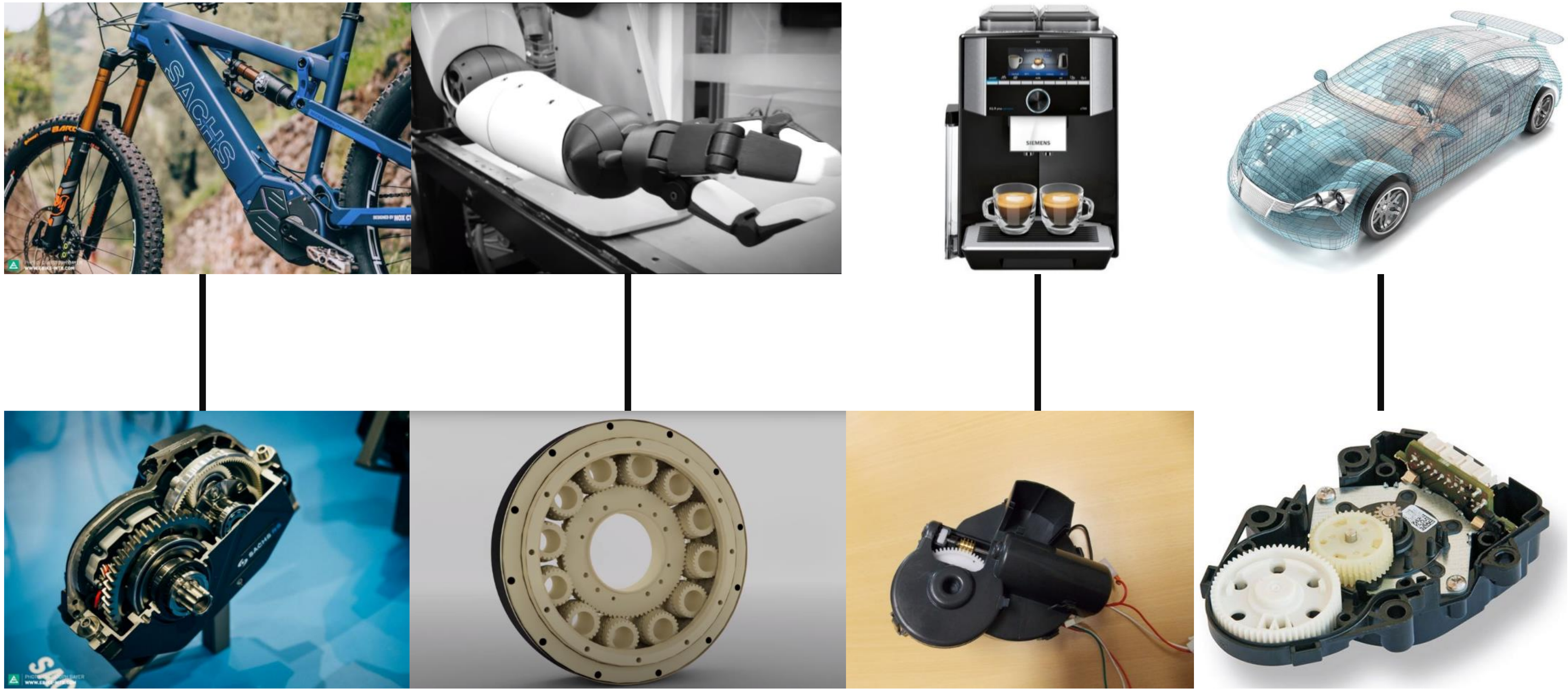
- Dr. Ivan Demšar

Wind barrier motorway protection

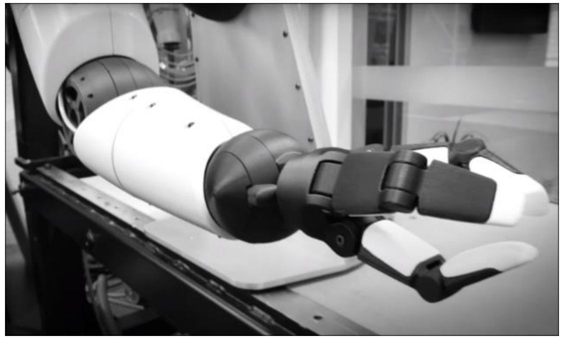
Dr. Marijo Telenta

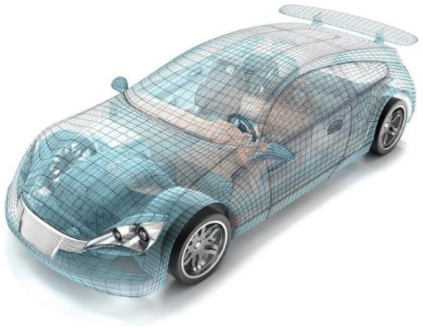


Polymer gear research - Motivation



Motivation

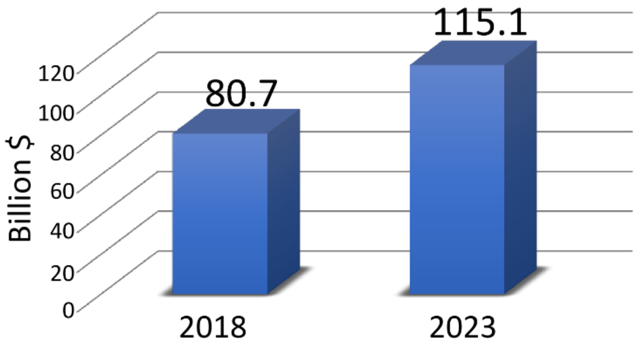




ENGINEERING POLYMERS

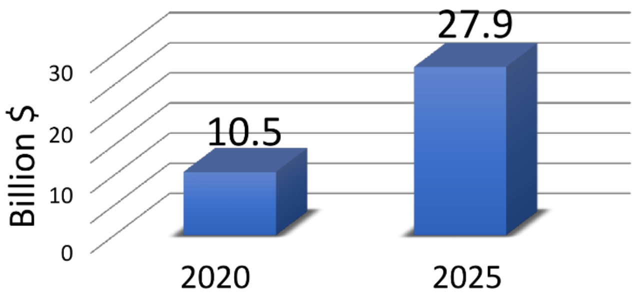
(global market):

CAGR 7.2 %



BIOPOLYMERS (global market):

CAGR 21.7 %

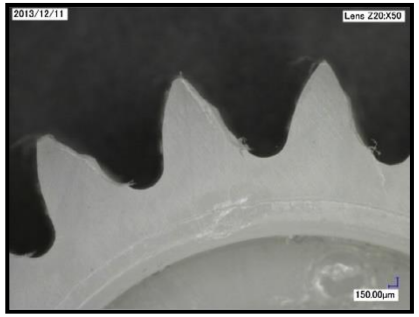


Markets and Markets™ Inc.

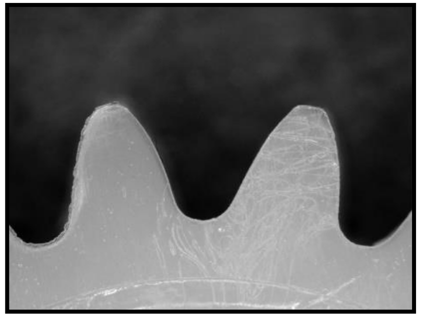
Motivation

- Polymer gears exposed to various failure mechanisms:

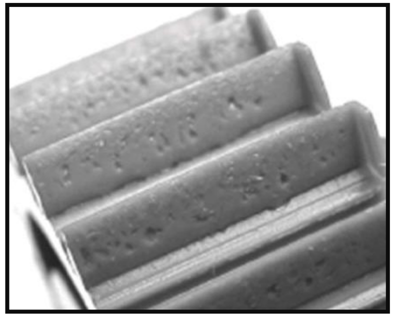
Fatigue



Wear



Thermal overload



Pitting

- Predominant failure mode depends:
  - **gearing geometry**
  - **material pair**
  - **load regime,**
  - **lubrication,**
  - **environmental conditions,**
- **Temperature rise** during running – influencing factor and indicator of the expected gear service life

Physical background

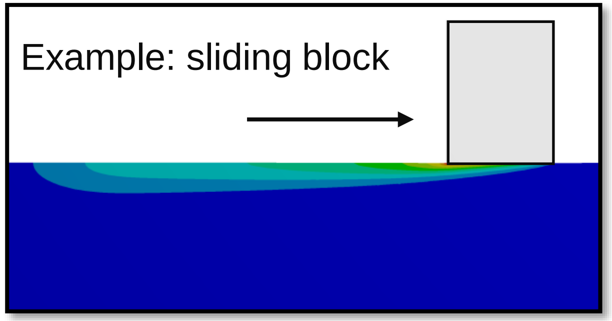
Thermal state of polymer gears:

