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Simulation of the thermal expansion of an inductively heated gear wheel for shrink fitting purposes

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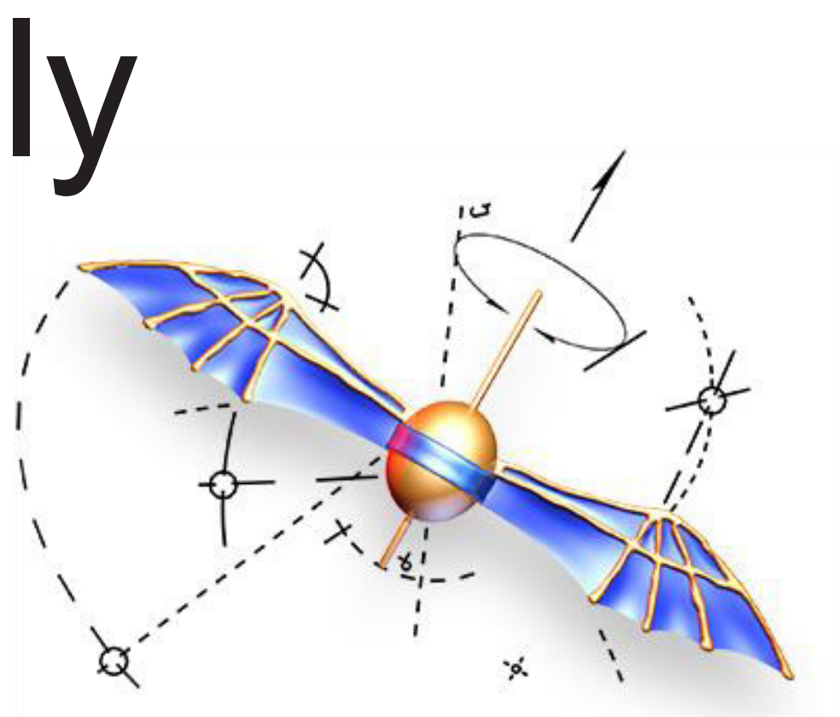


Introduction: Due to the advantages of induction heating as a method for precise and efficient local heating, it is perfectly suited for thermal shrink fitting of a gear wheel on a shaft [1,2]. In this work, a simulation model was established to study the induction heating of a gear wheel, its thermal expansion as well as the shrink fitting process.

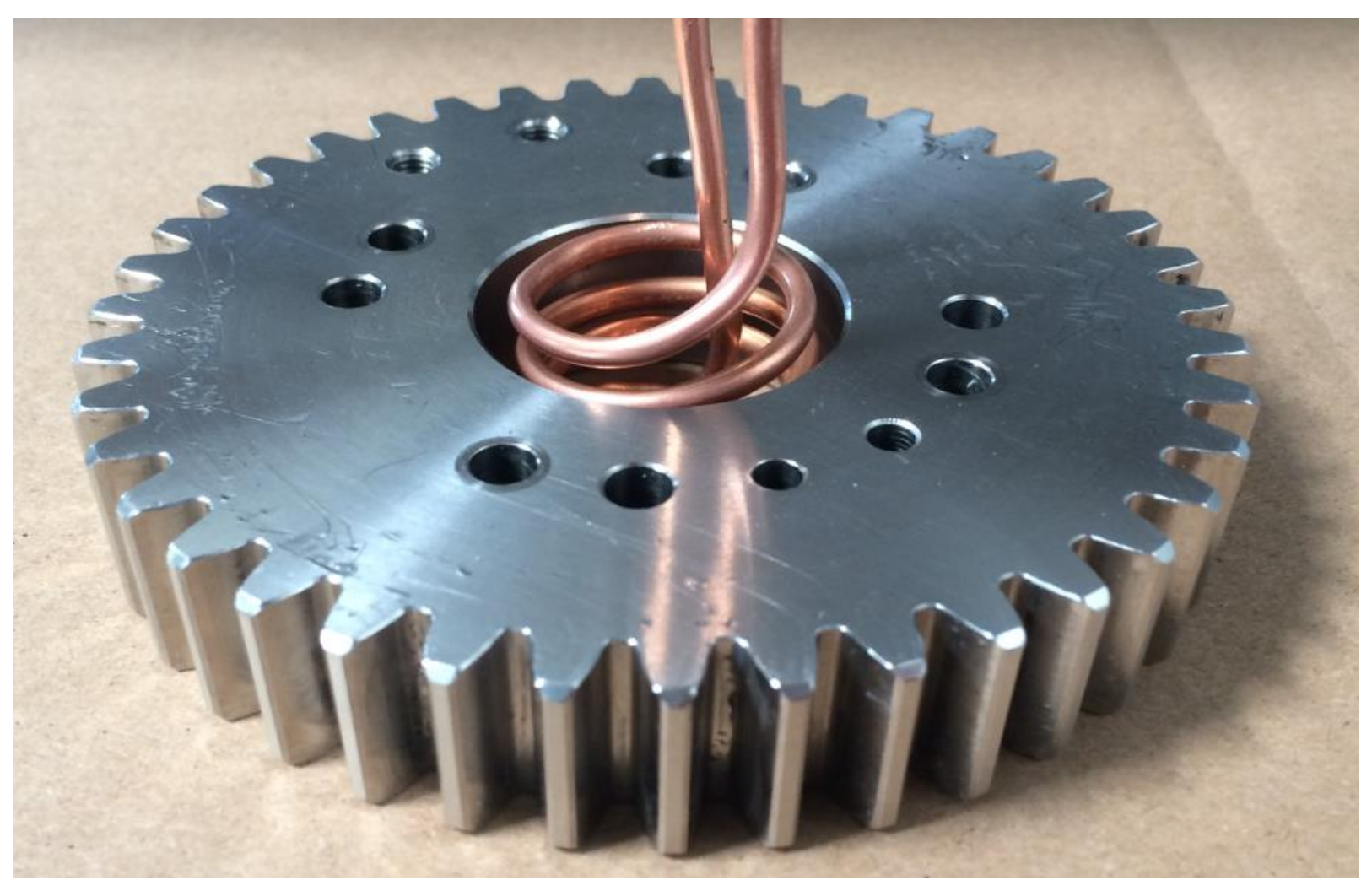


Figure 1. Gear wheel with an induction coil for pre-studies.

