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Temperature field - illustrative example

Modeling of multiphysical problems

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- Heat transfer through multilayer insulation
- Heat transfer through insulation with consideration of convection
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- Disc brake

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Typical examples from the temperature field

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Typical examples from the temperature field

Typical examples from the temperature field (analytical solution)

- Heat transfer through insulation
- Heat transfer through multilayer insulation
- Heat transfer through insulation considering convection
- Direct heating of a hollow tube with convection

Practical examples from the temperature field

- Power transistor
- Disc brake

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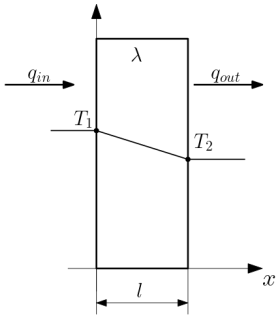
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Typical examples from the temperature field

Heat transfer through insulation

Consider an insulation board with a thickness of l, with a thermal conductivity of λ, through which the heat flow passes. The temperature on the inlet side is T_1 and on the outlet side T_2.



This is a steady state, starting from Laplace's equation

$$\Delta T = 0\,.$$

We assume that the flow falls homogeneously on the whole input side and the plate is equal, then the zero derivatives for the axes y and z apply.

So we get the equation

$$\frac{\partial^2 T}{\partial x^2} = 0\,.$$

We get integration

$$\frac{\partial T}{\partial x} = k_1\,.$$

From this it is clear that the direction of change of temperature is a constant and is therefore a straight line.

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The second derivative then gives a solution

$$T = k_1 \cdot x + k_2 \,.$$

where k_1 and k_2 are integration constants that we obtain from boundary conditions.

For $x = 0$ we get the equation

$$T_1 = k_1 \cdot 0 + k_2 \implies k_2 = T_1 \,,$$

for $x = l$

$$T_2 = k_1 \cdot l + k_2 \implies k_1 = \frac{T_2 - T_1}{l} \,.$$

Substitution then provides a relationship describing the change in temperature

$$T = \frac{T_2 - T_1}{l} \cdot x + T_1 \,.$$

An expression for calculating the heat flux can be derived from this relation. The elementary flow $\mathrm{d}q$, which passes through the surface $\mathrm{d}S$ is

$$\mathrm{d}q = -\lambda \frac{\partial T}{\partial x}\,\mathrm{d}S = -\lambda \frac{\partial}{\partial x}\left(\frac{T_2 - T_1}{l} x + T_1\right)\mathrm{d}S \,.$$

With planar geometry and neglection of boundary phenomena, the total flow can then be defined as

$$q = \lambda \frac{T_1 - T_2}{l} S \,.$$

In analogy with Ohm's law, the expression can still be modified to the following form

$$q = (T_1 - T_2)\,\frac{\lambda S}{l} = \frac{T_1 - T_2}{R} \,.$$

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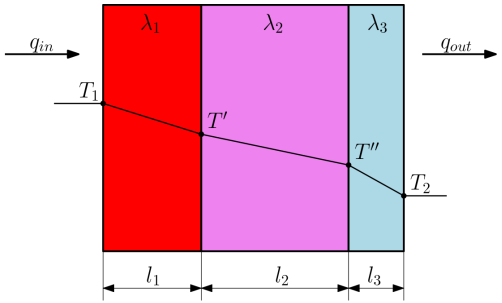
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Typical examples from the temperature field

Heat transfer through multilayer insulation

The results derived in the previous example can also be applied to multilayer insulations. The area S is the same for all layers, differing in thickness and thermal conductivity. At steady state, the same heat flux q will pass through the layers.



Based on the previously derived solution for heat flow, relationships can be defined for individual layers

$$q = \lambda_1 \frac{T_1 - T'}{l_1} S\,,$$

$$q = \lambda_2 \frac{T' - T''}{l_2} S\,,$$

$$q = \lambda_3 \frac{T'' - T_2}{l_3} S\,.$$

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The steady heat flux through the entire insulation can then be defined as a combination of the notation for the individual layers

$$q = \frac{T_1 - T_2}{\frac{l_1}{\lambda_1 S} + \frac{l_2}{\lambda_2 S} + \frac{l_3}{\lambda_3 S}} = \frac{T_1 - T_2}{R_1 + R_2 + R_3}\,.$$

It is thus clear that the insulating layers arranged one behind the other behave in a completely analogous manner as electrical resistances in connected in series.