- **Heat generation effects:**
  - Sliding friction effect (predominant)
  - Deformational hysteresis – structural and rolling friction

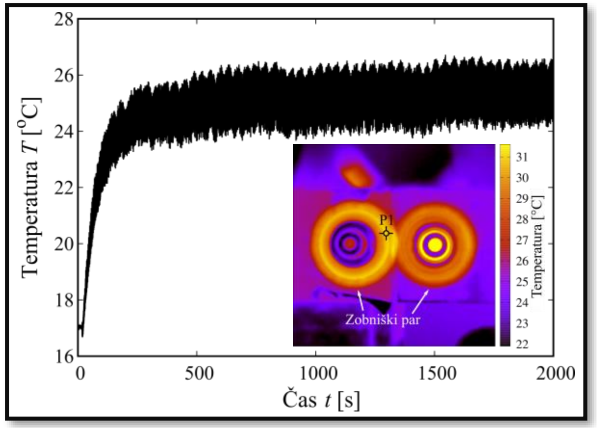
- **Heat dissipation:**
  - Thermal conduction through solids
  - Convective heat transfer
  - Contact conductance
  - Radiation (minor effect)

- **Heat partitioning:**
  - Distribution of generated heat between both gear bodies

Temperature rise – two components:



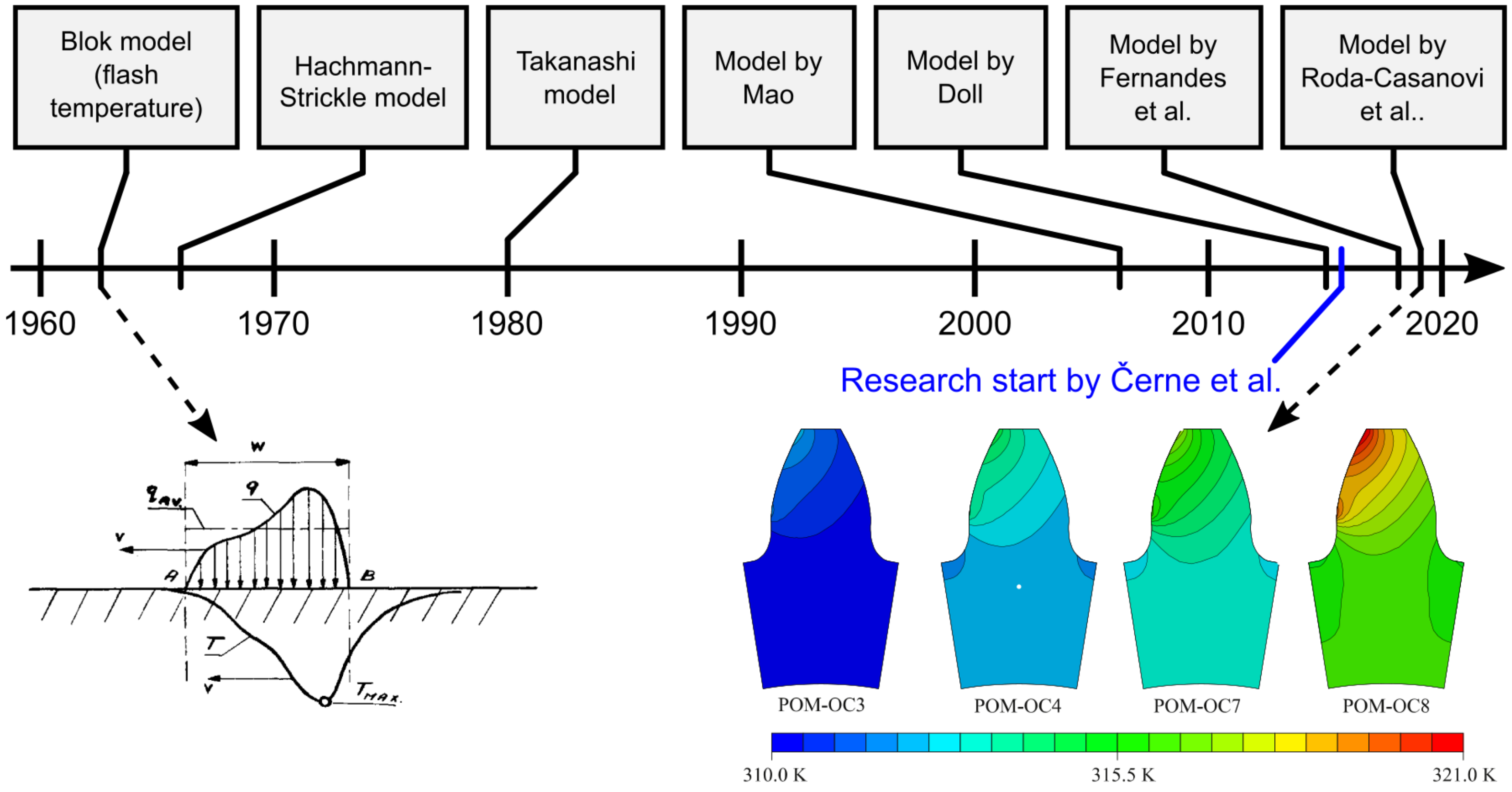
Flash temperature rise



Nominal temperature

State of the art

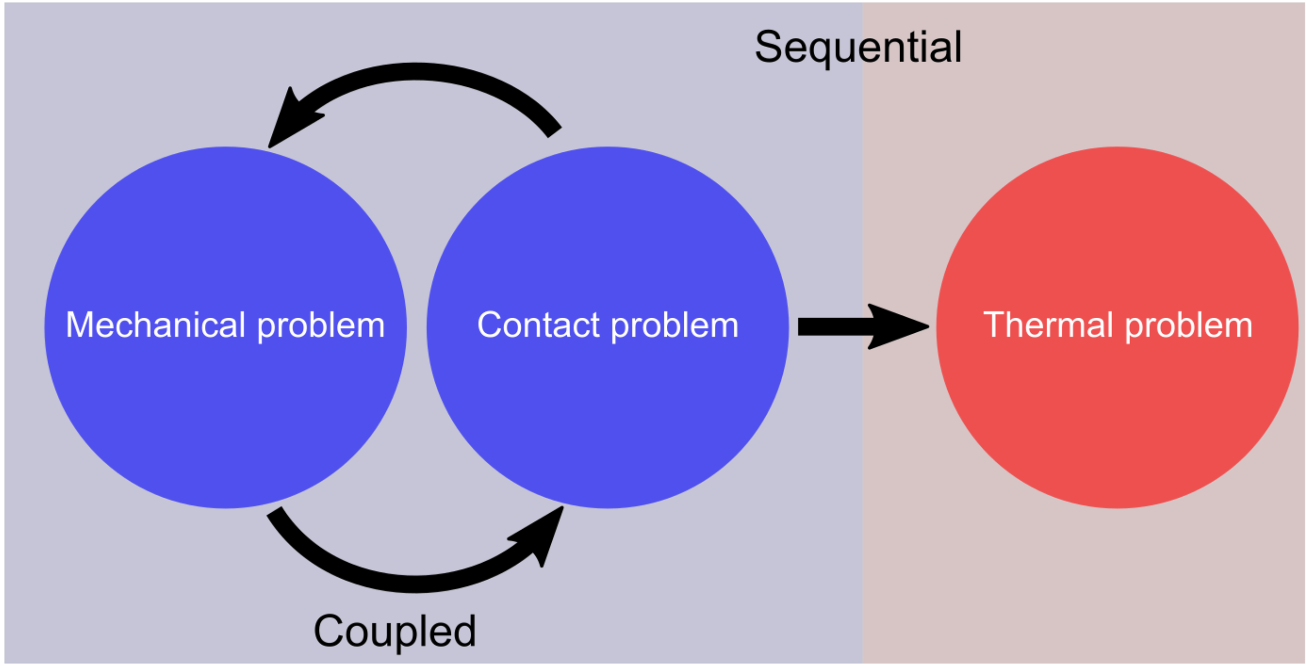
Existing polymer gear thermal models



Model development

Problem breakdown

- Processes taking place at two **very distinct time scales**:
    1. **Meshing cycle** - typically $t < 10^{-1}$ s
    2. **Running till steady state** reached - $t \geq 10^{3}$ s