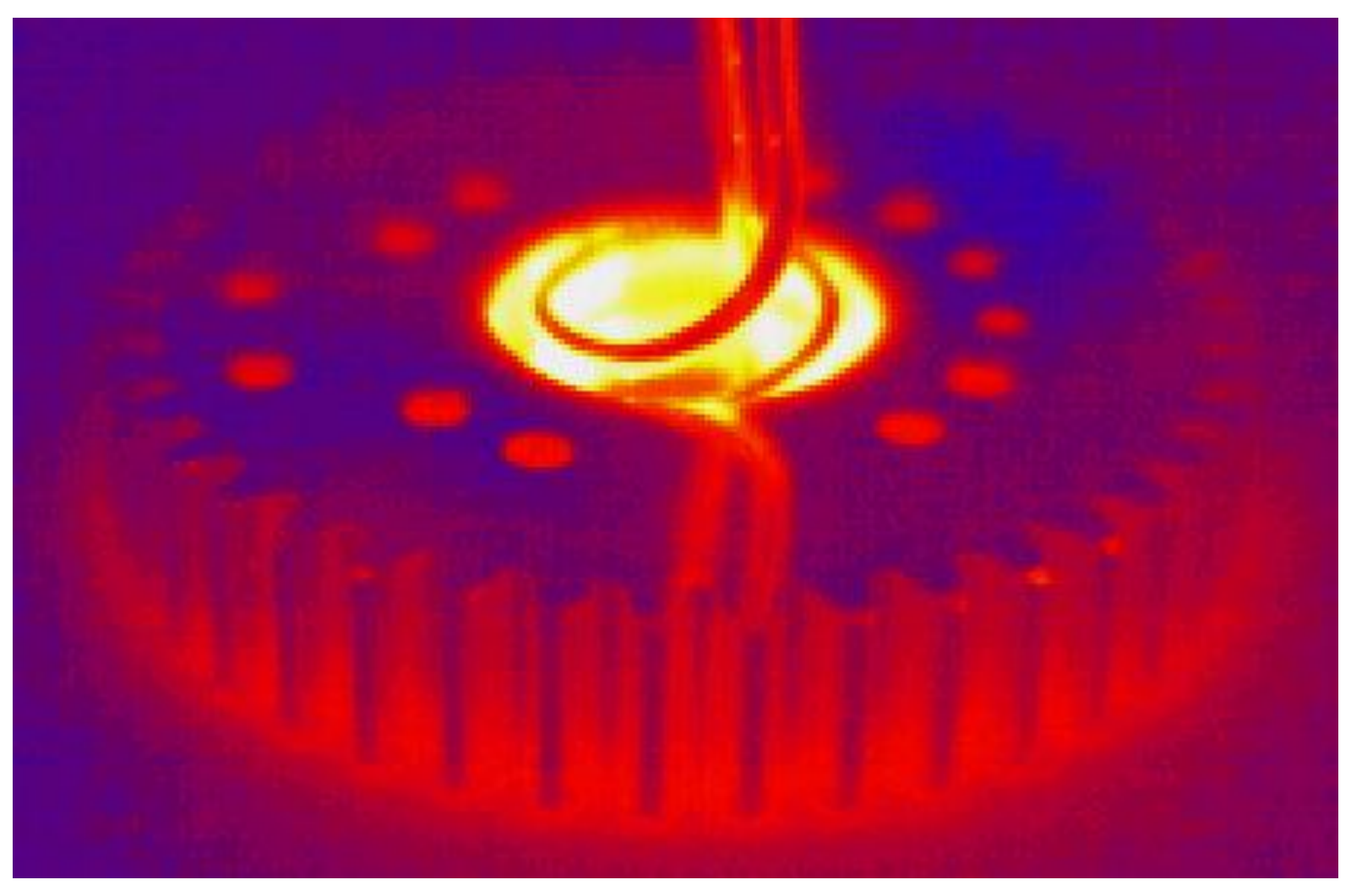


Figure 2. Thermographic investigation of the gear wheel and the induction coil after 5 s of electromagnetic heating.

