



Model created in COMSOL Multiphysics 6.4

# Quenching of a Bevel Gear

## *Introduction*

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The drivetrain of a vehicle transfers mechanical power from an engine to, ultimately, the wheels. The drivetrain is comprised of a number of components such as axles, gears, and so on, many of which experience high mechanical operating loads. The selection of material (often steel) and the subsequent manufacture become critical to their intended function. Steel components are often subjected to different post manufacture treatments for increased endurance, including shot peening and various types of heat treatments. In this example, we consider a bevel gear, such as exists in configurations where incoming and outgoing axles are not parallel. We simulate a heat treatment process where the bevel gear, made from steel, is initially at 900°C and immersed in a quenching oil at 60°C. The initially austenitic bevel gear undergoes phase transformations during the cooling, and the final phase composition and the residual stress state are computed.

## *Model Definition*

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In this section, the various aspects of the multiphysics problem of quenching a bevel gear are described.

### **GEOMETRY AND MESH**

In this example, a simple bevel gear is used. It has twenty teeth at a 40-degree cone angle, and a pitch diameter of 100 mm. By exploiting symmetry, a segment involving half a tooth is considered. [Figure 1](#) shows the bevel gear. The finite element mesh of the computational domain is shown in green. When the bevel gear is subjected to external cooling, it becomes relevant to resolve thermal gradients at the surface. Therefore, a boundary layer mesh is used in these regions. [Figure 2](#) shows a closeup of the mesh near the gear tooth, showing the boundary layer mesh.

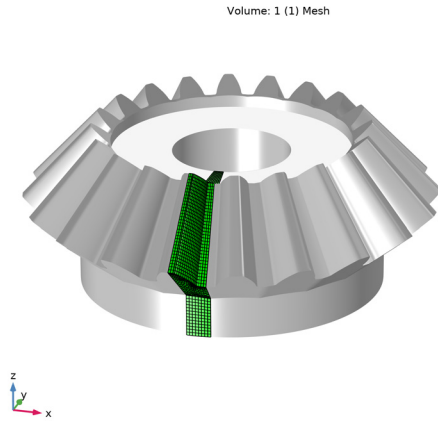


Figure 1: The bevel gear and the segment that is used in the simulation (in green).

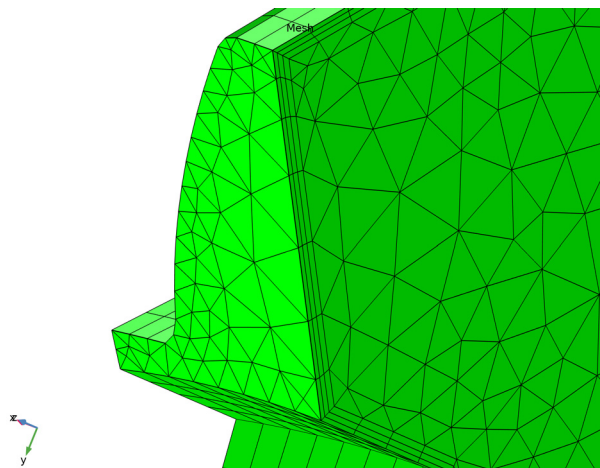


Figure 2: A boundary layer mesh is used for the external surfaces of the bevel gear.

### **MATERIAL PROPERTIES**

In quenching simulations, we must recognize and take into account that material properties are generally temperature dependent. Moreover, the properties differ between metallurgical phases. For example, the thermal conductivity of ferrite is different from that of austenite, the yield stress of martensite is different from that of pearlite, and so on. In

this example, the material properties for a general steel are imported from JMatPro® (Ref. 1). Material properties that are imported per phase are:

- Elastic moduli and the coefficient of thermal expansion
- Yield stress and hardening curves
- Thermal conductivity, density, and specific heat
- Electrical conductivity

### HEAT TRANSFER

To simulate that the bevel gear is cooled by a quenching oil, this mode of heat transfer must be modeled. Quenching (using oils, water, brine, air, and so on) is often modeled using convective heat transfer. The temperature dependent heat transfer coefficient is typically experimentally obtained for relevant flow conditions and combinations of quenching medium and component surface characteristics. Here, we use a fictitious, but nonetheless reasonable, heat transfer coefficient for immersion of a steel component in oil. Figure 3 shows this temperature-dependent heat transfer coefficient.