Model development

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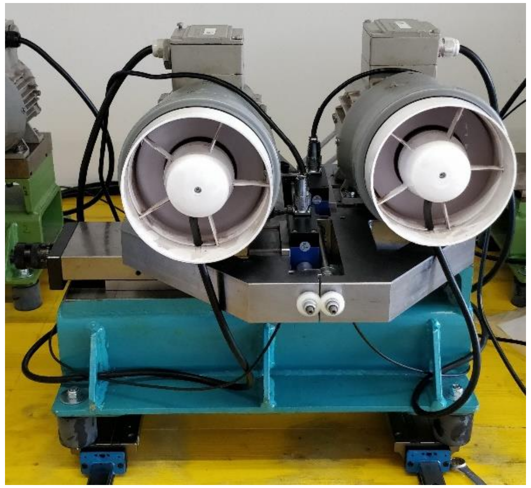
Case study – LECAD gear geometry

- **Polymer-polymer** involute spur gear pair
  - Pinion: POM (Ensinger Tecaform AH nat.)
  - Gear: PA66 (Ensinger Tecamid66 nat.)
- Cut samples

Parameter	Symbol [unit]	Value
Gear ratio	i [/]	1
Module	m [mm]	1
Teeth number	$z_{1,2}$	20
Pressure angle	α [°]	20
Face width	b [mm]	6
Shaft diameter	d_h [mm]	6



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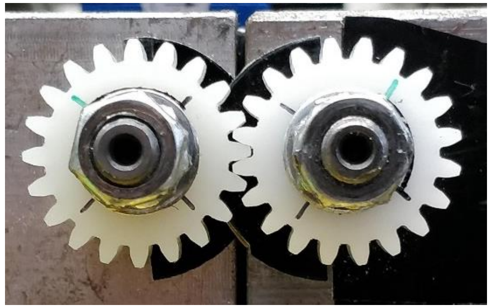
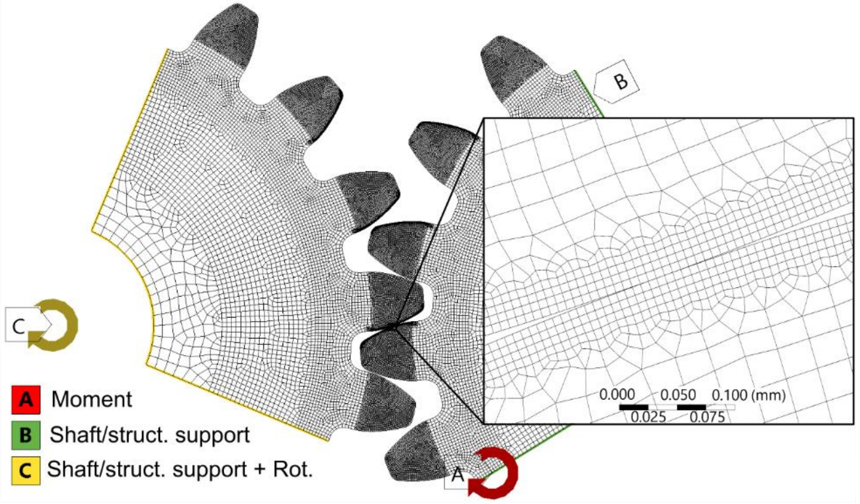
Mechanical contact problem (I) - model

- Goal: evaluate **contact response** during gear meshing
- **Transient FEM** contact analysis
- Geom. simplification: gear segment with **2D plane stress** presumption
- Gear profile: **involute**
- **Linear elasticity** assumption
- Nonlinear analysis due to
  - **geometric** and
  - **contact** nonlinearities