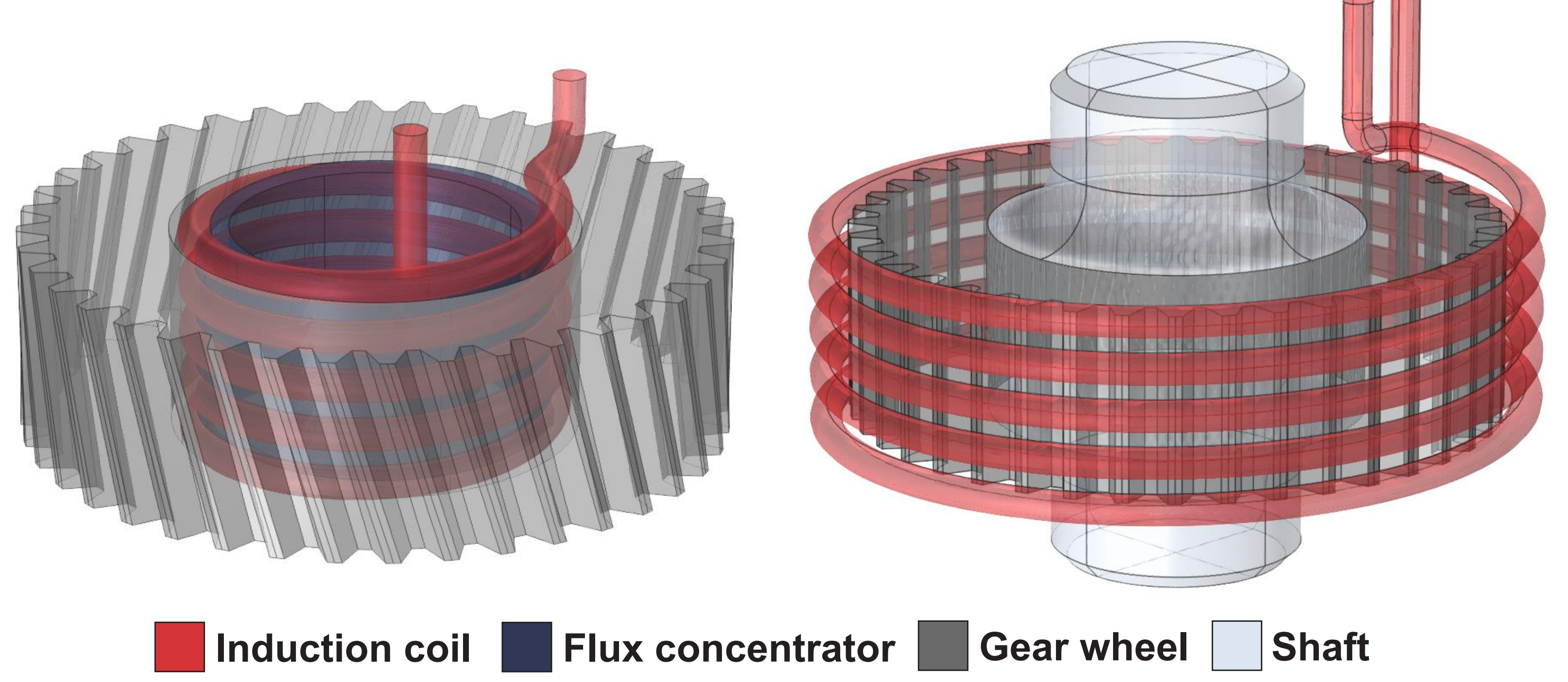
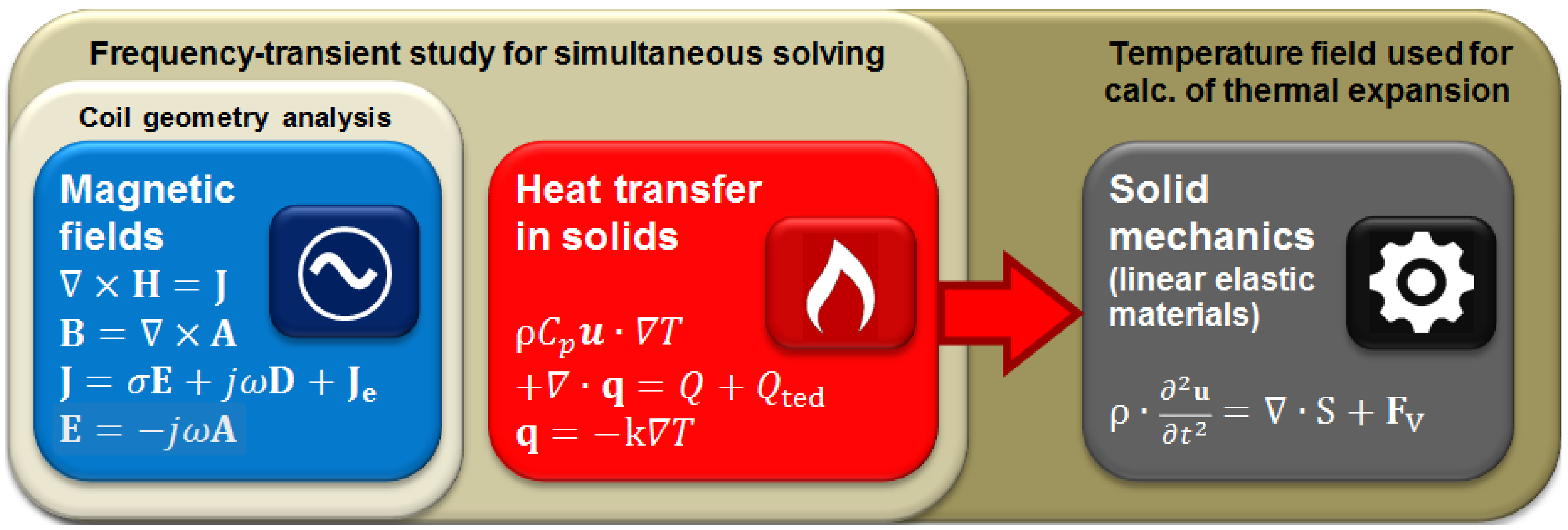


Figure 3. Gear wheel with induction coil for shrink fitting (left illustration) and the compound of gear wheel and shaft with induction heating for the application of unloosening (right illustration).

Computational Methods: Three physic interfaces are used to model the process shown in Figure 2 with the connections between them and the used studies.



Frequency-transient study for simultaneous solving

Coil geometry analysis

Magnetic fields

$$\nabla \times \mathbf{H} = \mathbf{J}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{J} = \sigma\mathbf{E} + j\omega\mathbf{D} + \mathbf{J}_\mathrm{e}$$
$$\mathbf{E} = -j\omega\mathbf{A}$$

Heat transfer in solids

$$\rho C_p \boldsymbol{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_\mathrm{ted}$$
$$\mathbf{q} = -\mathrm{k}\nabla T$$

Temperature field used for calc. of thermal expansion

Solid mechanics (linear elastic materials)

$$\rho \cdot \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \mathrm{S} + \mathrm{F}_\mathrm{V}$$

Figure 4. Applied physic interfaces with their PDEs used in COMSOL Multiphysics® and calculated studies.

At first, 'Coil geometry analysis' was carried out, in which the current density in the coil was calculated. In a 'Frequency-transient study', the magnetic and temperature field were calculated simultaneously to consider mutual influences of each other. Finally, the time-dependent expansion of the gear wheel was investigated. An iterative solver based on the multigrid-method was used to reduce the calculation time in comparison to a direct solver, especially for the amount of almost 10^6 finite elements (see Fig. 5).