The thermal diffusivity of the steel is computed from the thermal material properties of the individual phases and the current phase composition automatically, using an averaging scheme for effective material properties in the Metal Processing Module.

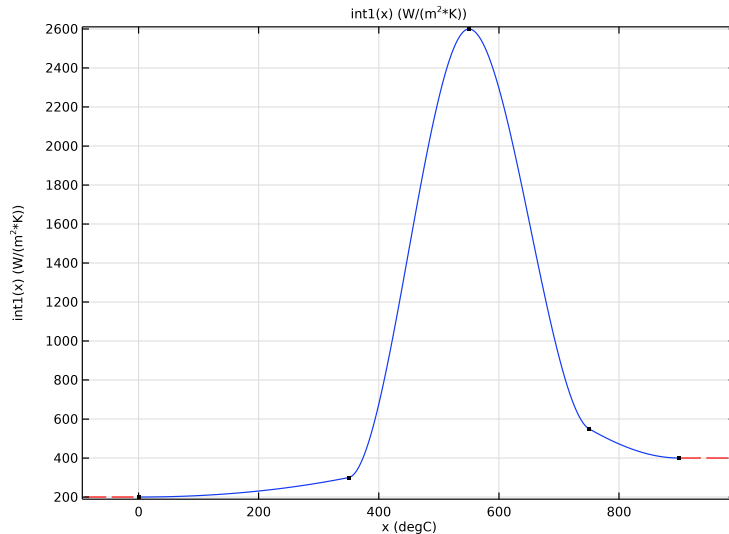


Figure 3: The temperature-dependent heat transfer coefficient for the quenching oil.

## PHASE TRANSFORMATIONS

When the bevel gear is cooled from its initial temperature, the austenite will decompose into a combination of other phases. The ferritic, pearlitic, bainitic, and martensitic phase transformations can be characterized in a number of ways. Experiments can be performed, literature sources can be consulted, computational methods can be employed, and so on. In this example, just like with the phase material properties, we elect to import phase transformation data for a general steel from JMatPro® (Ref. 1). The imported data includes the following information:

- Phase transformation data for austenite decomposition into ferrite
- Phase transformation data for austenite decomposition into pearlite
- Phase transformation data for austenite decomposition into bainite
- Phase transformation data for austenite decomposition into martensite
- Transformation induced plasticity (TRIP) data for each phase transformation
- Latent heat transformation data for each phase transformation

## STRESSES AND STRAINS

The bevel gear model is constrained by applying symmetry boundary conditions and by pinning a point to prevent rigid body translations, but otherwise the bevel gear is free to deform. The material is taken to be linear elastic, with isotropic hardening plasticity. The material properties are computed from the mechanical material properties of the individual phases, just as is done for the thermal properties.

## *Results and Discussion*

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After cooling the bevel gear for a duration of four minutes from its initial temperature of 900°C, the austenite has decomposed into a combination of other phases. [Figure 4](#), [Figure 5](#), [Figure 6](#), and [Figure 7](#) show respectively the phase fractions of ferrite, pearlite, bainite, and martensite. In this example, we used a fictitious oil and a bevel gear made from a general example steel. The final phase composition is mostly bainitic, with some ferrite at the interior of the bevel gear, and gear teeth that are partially martensitic. Note that the final phase composition at any given location is essentially governed by two factors:

- The rate at which the temperature has decreased from the austenitic state.
- The phase transformation kinetics, given by the material (its chemical composition, austenite grain size, and so on).