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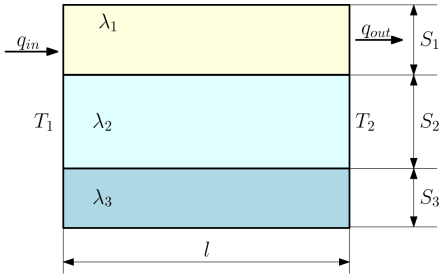
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Typical examples from the temperature field

Heat transfer through multilayer insulation

The insulation layers can also be arranged parallel to the direction of heat flow transfer (not used in practice).



Because in the case of parallel insulation layering, the area on which the flow falls is different

$$q = q_1 + q_2 + q_3 \, .$$

We define for individual layers from a known relationship

$$q_1 = (T_1 - T_2) \, \frac{\lambda_1 S_1}{l} \, ,$$

$$q_2 = (T_1 - T_2) \, \frac{\lambda_2 S_2}{l} \, ,$$

$$q_3 = (T_1 - T_2) \, \frac{\lambda_3 S_3}{l} \, ,$$

The total flow can then be written as

$$q = (T_1 - T_2) \left(\frac{\lambda_1 S_1}{l} + \frac{\lambda_2 S_2}{l} + \frac{\lambda_3 S_3}{l} \right) \, .$$

If we again define the thermal conductivity $G = \frac{1}{R}$ analogously to electrical quantities, the relation can be written in the form

$$q = (T_1 - T_2) \, (G_1 + G_2 + G_3) \, .$$

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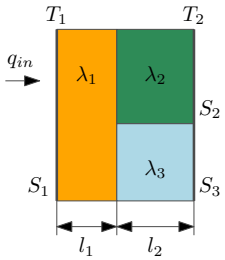
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Typical examples from the temperature field

Heat transfer through multilayer insulation

The insulating layers can be arranged in a general series-parallel combination.



It applies to the resistances of individual layers

$$R_1 = \frac{l_1}{\lambda_1 S_1}, R_2 = \frac{l_2}{\lambda_2 S_2}, R_3 = \frac{l_3}{\lambda_3 S_3}.$$

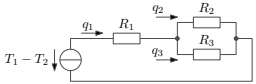
The total resistance can be expressed in the form

$$R = R_1 + \frac{R_2 R_3}{R_2 + R_3}.$$

The total heat flux can then be written as

$$q = \frac{T_1 - T_2}{R}.$$

By analogy, the original image can be expressed in the form of an equivalent circuit



The difference $T_1 - T_2$ corresponds to the electric voltage U and the current q to the electric current. It can be stated that Kirchhoff's laws and methods of analysis of electrical circuits also apply.

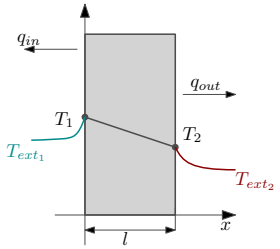
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Typical examples from the temperature field

Heat transfer through insulation with consideration of convection

Consider an insulation board with a thickness of l, with a thermal conductivity of λ, through which the heat flow passes. It is physically more realistic to consider the transfer of heat to the surrounding medium on the inlet and outlet side. Knowledge of temperatures T_1 and T_2 is thus replaced by convection boundary condition.



This is a steady state, starting from Laplace's equation

$$\Delta T = 0\,.$$

We assume that the flow falls homogeneously on the whole input side and the plate is equal, then the zero derivatives for the axes y a apply z.

So we get the equation

$$\frac{\partial^2 T}{\partial x^2} = 0\,.$$

We get integration

$$\frac{\partial T}{\partial x} = k_1\,.$$

From this it is clear that the direction of change of temperature is a constant and is therefore a straight line.