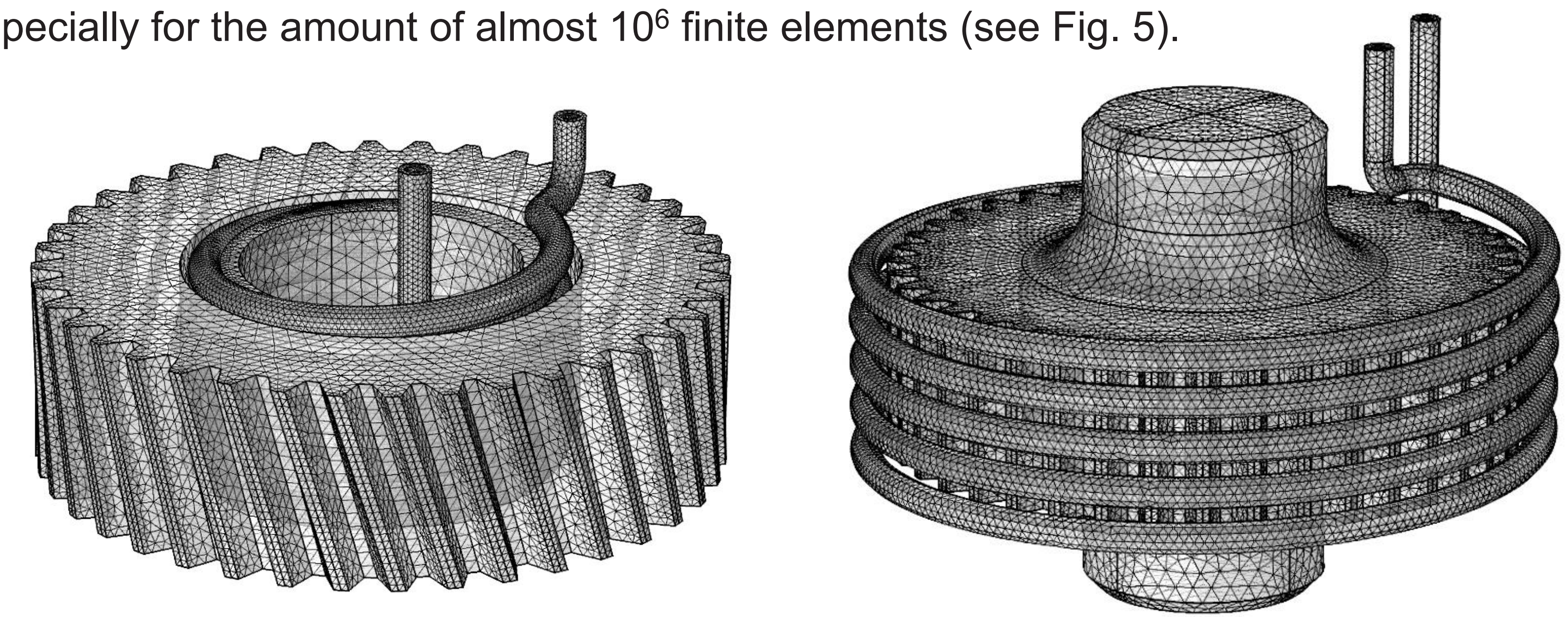


Figure 5. Finite element meshes for both cases with a number of about $9.6 \cdot 10^5$ (left) and $7.8 \cdot 10^5$ (right) finite elements (right) [without the surrounding air domain].

Results: The influence of the flux concentrator was compared to the case without using a flux concentrator. In Figure 6, it is depicted that the magnetic flux is concentrated to the inner surface of the gear wheel.

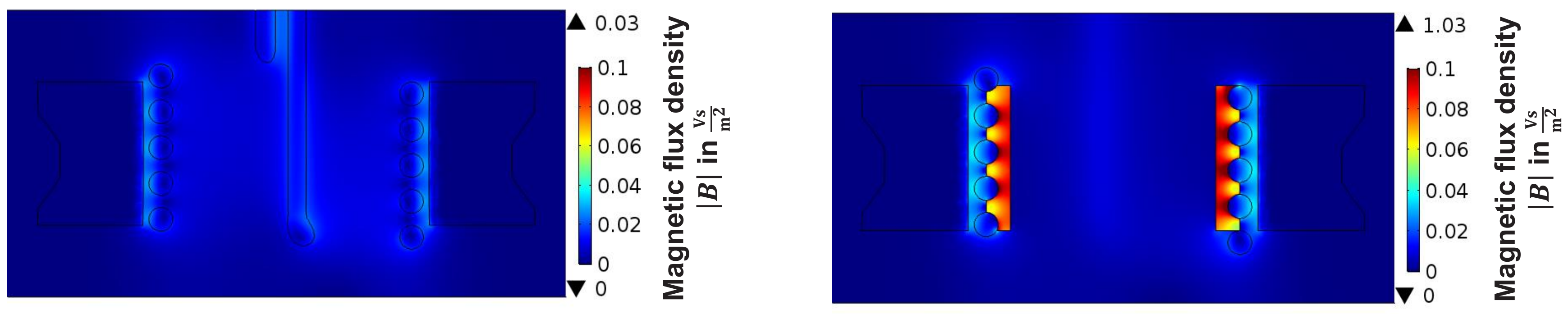


Figure 6. Magnetic flux density (absolute value) in a vertical and middle cross section through the system without flux concentrator (left) and with flux concentrator (right); I_coil = 400 A, f = 40 kHz.

The electromagnetic heating causes a rise in temperature. The temperature field for the variant with flux concentrator is shown in Figure 7. The thermal expansion caused by the increase in temperature is shown in Figure 8.