This suggests that for a given choice of steel, the final phase composition near the surface of a component can be reasonably well controlled through the choice of quenching

medium and the method of application (examples are water spray cooling, oil quenching, air quenching, and so on). However, the austenite decomposition inside a bulky component will be dictated by heat conduction, and therefore only indirectly controllable by the conditions imposed on the surfaces of the component.

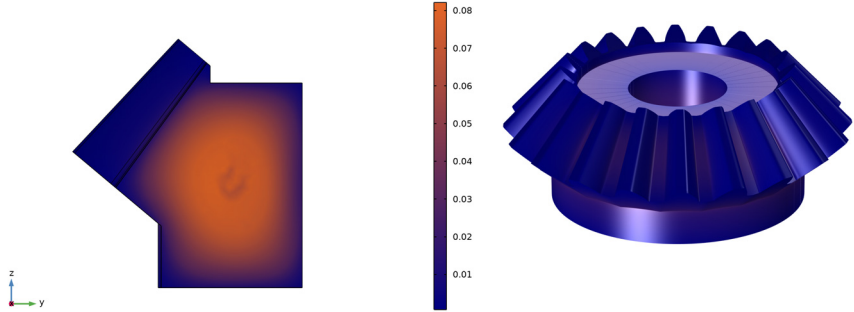


Figure 4: Phase fraction of ferrite after cooling.

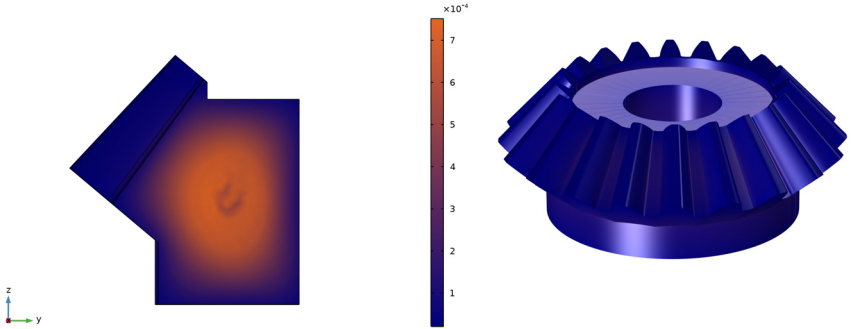
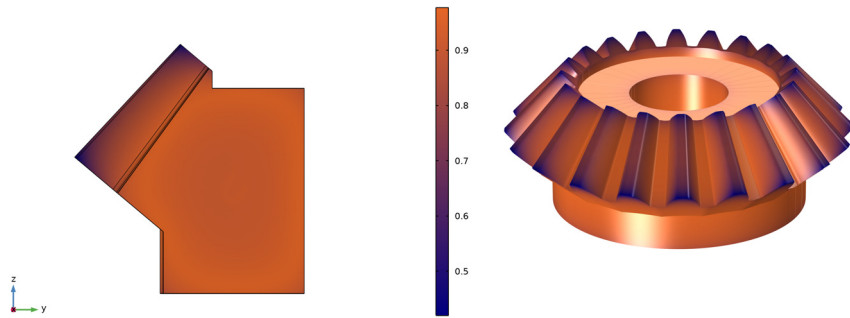
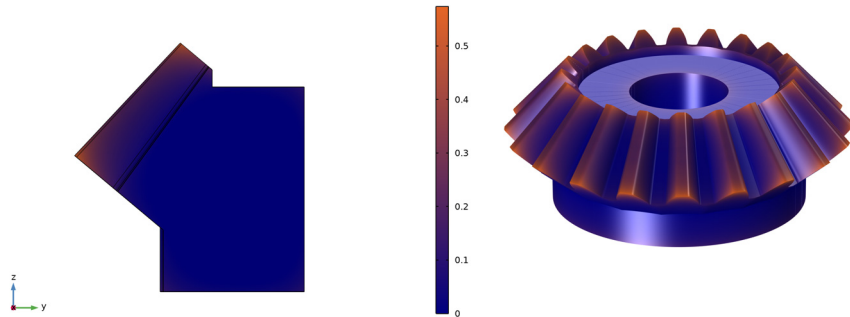


Figure 5: Phase fraction of pearlite after cooling.