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The second derivative then gives a solution

$$T(x) = k_1 \cdot x + k_2 \,.$$

where k_1 and k_2 are integration constants. The solution is based on the boundary condition for convection (a negative sign indicates heat dissipation to the outside):

$$q = -\lambda \frac{\partial T}{\partial x} = \alpha(T - T_{\text{ext}}).$$

Substituting the relation for the solution $T(x)$ and $\frac{\partial T}{\partial x}$ we then get:

$$-\lambda k_1 = \alpha \left(k_1 \cdot x + k_2 - T_{\text{ext}}\right)$$

In the case of heat dissipation, we then obtain for $x = 0$:

$$-\lambda \left(-k_1\right) = \alpha_1 (k_1 \cdot 0 + k_2 - T_{\text{ext}_1}) \,,$$

$$\lambda \cdot k_1 = \alpha_1 (k_2 - T_{\text{ext}_1}) \,,$$

since the derivative in the direction of the normal is negative at this edge.

For heat removal by convection for $x = l$ it is also necessary to take into account the flow orientation as a vector quantity, then we obtain:

$$-\lambda \cdot k_1 = \alpha_2 (k_1 \cdot l + k_2 - T_{\text{ext}_2})$$

We get the integration constants k_1 and k_2 from the boundary condition, then we get a set of equations:

$$\begin{bmatrix} -\lambda & \alpha_1 \\ \lambda + \alpha_2 l & \alpha_2 \end{bmatrix} \cdot \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} \alpha_1 T_{\text{ext}_1} \\ \alpha_2 T_{\text{ext}_2} \end{bmatrix} .$$

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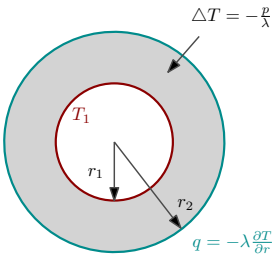
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Typical examples from the temperature field

Direct heating of a hollow tube with convection

In addition to the transfer of heat through planar geometry, we very often encounter cylindrical geometry. Consider a hollow conductor of conductive material heated by internal losses p. Inside, it flows through cooling water circulating through a constant temperature exchanger T_1. On the outside, we consider the convection of heat into the environment defined by the ambient temperature T_{ext} and the heat transfer coefficient α.



To describe the temperature of direct heating, we start from the Poisson equation in the form

$$\Delta T = -\frac{p}{\lambda}\,.$$

The one-dimensional solution of this equation in the radial direction can be written as:

$$\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial T}{\partial r} = -\frac{p}{\lambda}\,.$$

We integrate the equation

$$r\frac{\partial T}{\partial r} = -\frac{p}{\lambda}\frac{r^2}{2} + k_1.$$

Let's adjust

$$\frac{\partial T}{\partial r} = -\frac{p}{\lambda}\frac{r}{2} + \frac{k_1}{r}.$$

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Typical examples from the temperature field

Direct heating of a hollow tube with convection

After integration we get a general solution for temperature

$$T(r) = -\frac{pr^2}{4\lambda} + k_1 \ln r + k_2 \,,$$

where k_1 and k_2 are integration constants.

Then for $r = r_1$:

$$T_1 = -\frac{pr_1^2}{4\lambda} + k_1 \ln r_1 + k_2 \,,$$

For the solution $r = r_2$ we start from the boundary condition for convection:

$$q = -\lambda \frac{\partial T}{\partial r} = \alpha(T - T_{\text{ext}}).$$

Substitution

$$\frac{\partial T}{\partial r} = -\frac{p}{\lambda}\frac{r_2}{2} + \frac{k_1}{r_2}$$

to the previous relationship we get:

$$-\frac{pr_2}{2\lambda} + \frac{k_1}{r_2} = \frac{\alpha(T_{\text{ext}} - T_2)}{\lambda} \,,$$

where

$$T_2 = -\frac{pr_2^2}{4\lambda} + k_1 \ln r_2 + k_2 \,.$$

The integration constants k_1 and k_2 are then obtained by solving a system of equations:

$$\begin{bmatrix} \ln r_1 & 1 \\ \frac{1}{r_2} + \frac{\alpha}{\lambda} \ln r_2 & \frac{\alpha}{\lambda} \end{bmatrix} \cdot \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} T_1 + \frac{pr_1{}^2}{4\lambda} \\ \frac{pr_2}{2\lambda} + \frac{\alpha T_{\text{ext}}}{\lambda} + \frac{\alpha p r_2^2}{4\lambda^2} \end{bmatrix}$$

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Power transistor

Due to the passage of electric current, the transistor heats up and must be cooled. The heatsink must be designed so that the chip temperature does not exceed the required temperature of 90°C.