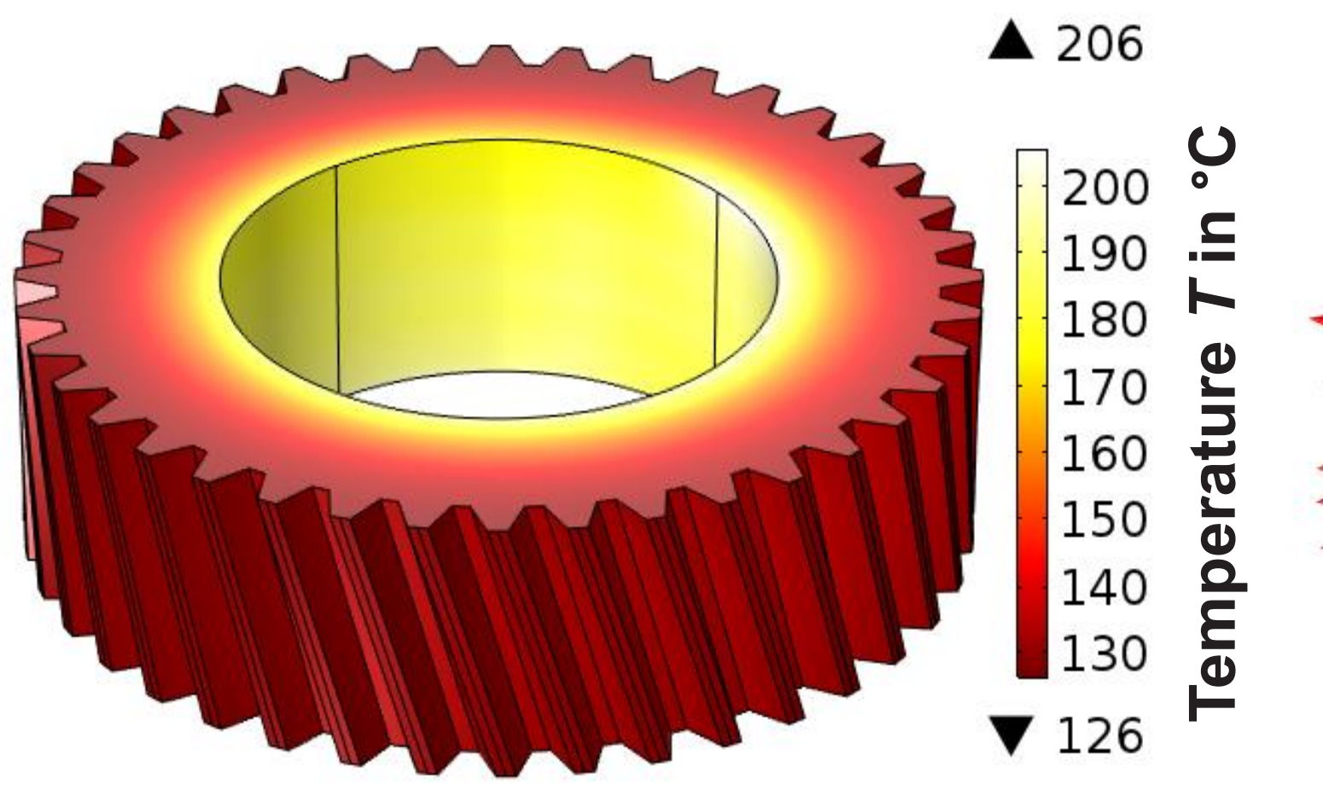


Figure 7. Temperature field for variant with flux concentrator (process parameters: t = 3 min, I_coil = 400 A, f = 40 kHz).

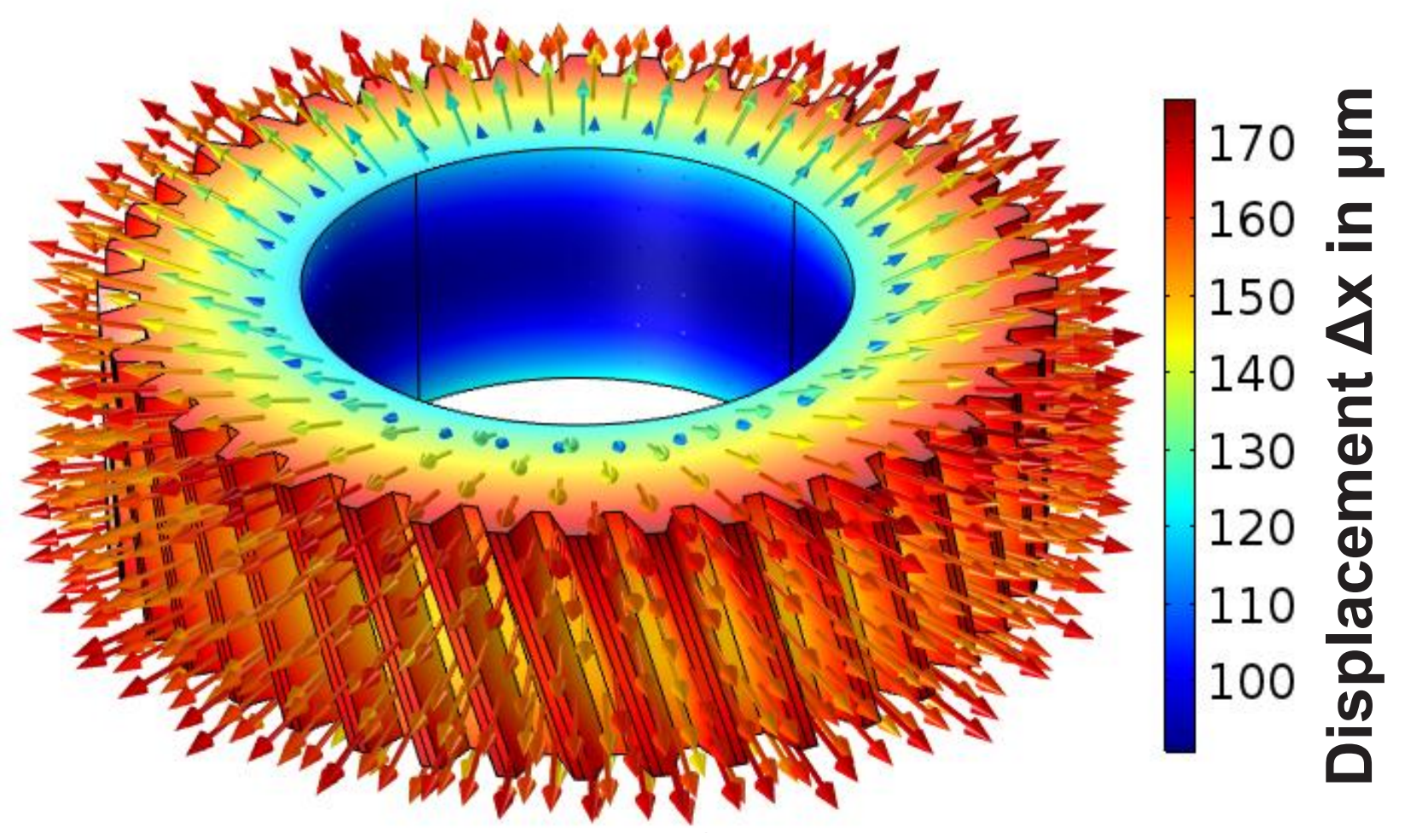


Figure 8. Displacement field with arrows to illustrate the direction of the expansion (process parameters as in Figure 5).

To summarize the results of the time-dependent thermal expansion, the averaged temperature and the minimal displacements at the inner surface of the gear wheel are depicted as function of the time in Figure 9.