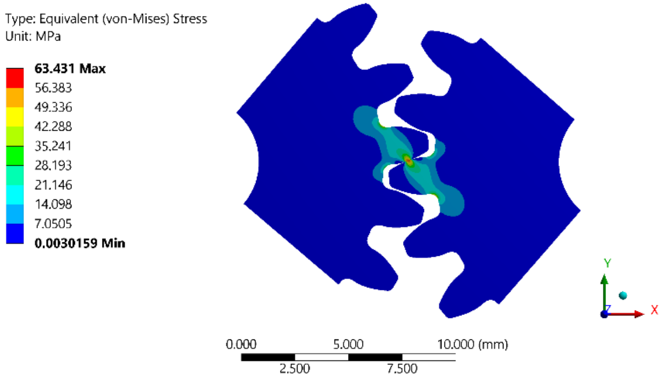




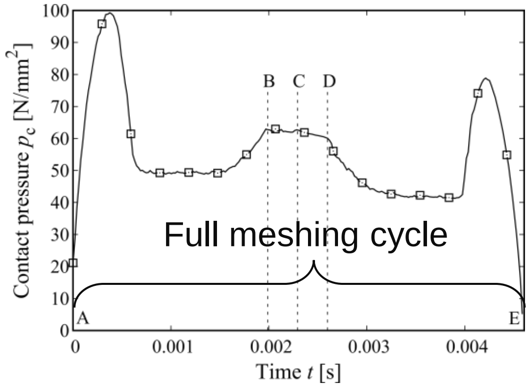
Model development

Mechanical contact problem (II) - results

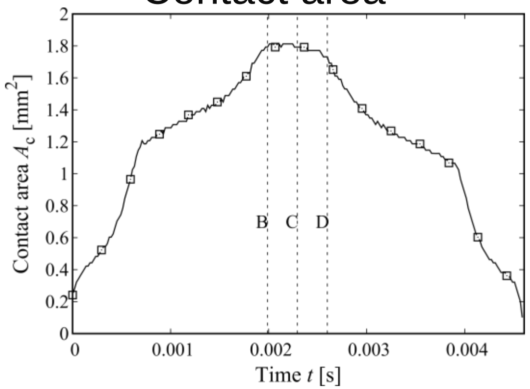
Meshing cycle simulation



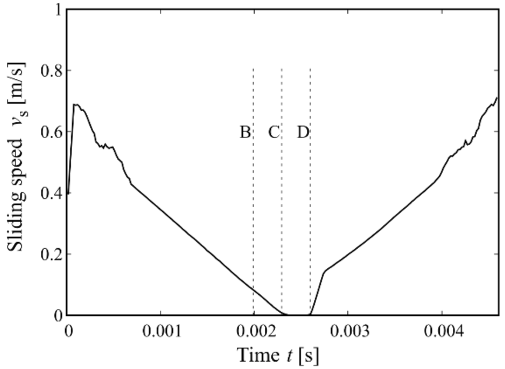
Contact pressure



Contact area



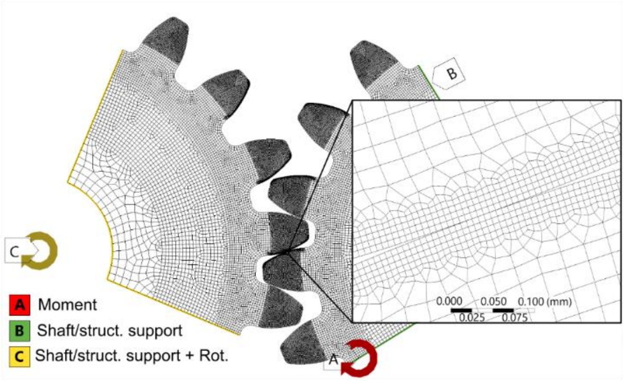
Sliding speed

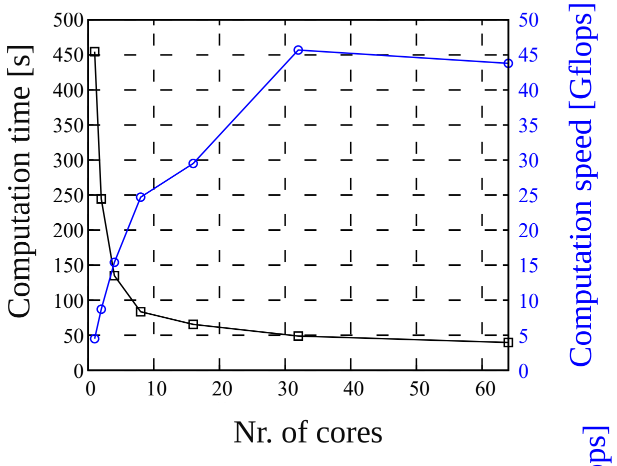


Model development

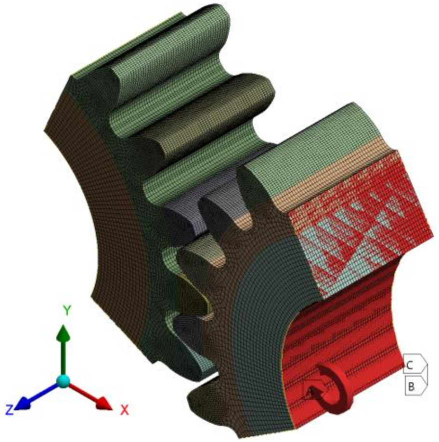
Scalability of the FEM mechanical model

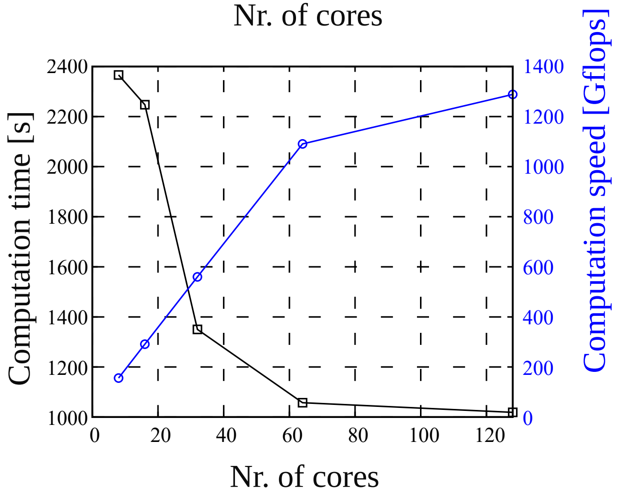
- **2D model:**





- **3D model:**





Model development

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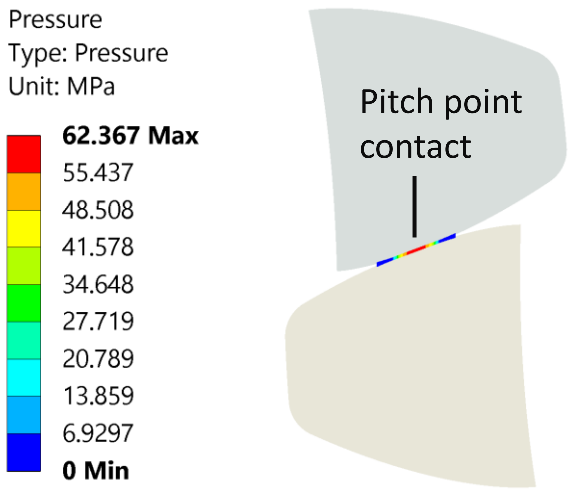
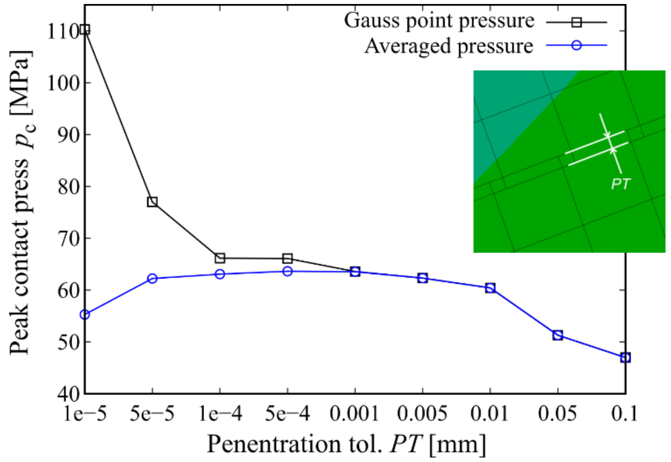
Mechanical contact problem (II) – convergence and accuracy of results issues

- Correct contact modelling of key importance
- Convergence issues can occur in the analysis



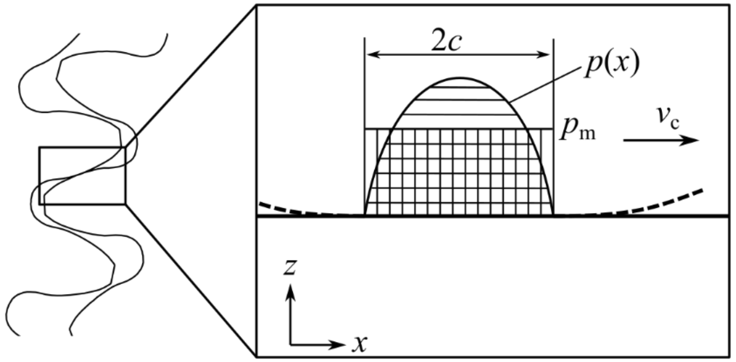
Example: penetration tolerance influence



- **Contact response verification:**
  - ➢ Hertz theory (VDI 2736)

$$\sigma_H = Z_E \cdot Z_H \cdot Z_\varepsilon \cdot Z_\beta \cdot \sqrt{\frac{F_t}{b_w \cdot d_1} \cdot \frac{i_t + 1}{i_t}}$$

Thermal problem (I) – Local temperature rise



- Heat partitioning coefficient

$$\Delta T_{\mathrm{l,d}} = U_{\mathrm{d}} \int_0^t \int_{-c(t')}^{c(t')} \boxed{\psi(x',t')}\, f_{\mathrm{d}}(x',t')\mathrm{d}x'\mathrm{d}t'$$

Pinion

$$\Delta T_{\mathrm{l,f}} = U_{\mathrm{f}} \int_0^t \int_{-c(t')}^{c(t')} \boxed{[1-\psi(x',t')]}\, f_{\mathrm{f}}(x',t')\mathrm{d}x'\mathrm{d}t'$$

Gear

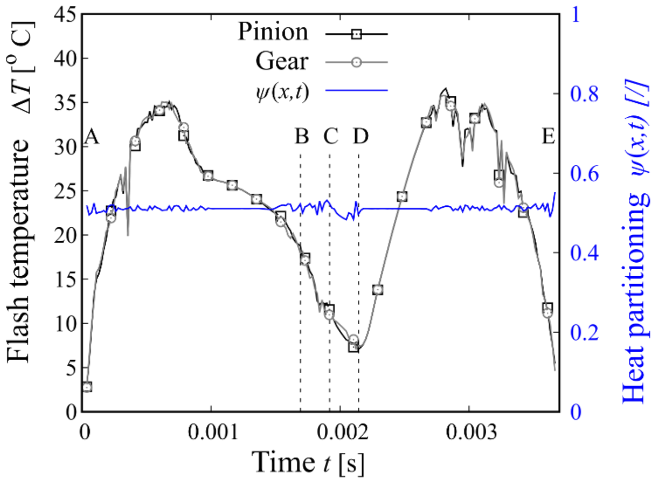
Heat partitioning coef.

- Parabolic heat flux function:

$$q_{\mathrm{l}}(x,t) = \mu \cdot v_{\mathrm{s}}(t) \cdot p_{\mathrm{c}}(t) \left[1 - \frac{x^2}{c(t)^2}\right]^{\frac{1}{2}}$$

- Contact temperature equality:

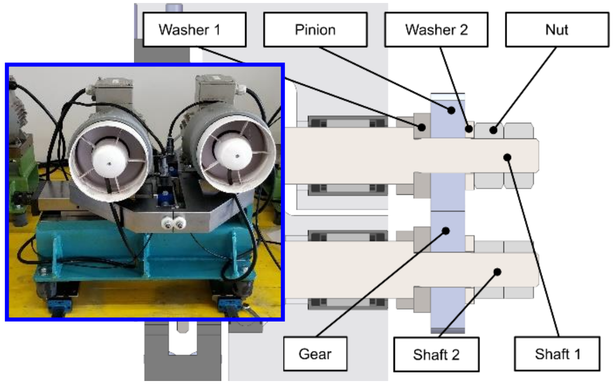
$$\Delta T_{\mathrm{l,d}}(-c(t) < x < c(t), z=0) = \Delta T_{\mathrm{l,f}}(-c(t) < x < c(t), z=0)$$