The electric current field is described by the equation in the form

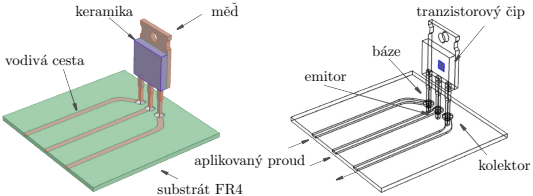
$$\operatorname{div} \gamma \operatorname{grad} \varphi = 0$$

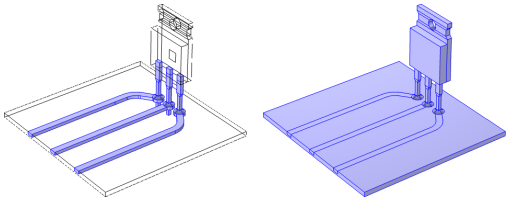
supplemented by boundary conditions of a known current density at the base, collector and emitter.

The temperature field is described by the equation in the form

$$\operatorname{div}\ (\lambda \operatorname{grad} T) = -w\,,$$

supplemented by the boundary conditions of convection. The term $w = \frac{J^2}{\gamma}$ represents the losses obtained from the current field solution.



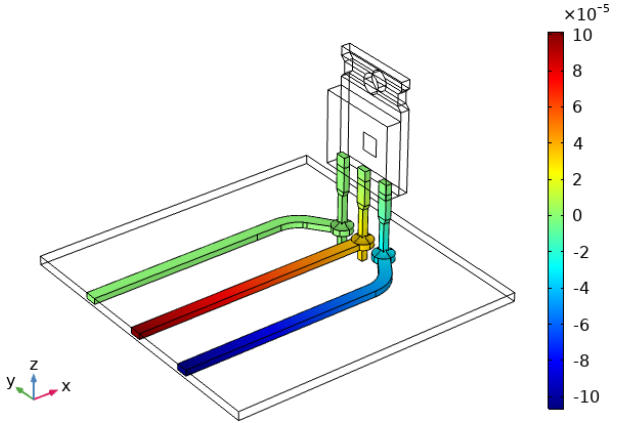


Area for solving current and temperature field

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Typical examples from the temperature field

Power transistor



Distribution of electric potential

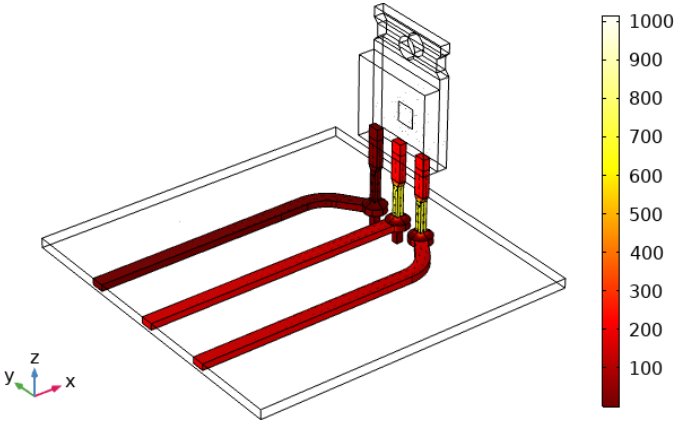
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Typical examples from the temperature field

Power transistor



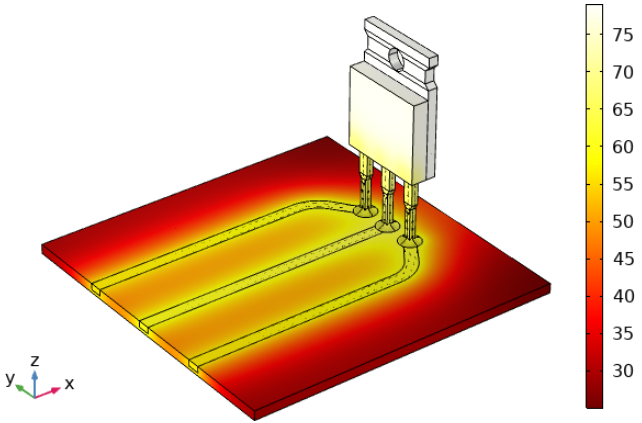
Distribution of Joule losses

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Typical examples from the temperature field

Power transistor



Temperature distribution (maximum temperature is 81 °C)

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Disc brake

A vehicle weighing 1800 kg is moving at a speed of 90 km / h. The driver brakes for 2 seconds and reduces the speed to 25 km / h. The radius of the disc is 14 cm and its thickness is 13 mm.