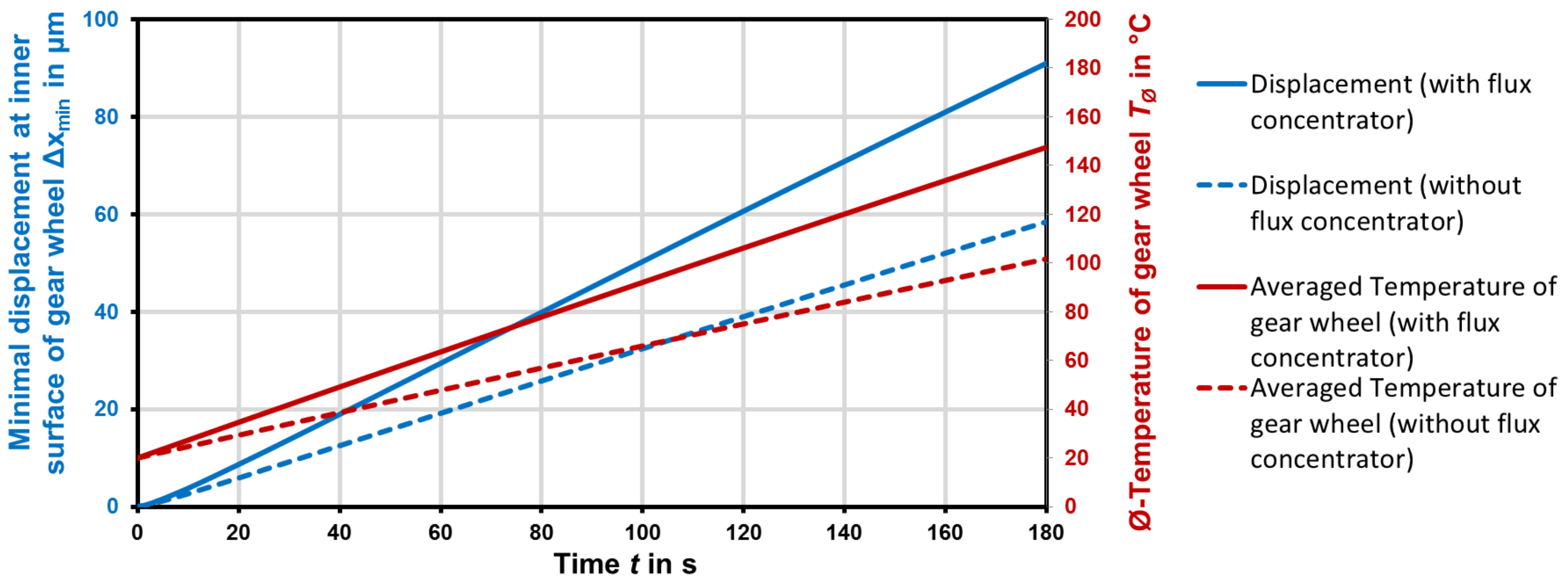


Figure 9. Diagram for the minimal displacement and averaged temperature.

Table 1. Comparison of simulation results to analytical calculations for two interference fits

Interference fit	Max. interference	Necessary expansion for fitting	Necessary temperature for fitting	Necessary temperature and time for fitting as simulation results			
				With flux concentrator		Without flux concentrator	
				Temperature	Time	Temperature	Time
$\frac{\mathrm{H7}}{\mathrm{r6}}$	76 µm	114 µm	97.2 °C	99.7 °C	111 s	101.2 °C	179 s
$\frac{\mathrm{H8}}{\mathrm{u8}}$	198 µm	297µm	221.2 °C	228 °C	293 s	226 °C	466 s

Comparing the simulation results with analytical calculations, there is only a deviation of few percentage (see Tab. 1). Besides this, the simulation results of the mechanical stresses allow to evaluate, if the process control concerning the rapidness of heating-up is mechanically possible. In this study, the type of interference fit is chosen depending on the mechanical load, i.e. if the torque to resist is higher, there is an interference fit with larger max. interference to select.

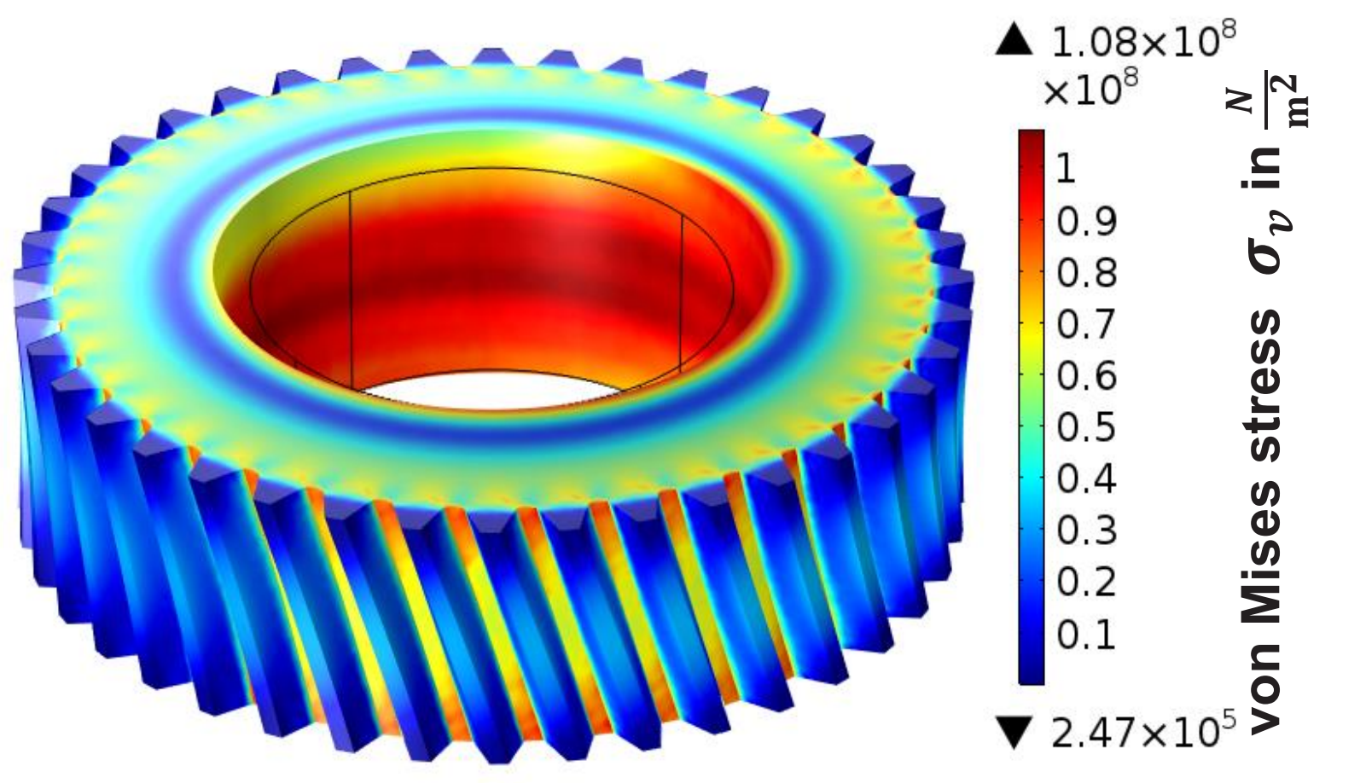


Figure 10. Equivalent stress: von Mises stress t = 2 min, I_coil = 400 A, f = 40 kHz.