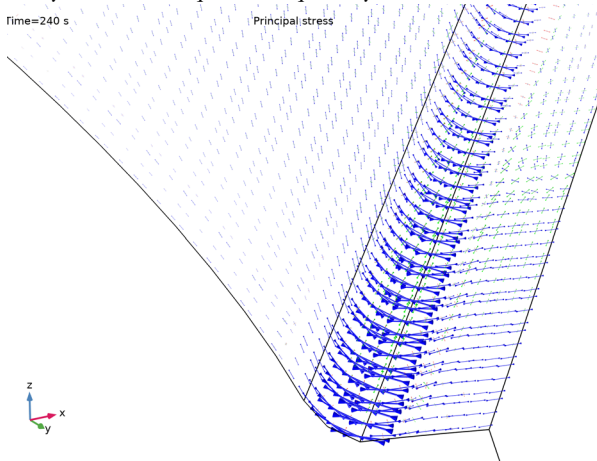
*Figure 6: Phase fraction of bainite after cooling.*



*Figure 7: Phase fraction of martensite after cooling.*

Components like bevel gears are typically integral components of vehicle drivetrains. As such, they have to be designed and manufactured to withstand operating conditions in the high cycle fatigue regime. During operation, gear teeth essentially experience pulsating loading, causing bending, and a critical region becomes the root of each gear tooth, where fatigue cracks may emanate. In [Figure 8](#), we look at the principal state at the root of the gear. These principal stresses are the residual stresses after quenching, and we note that along the surface, and perpendicular to the root itself, stresses are mostly compressive. Given that gear teeth experience bending during operation, these compressive residual

stresses should be beneficial to the fatigue endurance of the bevel gear, but a more detailed study would be required to quantify this.



*Figure 8: Residual principal stresses near the root of the gear tooth.*

In this example, the cooling was applied uniformly at the surfaces. This emulates a rapid immersion of a single bevel gear into the quenching oil. In reality, these types of drivetrain components are often placed, several at a time, on a tray which is lowered into the quenching oil. This adds complexity, as the bevel gears will be gradually lowered into the oil, and where they might affect one another through thermal radiation, and so on. This, in turn, may affect roundness and other critical geometrical features of the post-quenched bevel gears.

### *Notes About the COMSOL Implementation*

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In this example, phase material properties and phase transformation data for a general steel were imported from JMatPro® (Ref. 1). Material properties are imported automatically as separate materials, each representing a separate phase. Phase transformation data is imported for each phase transformation, and *Phase Transformation* nodes are created at the physics interface level automatically. Both imports are performed from the same XML file that was previously exported from JMatPro®.

- Phase transformation data is imported by selecting *Import Phase Transformations* in the physics interface context menu.
- Phase material properties are imported by selecting *Import Materials* from the *Materials* context menu under *Global Definitions* or under *Materials* at the component level (not available in 0D).

## Reference

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1. Sente Software, Ltd., United Kingdom.

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**Application Library path:** Metal\_Processing\_Module/Steel\_Quenching/  
quenching\_of\_a\_bevel\_gear


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## Modeling Instructions




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From the **File** menu, choose **New**.

### NEW




In the **New** window, click  **Model Wizard**.

### MODEL WIZARD

- 1 In the **Model Wizard** window, click  **3D**.
- 2 In the **Select Physics** tree, select **Heat Transfer > Metal Processing > Steel Quenching**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **General Studies > Time Dependent**.
- 6 Click  **Done**.

### MESH 1

#### Import 1

- 1 In the **Mesh** toolbar, click  **Import**.
- 2 In the **Settings** window for **Import**, locate the **Import** section.
- 3 Click  **Browse**.
- 4 Browse to the model's Application Libraries folder and double-click the file `quenching_of_a_bevel_gear_mesh.mphbin`.
- 5 Click  **Import**.