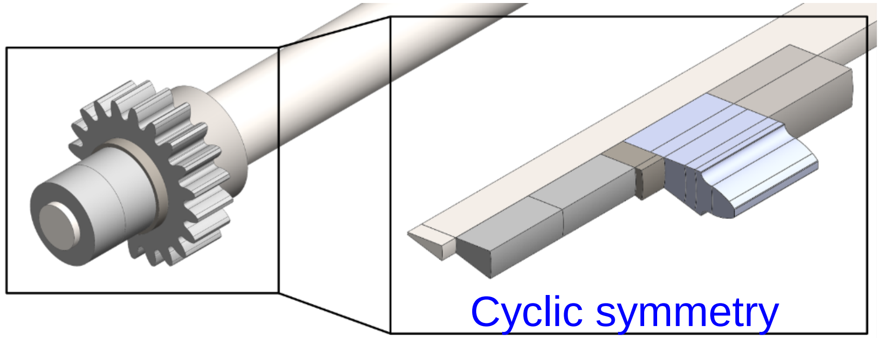
Model development

Thermal problem (II) – Nominal (bulk) temperature rise

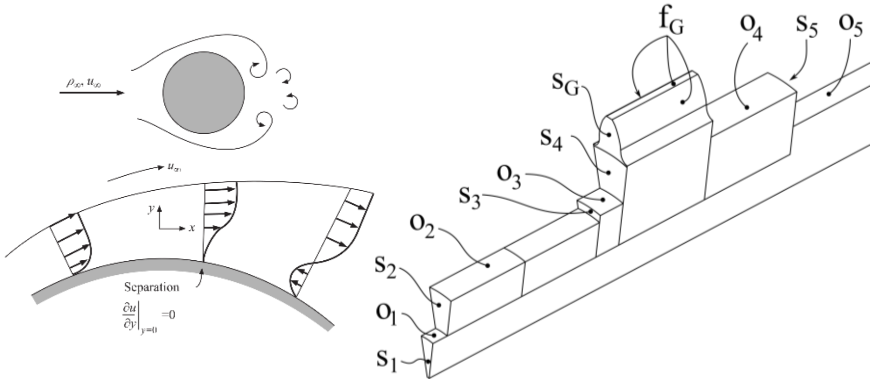
Geometric model:



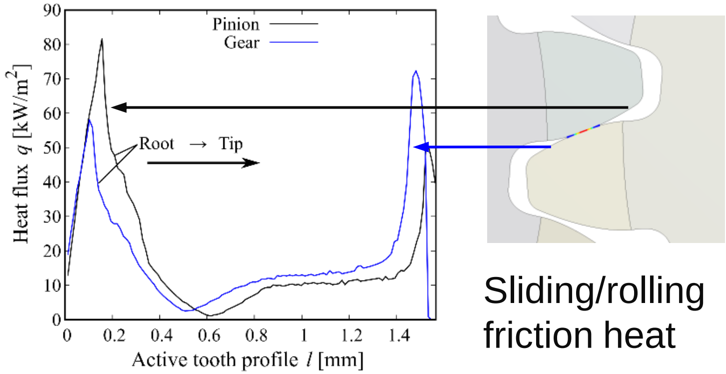
FEM geometry:



Convection:



Heat generation (based on mech. FEM):



Sliding/rolling friction heat

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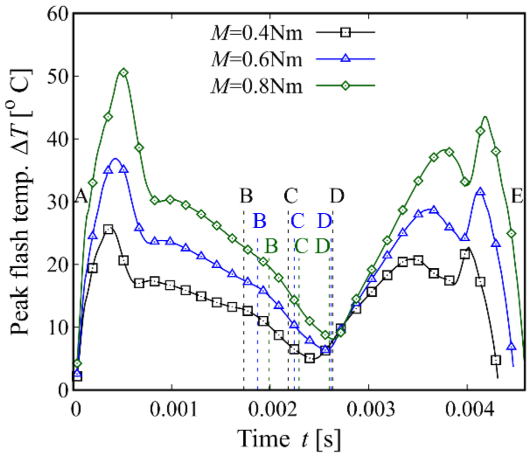
Thermal problem (III) – Obtainable results

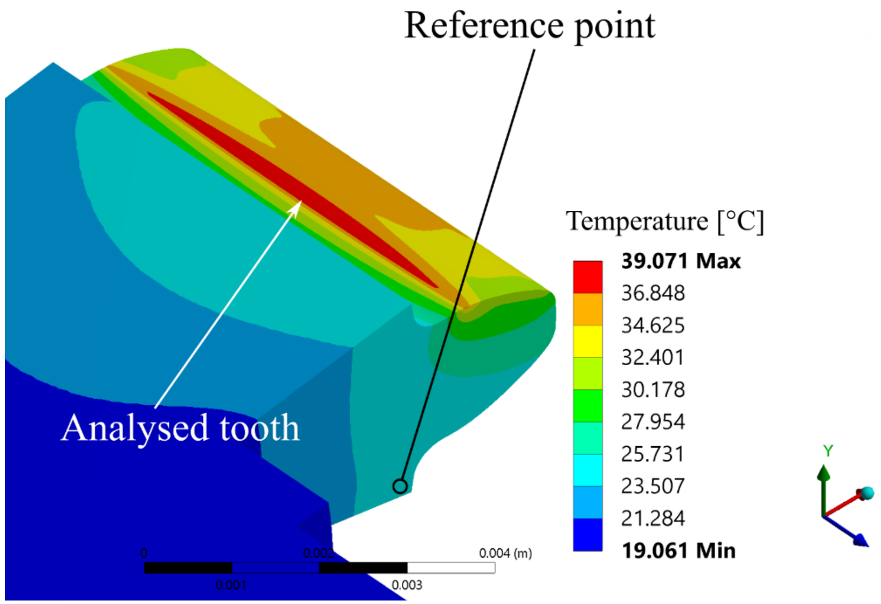
Load conditions:

n [rpm]	M [N] → 0,4	0,6	0,8
956	C1	C2	C3
1147	C4	C5	C6
1434	C7	C8	C9

Flash temp (semi-analytical model):



Nominal temperature:



Model development

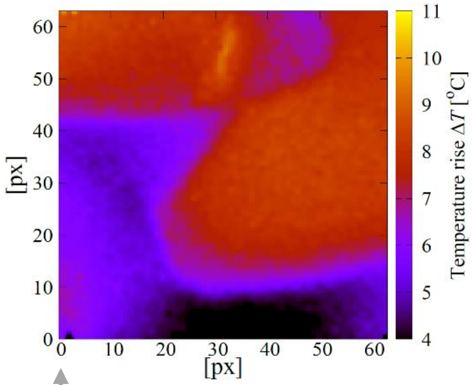
Experimental validation – Free thermal flow (FTF) tests

Load conditions:

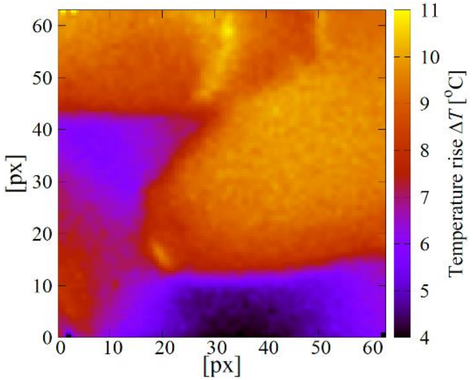
n [rpm]	M [N] → 0,4	0,6	0,8
956	C1	C2	C3
1147	C4	C5	C6
1434	C7	C8	C9

HS thermal camera measurements: ~1900 fps

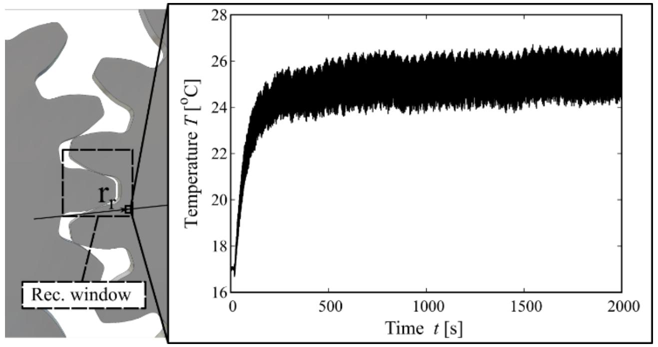
Temperature gradients:



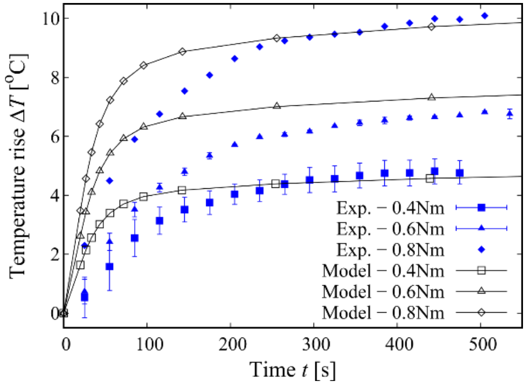
(Same running cycle)



Measurement window:



Nominal temp. at root:



n = 1150min^{-1}

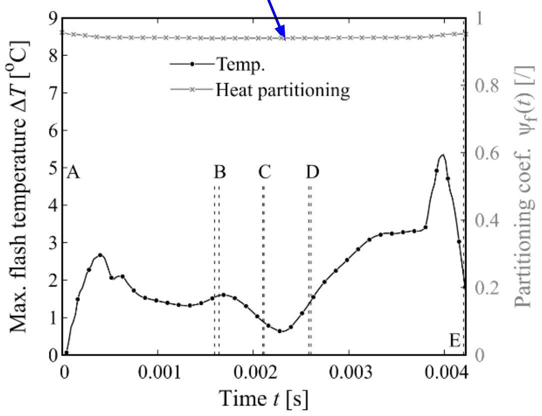
Discussion

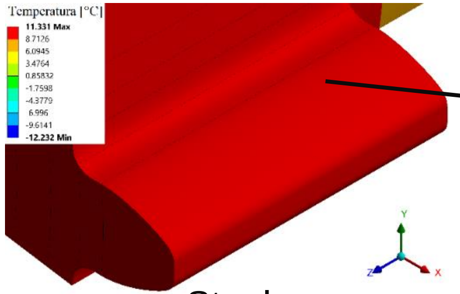
Model application to thermally dissimilar material pairs

- **Case study**: steel (42CrMo4) + POM-C

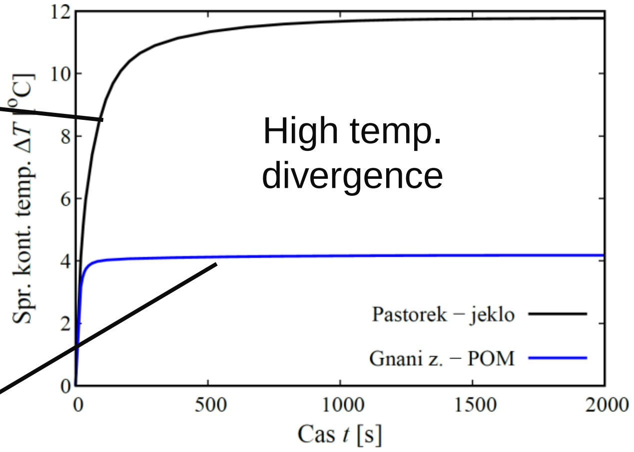
Load:
- M = 0,6 Nm
- n = 1147 min^{-1}

Partitioning coef.

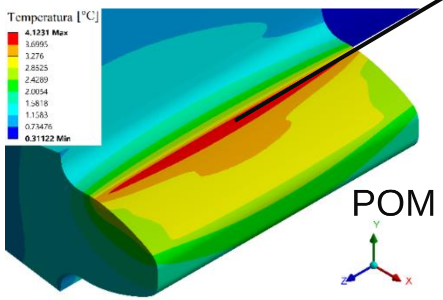




Steel gear



High temp. divergence



POM gear

Presumption of constant heat partitioning inadequate

Parameter	Symbol [Unit]	POM (Tecaform AH)	S. (42CrMo4)
Density	ρ[kg/m3]	1410	7800
Specific heat	c_p [J/(kgK)]	1400	≈470
Thermal conductivity	k [W/(mK)]	0.39	≈42.5

Discussion

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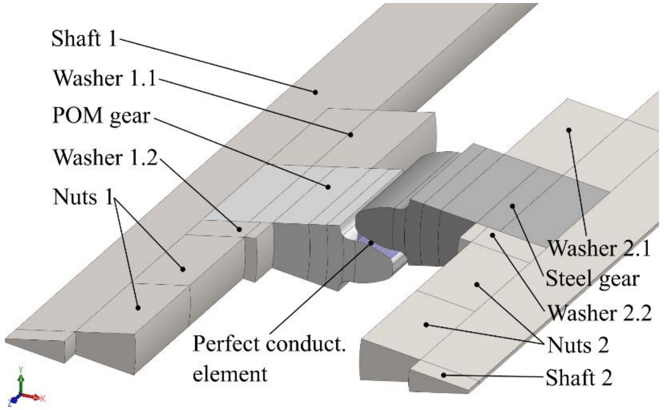
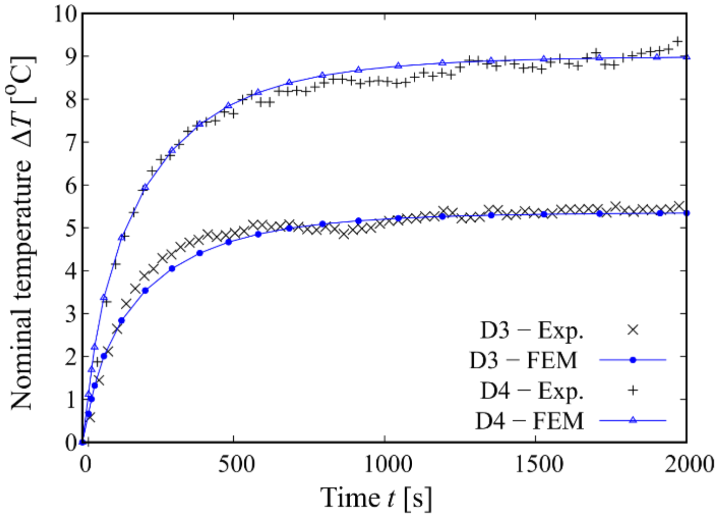
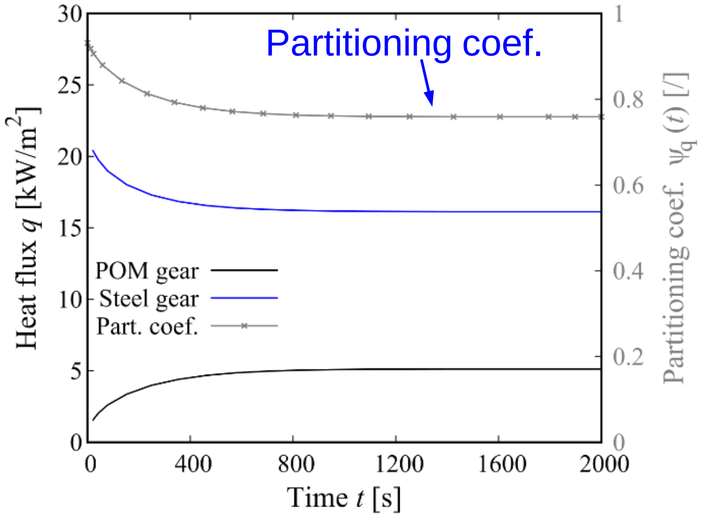
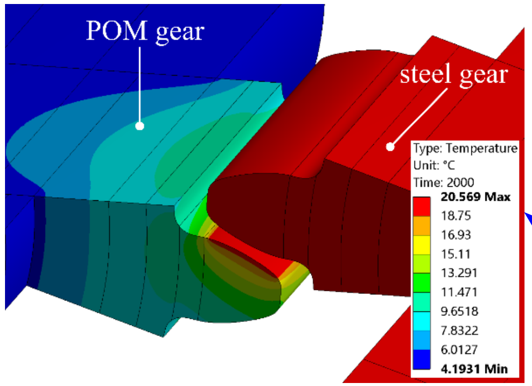
Model application to thermally dissimilar material pairs