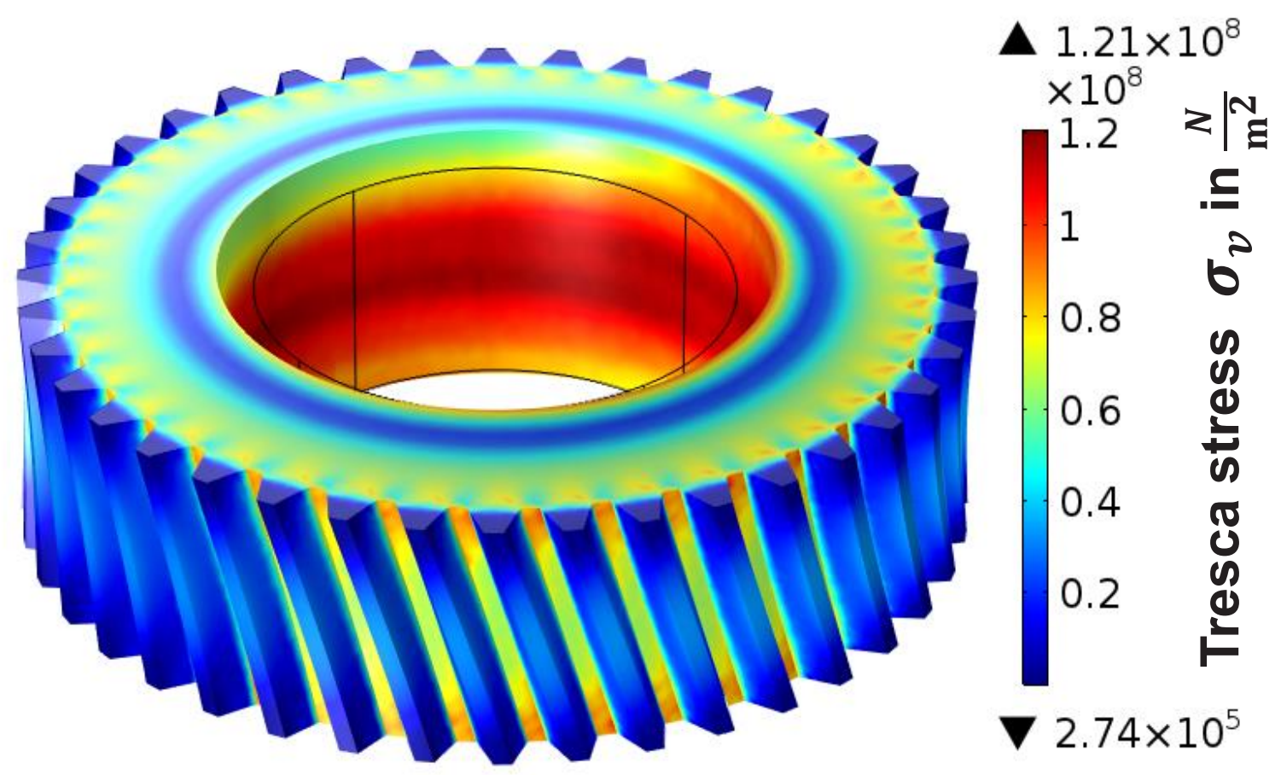


Figure 11. Equivalent stress: Tresca stress t = 2 min, I_coil = 400 A, f = 40 kHz.

In Figure 10 and Figure 11, the equivalent stresses of the types 'von Mises' and 'Tresca' are shown, respectively. The type of steel '16MnCr5' has a yield strength of $R_{\mathrm{p},0.2}$ = 630 N/mm², which is approximately 5 times higher than the maximum arising equivalent stresses, so that the process time for induction heating could be even significantly reduced by increasing the coil current.