The temperature field is described by a time-varying equation in the form

$$\operatorname{div}\ (\lambda \operatorname{grad} T) = \rho c_{\mathrm{p}} \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \operatorname{grad} T \right) - w\,,$$

supplemented by boundary conditions of convection and radiation. The term w represents losses proportional to the change in kinetic energy. The motion term contains an expression

$$v_x = \frac{-y \cdot v(t)}{R} \quad \text{a} \quad v_y = \frac{x \cdot v(t)}{R}\,,$$

where R is the radius of the disk and $v(t)$ is the time-dependent velocity.

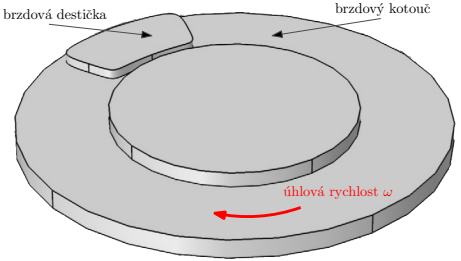
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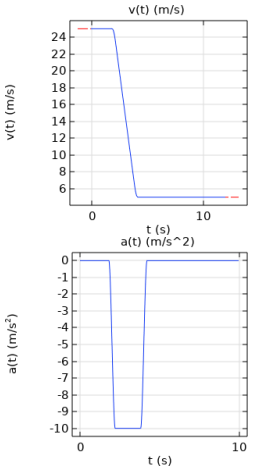
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Typical examples from the temperature field

Disc brake





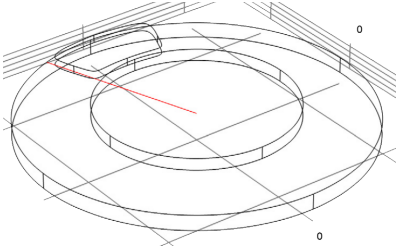
Prescribed time profile of speed and acceleration

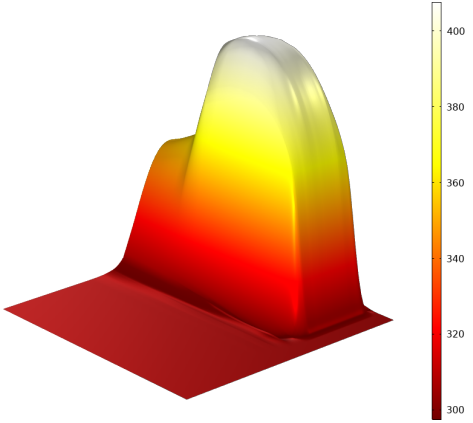
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Typical examples from the temperature field

Disc brake





Temperature profile along the red line

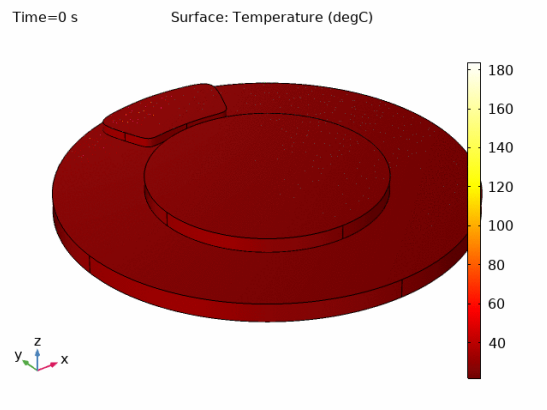
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Typical examples from the temperature field

Disc brake



Time evolution of temperature distribution

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Examples of the use of induction heating in practice

Examples of the use of induction heating in practice

- Induction heating of copper ticket
- Sliding induction heating of a ferromagnetic part
- Soldering inductor design

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A typical example of induction heating is the heating of a ticket, ie a conductive charge in a circular or cylindrical inductor (solenoid). For example, heating a copper billet.