- **Necessary upgrade:** modelling of a tooth pair in active contact









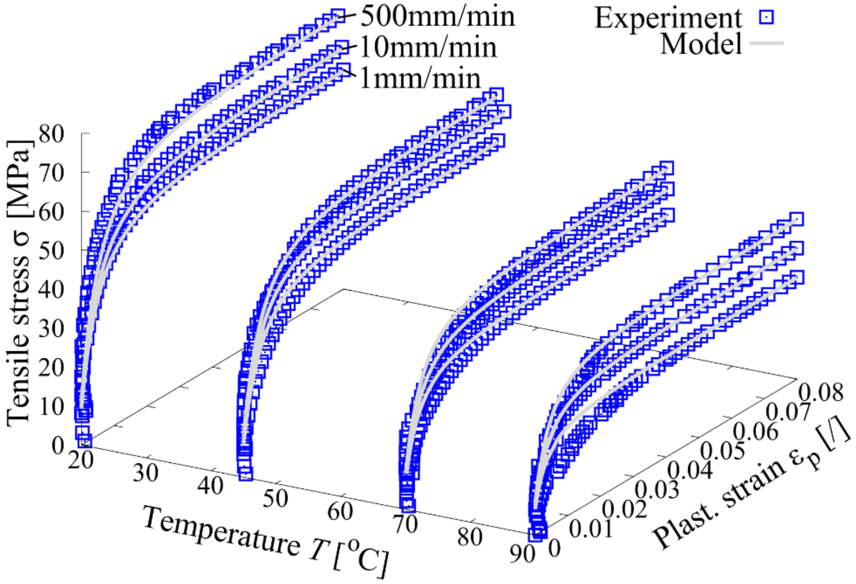
General form of the developed model

Discussion

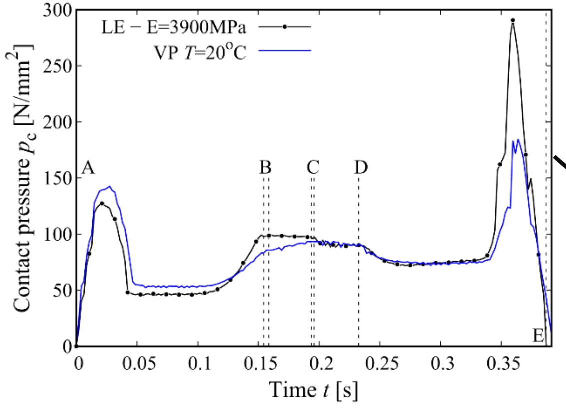
Influence of viscoplastic (VP) properties on the temperature rise

- Case study: steel (42CrMo4) + POM-C
- Analysis of thermo-viscoplastic properties of POM-C
- Analytical modelling – **Anand** model
    - Development of nonlin. regression model for parameter identification
    - Full gear meshing analysis

Symbol [Unit]	Value
s_0 [MPa]	17.167
Q/R [K^{-1}]	16210.803
A [s^{-1}]	1.03108E+11
ξ [/]	7.2047
m [/]	0.107544
h_0 [MPa]	21055.185
$\hat{s}$ [MPa]	100
n [/]	0.01276
a [/]	1.447

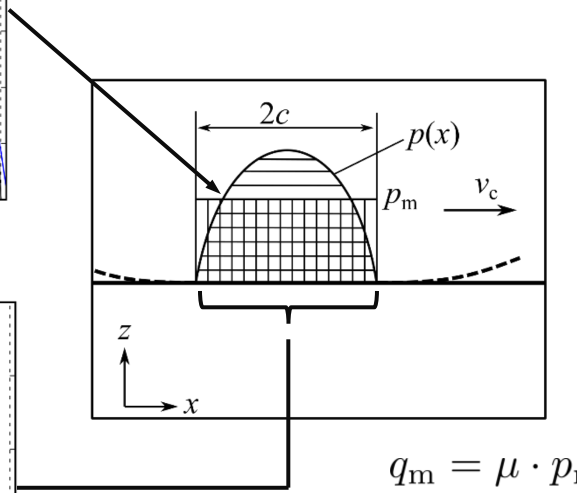


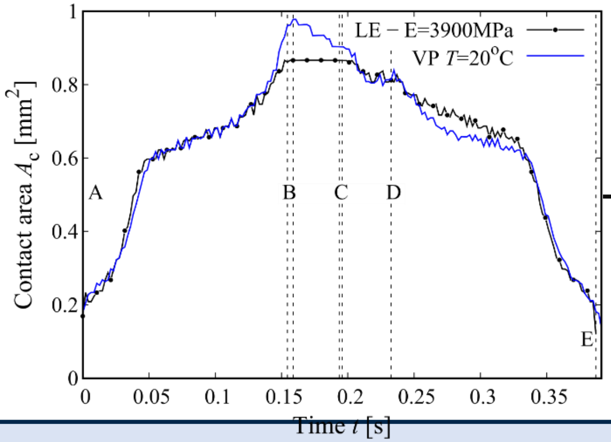
Influence of viscoplastic (VP) properties on the temperature rise



VP effect – drop in material stiffness:

- Lower contact pressure
- Increase in contact area

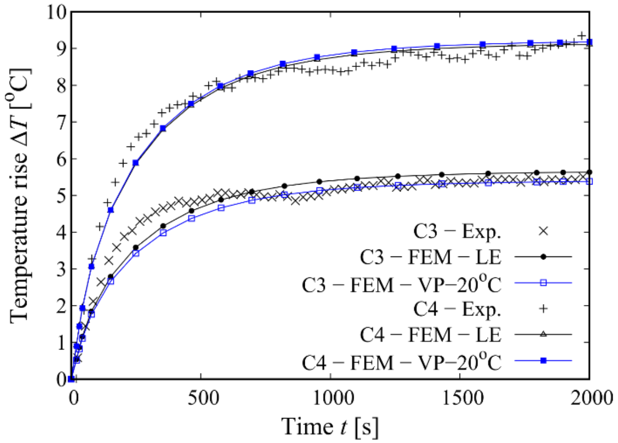




$$q_m = \mu \cdot p_m \cdot v_s$$

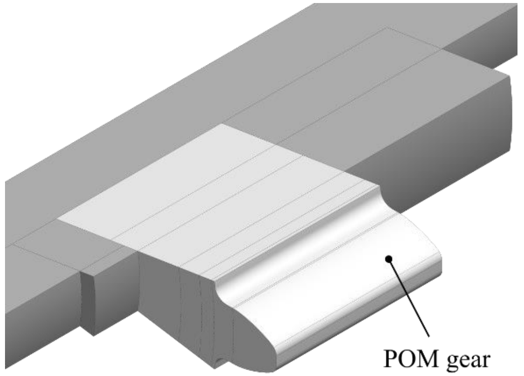
$$Q_m = q_m \cdot A_c = \mu p_m v_s A_c$$

Offsetting effect ↓ ↑



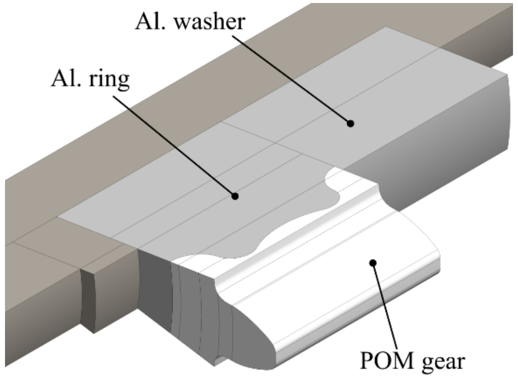
- Little to no VP influence on the nominal temperature
- **Linear elasticity presumption acceptable**

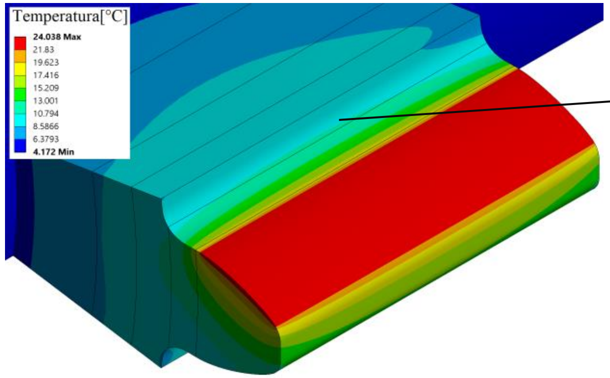
Model use for polymer gear thermal optimisation

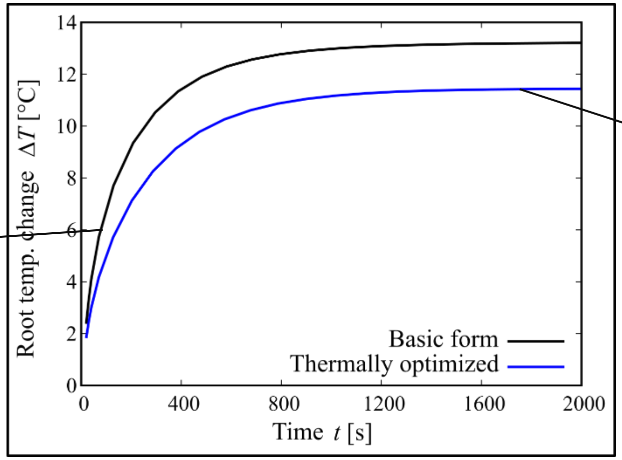


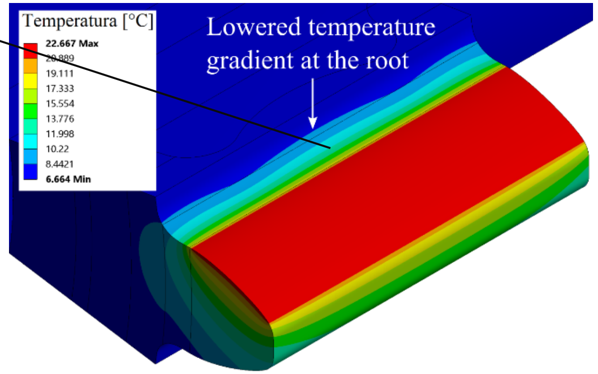
Example 1: metal rings for improved heat transfer:

- ➢ 15 % drop in root temperature attainable









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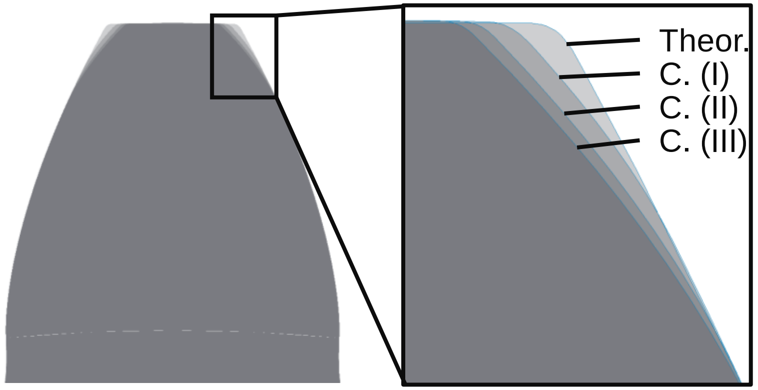
Model use for polymer gear thermal optimisation

Example 2: tooth profile optimisation

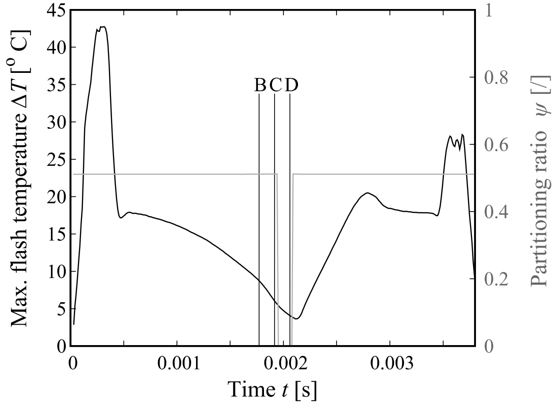


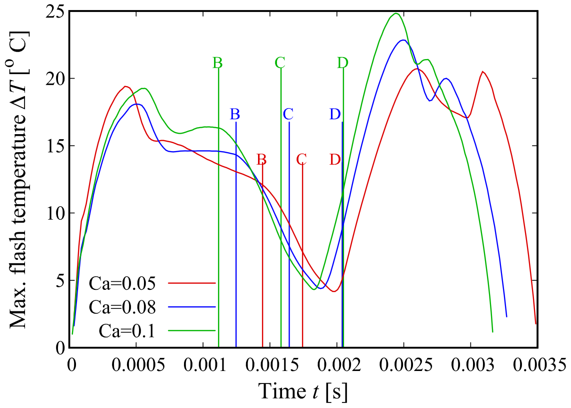
Profile modification parameter	Progressive tip relief width	Starting diameter
Configuration	C_a[mm]	d_{Ca} [mm]
Config. (I)	0.05	21.5
Config. (II)	0.08	21.23
Config. (III)	0.1	21.1

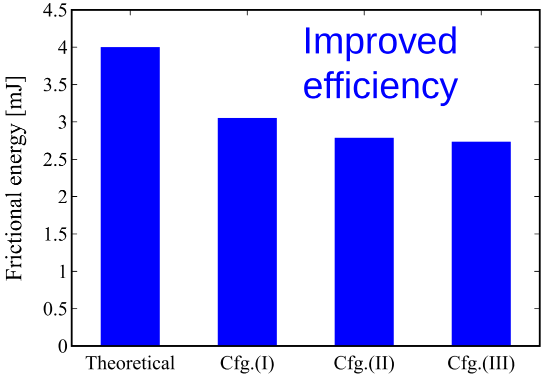
Theoretical geometry

Modified geometries

Generated frictional heat



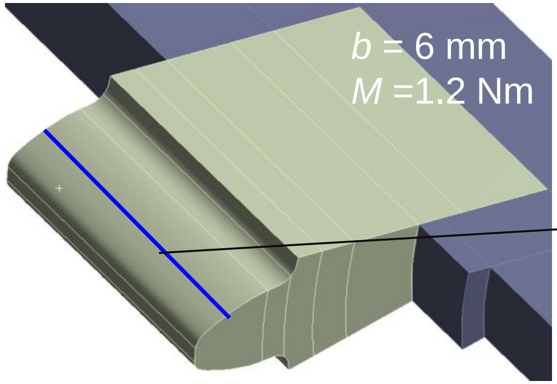


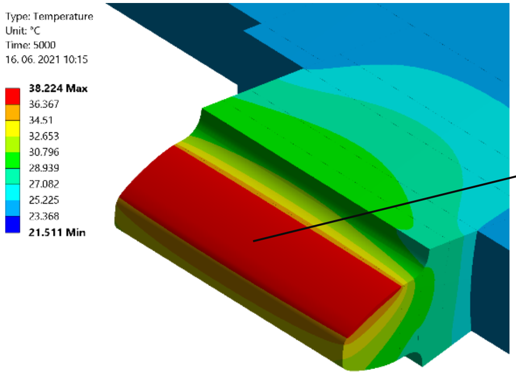


Discussion

Insights on polymer gear testing

- **Free thermal flow (FTF) testing**





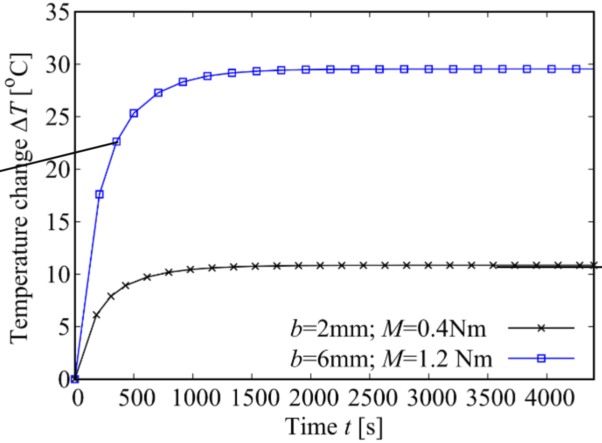
Example:

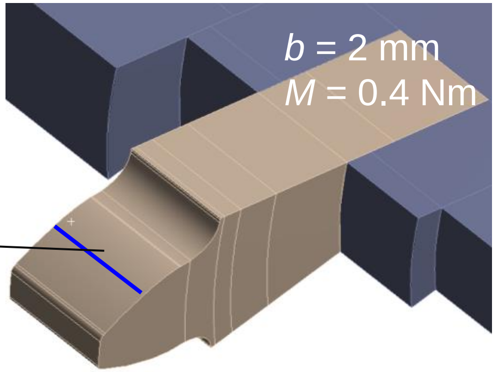
Same material pair

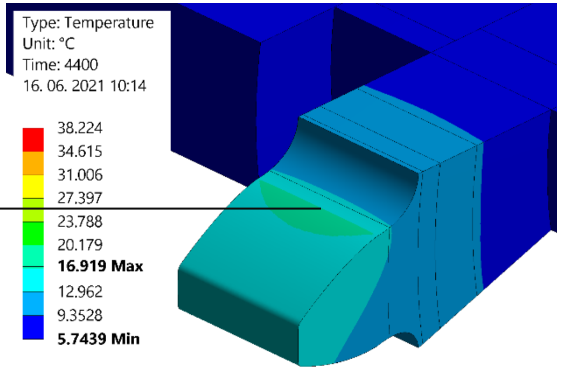
Same line distributed force load:

$$F_{\mathrm{n}} = 21.3\ \mathrm{N/mm}$$

Very different thermal response
(difference in generated heat)







FTF tests: only gears with same geometry should be compared

Conclusion

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Benefits of the developed model:

- High versatility – applicability to any type of cylindrical spur gear pair
- Applicabilty to wide variety of material pairs
- Possibilities for thermal gear optimisation
- Computational efficiency

Open challenges

- Precise coefficient of friction (COF) characterisation
- Necessity for high-end (commercial) FEM software
- Not yet upgraded to use on helical and other gear types

Thank you!

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