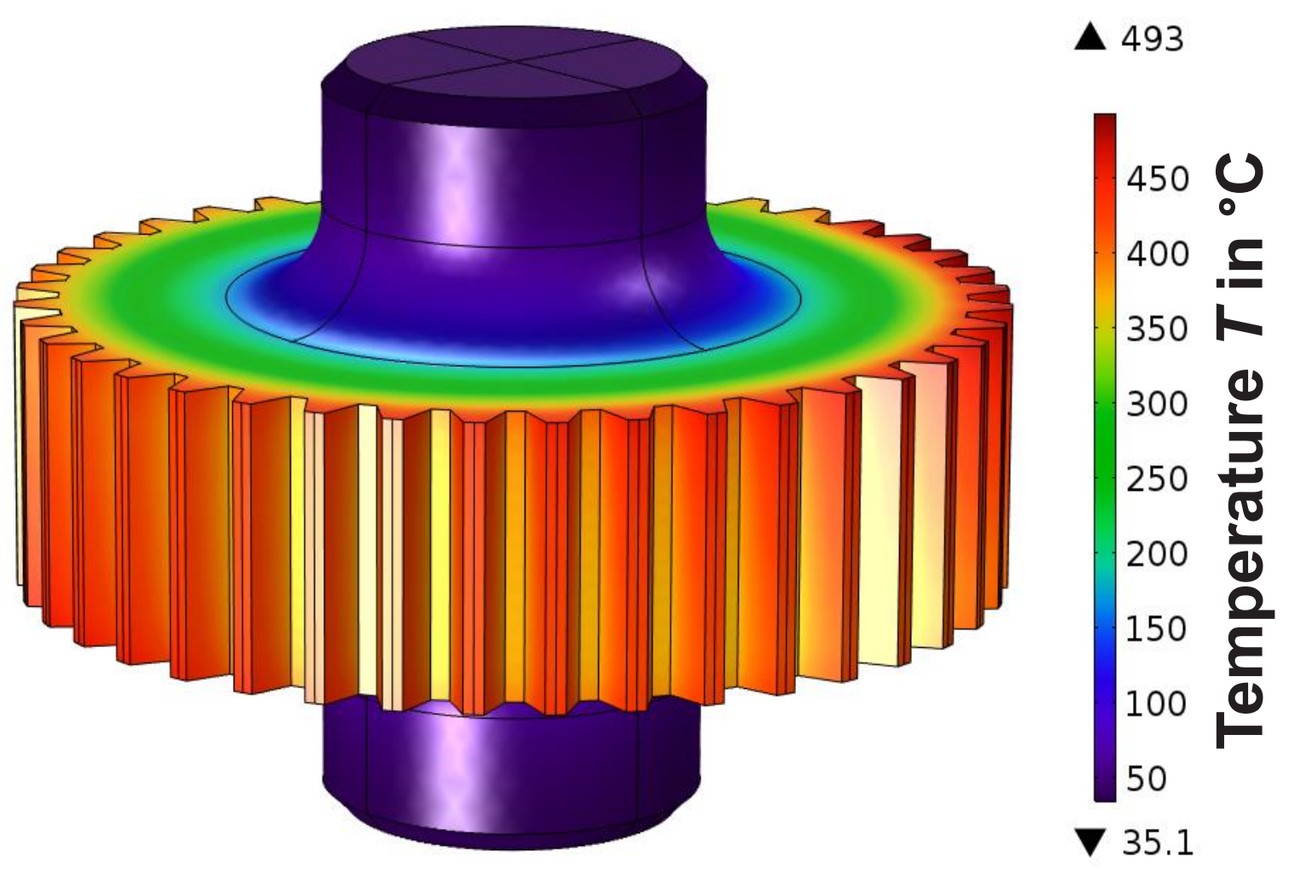


Figure 12. Temperature for gear wheel on shaft t = 2 min, I_coil = 600 A, f = 40 kHz.

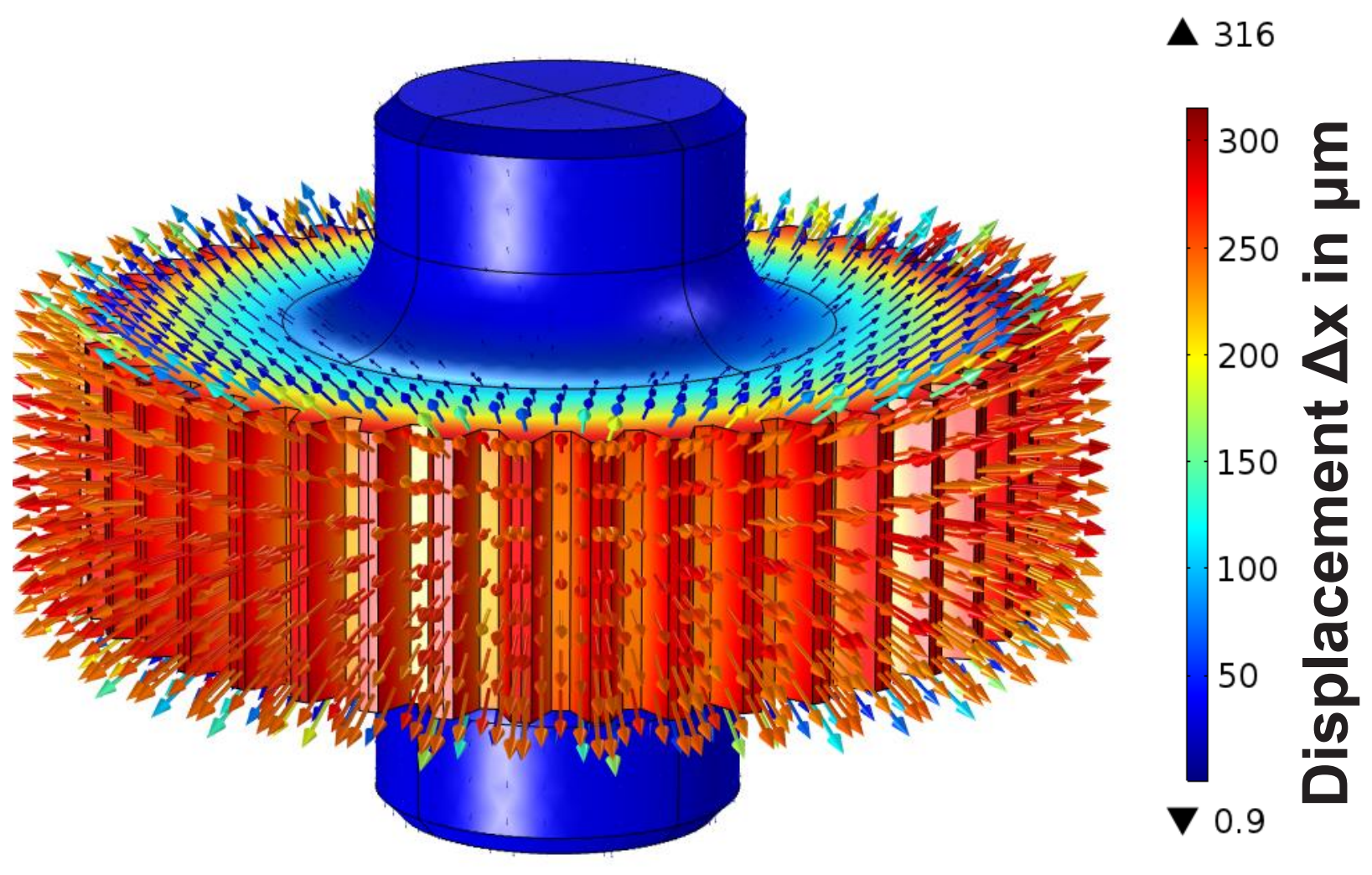


Figure 13. Thermal expansion of gear wheel t = 2 min, I_coil = 600 A, f = 40 kHz.

In Figure 12 and Figure 13, the temperature field and the field of thermal expansion for the application of detaching the gear wheel shrunk on a shaft are illustrated, respectively. The induction heat is located at the outer diameter of the gear wheel to cause sufficient expansion in short time and does not influence the shaft at the inner position.

Conclusions: A simulation model was established to iteratively study the thermal expansion of an inductively heated gear wheel for shrink fitting on a shaft. Suitable parameters for the coil current and the frequency of the alternating field were identified. Further on, the detaching of a gear wheel was also studied for getting specific information about the process operation.

References:

1. P. Pedersen, On Shrink Fit Analysis and Design, Comput Mech, Vol. 37, pp. 121–130, (2006)
2. S. Wang et al., Analysis on the Process of Induction Heating for Shrink-Fit Chuck, Advanced Materials Research, Vols. 383-390, pp. 2850-2855 (2012)

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