A common solution of electromagnetic

$$\Delta \underline{\boldsymbol{A}} - \mathrm{j}\omega\gamma\mu\underline{\boldsymbol{A}} = -\mu\underline{\boldsymbol{J}}_{\mathrm{ext}}\,,$$

and temperature fields

$$\mathrm{div}\ (\lambda\,\mathrm{grad}\,T) = \rho c_{\mathrm{p}}\frac{\partial T}{\partial t} - w\,,$$

it is also possible to respect the thermal nonlinearity of the electrical conductivity of copper defined by the relation

$$\gamma\,(T) = \frac{1}{\rho_0\,(1+\alpha\,(T-T_0))}\,,$$

where ρ_0 is the resistivity, α the temperature coefficient of resistivity and T_0 is the reference (default) temperature.

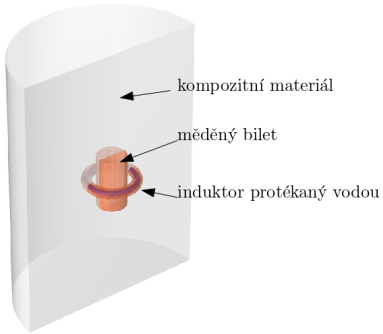
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Examples of the use of induction heating in practice

Induction heating of copper ticket



The inductor is cooled by water with turbulent flow

$$Q_{\mathrm{c}} = \frac{\frac{\mathrm{d}M}{\mathrm{d}t} c_{\mathrm{p}} \left(T_{\mathrm{in}} - T\right)}{2\pi r S},$$

where $\frac{\mathrm{d}M}{\mathrm{d}t}$ is the mass flow of cooling water, T_{in} is the inlet temperature, S is the channel cross-section and r is the radius.

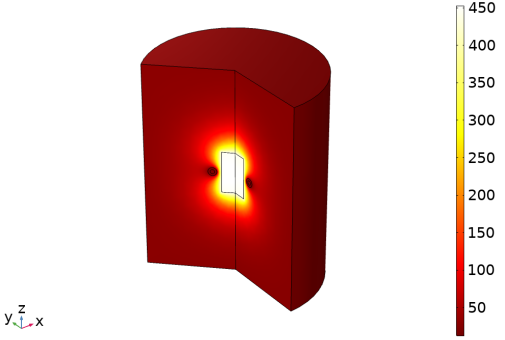
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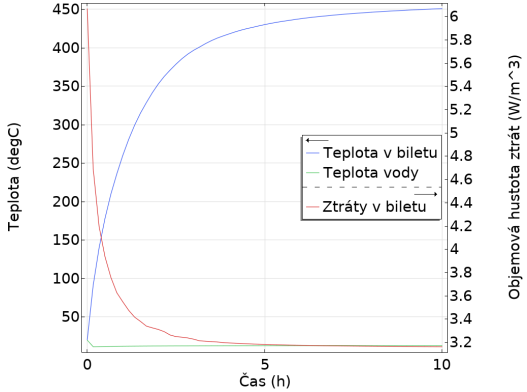
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Examples of the use of induction heating in practice

Induction heating of copper ticket



Temperature distribution



Time evolution of temperature and volume losses in the middle of billet

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Using a numerical model, it is also possible to solve sliding induction heating. The speed of the movement is usually negligible with respect to the speed of time change of the harmonic current. Therefore, the slider is neglected in the description of both fields.

It is thus possible to solve the shift by shifting the mesh. It is thus necessary to create a contact problem in COMSOL. the surfaces of the two parts that are in contact but will be shifted relative to each other are defined as a so-called identical pair.

The charge in the form of a ferromagnetic part is moved at a speed v through a toroidal coil with N that carries current I with a frequency of f.

The problem is analyzed for two different frequencies with emphasis on the necessary network change.

$$f_1 = 1\,\mathrm{kHz}$$

$$f_2 = 25\,\mathrm{kHz}$$

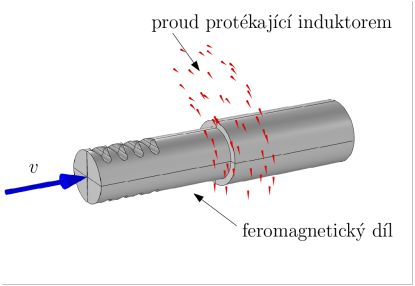
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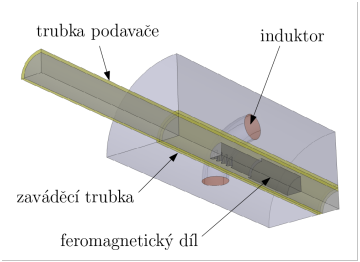
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Examples of the use of induction heating in practice

Sliding induction heating of a ferromagnetic part



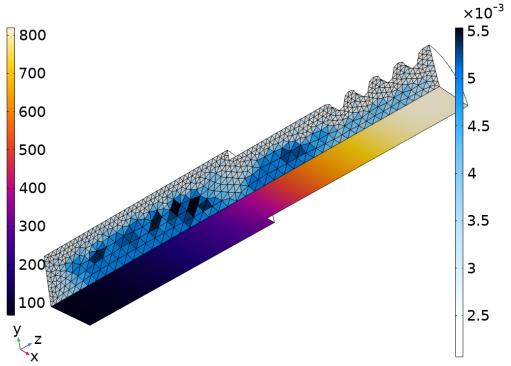


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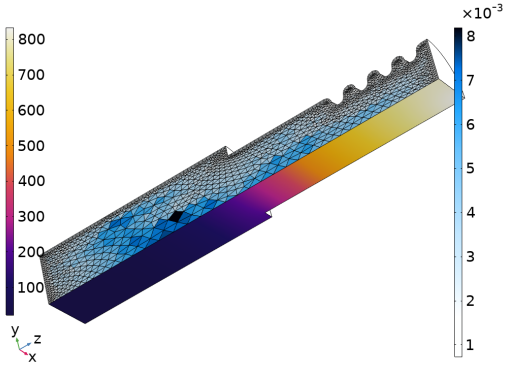
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Examples of the use of induction heating in practice

Sliding induction heating of a ferromagnetic part



Size of mesh elements in the batch and temperature distribution for $f = 1\,\mathrm{kHz}$



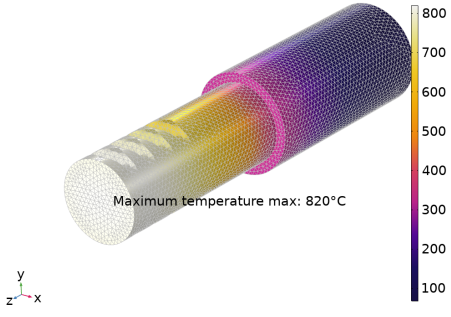
Size of mesh elements in the batch and temperature distribution for $f = 25\,\mathrm{kHz}$

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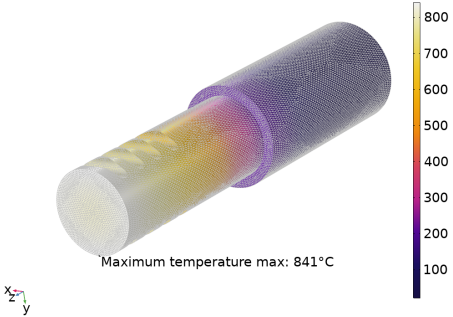
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Examples of the use of induction heating in practice

Sliding induction heating of a ferromagnetic part



Temperature distribution for $f = 1\,\mathrm{kHz}$



Temperature distribution for $f = 25\,\mathrm{kHz}$

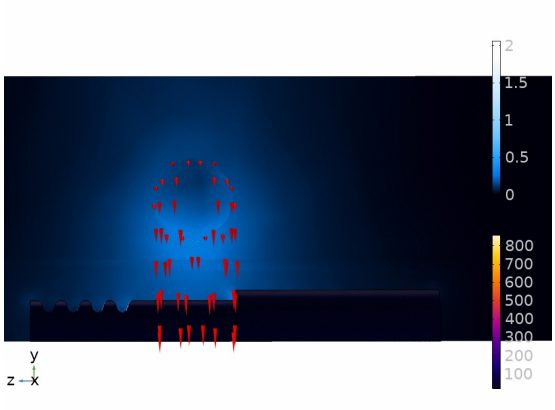
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Examples of the use of induction heating in practice

Sliding induction heating of a ferromagnetic part



Inductor charge shift

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Examples of the use of induction heating in practice

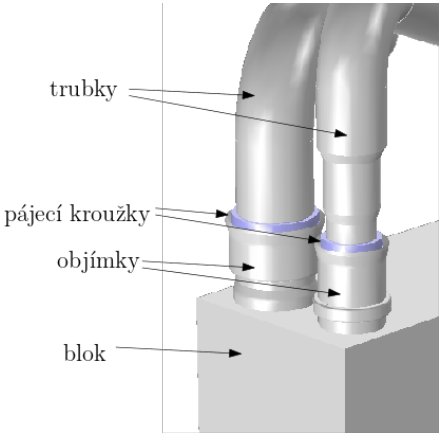
Design of inductor for soldering

This proposal was implemented as a contract research project with a specific industrial partner.

The customer came up with a requirement for the design, optimization and prototype production of an inductor for a special application of aluminum soldering.

He came up with the given shape of the soldered components and other limits that had to be observed:

- given the maximum process time item reaching the exact required soldering temperature $T_{\max} \pm 20°\mathrm{C}$
- maximum absorbed power (limited by power supply)
- source limited frequency band - ie inductor impedance
- production repeatability and accuracy



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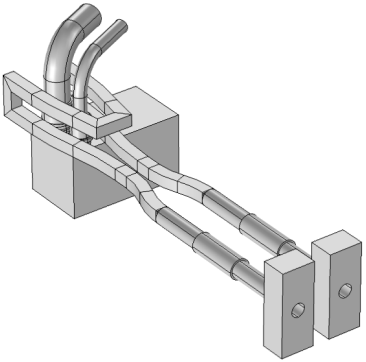
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Examples of the use of induction heating in practice

Design of inductor for soldering

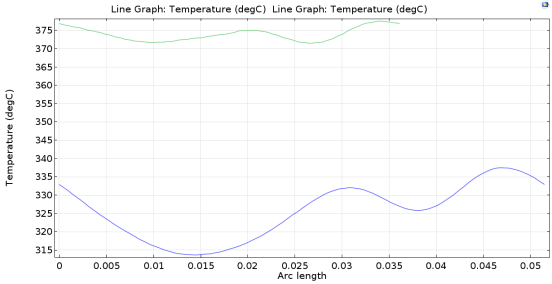
From the previous project we knew the behavior of the inductor from the Cu profile $8 \times 8\,\mathrm{mm}$ in combination with the source and the customer's line.

We came out of this information and tried to be the first to design an approximate shape from this profile.



It was important not to deviate too much in impedance, so that the inductor in the batch soldering process was in the optimal frequency window, which allowed using the full potential of the source.

Another important factor was the simultaneous melting of both solder rings around the entire circumference. For this reason, it was necessary to monitor the temperature around the circumference of both rings in the model.

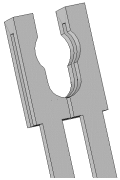


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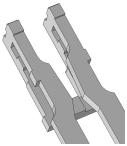
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Examples of the use of induction heating in practice

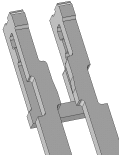
Design of inductor for soldering



variant 1



variant 3



variant 2

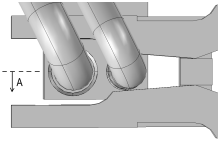
Thus, several proposals were selected and analyzed using the numerical model. The closest to the required parameters was the third variant, which was further modified and recalculated with regard to further detailed comparison and fine-tuning of requirements.

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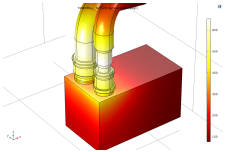
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Examples of the use of induction heating in practice

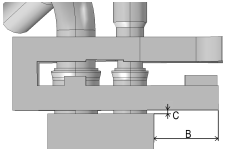
Design of inductor for soldering



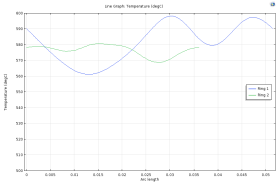
Final variant - top view



Final variant - heat distribution



Final variant - side view



Final variant - comparison of temperature on rings

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Děkuji za pozornost

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Fakulty of Electrical Engineering
University of West Bohemia