### GLOBAL DEFINITIONS




#### Parameters 1

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 In the table, enter the following settings:

Name	Expression	Value	Description
Tinit	900[degC]	1173.2 K	Initial temperature
Tamb	60[degC]	333.15 K	Ambient (oil) temperature

#### *Interpolation 1 (int1)*


- 1 In the **Home** toolbar, click  **Functions** and choose **Global > Interpolation**.
- 2 In the **Settings** window for **Interpolation**, locate the **Definition** section.
- 3 From the **Data source** list, choose **File**.
- 4 Click  **Browse**.
- 5 Browse to the model's Application Libraries folder and double-click the file `quenching_of_a_bevel_gear_htc.txt`.
- 6 Locate the **Data Column Settings** section. In the **Unit** text field, type  $W/(m^2 \cdot K)$ .
- 7 In the table, click to select the cell at row number 1 and column number 3.
- 8 In the **Unit** text field, type `degC`.
- 9 Locate the **Interpolation and Extrapolation** section. From the **Interpolation** list, choose **Piecewise cubic**.
- 10 Click  **Plot**.

## HEAT TRANSFER IN SOLIDS (HT)

#### *Initial Values 1*

- 1 In the **Model Builder** window, expand the **Heat Transfer in Solids (ht)** node, then click **Initial Values 1**.
- 2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 3 In the  $T$  text field, type `Tinit`.

#### *Heat Flux 1*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Heat Flux**.
- 2 In the **Settings** window for **Heat Flux**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **All boundaries**.
- 4 Select Boundaries 2–11, 13, and 14 only.
- 5 Locate the **Heat Flux** section. From the **Flux type** list, choose **Convective heat flux**.
- 6 In the  $h$  text field, type `int1(T)`.


7 In the  $T_{\text{ext}}$  text field, type  $T_{\text{amb}}$ .

## SOLID MECHANICS (SOLID)


### *Linear Elastic Material I*

In the **Model Builder** window, expand the **Solid Mechanics (solid)** node, then click **Linear Elastic Material I**.


### *Plasticity I*

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Plasticity**.
- 2 In the **Settings** window for **Plasticity**, locate the **Plasticity Model** section.
- 3 Find the **Isotropic hardening model** subsection. From the list, choose **Hardening function**.

### *Symmetry I*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Symmetry**.
- 2 Select Boundaries 1 and 12 only.

### *Prescribed Displacement I*

- 1 In the **Physics** toolbar, click  **Points** and choose **Prescribed Displacement**.
- 2 Select Point 13 only.
- 3 In the **Settings** window for **Prescribed Displacement**, locate the **Prescribed Displacement** section.
- 4 From the **Displacement in z direction** list, choose **Prescribed**.

## MATERIALS

Import the material properties, collected in separate phase materials for austenite, ferrite, and so on.

- 1 In the **Materials** toolbar, click **Import Materials** and choose **Import Materials**.
- 2 In the **Import Materials** dialog, click  **Browse**.
- 3 Browse to the model's Application Libraries folder and double-click the file `quenching_of_a_bevel_gear_JMatPro_general_steel.xml`.
- 4 Click **OK**.

## AUSTENITE DECOMPOSITION (AUDC)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Austenite Decomposition (audc)**.
- 2 In the **Settings** window for **Austenite Decomposition**, locate the **Material Properties** section.

- 3 Click **Create Compound Material** in the upper-right corner of the section.
- 4 Locate the **Solid Mechanics** section. Select the **Enable phase plasticity** checkbox.
- 5 From the **Thermal strain formulation** list, choose **Density based**.

Import the phase transformation data for the different phase transformations. This information is contained in the same file as the phase material properties.

#### *General Steel, Austenite to Ferrite*

- 1 Right-click **Component 1 (comp1)** > **Austenite Decomposition (audc)** and choose **Import Phase Transformations**.
- 2 Browse to the model's Application Libraries folder and double-click the file `quenching_of_a_bevel_gear_JMatPro_general_steel.xml`.

#### *Austenite*

- 1 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.
- 2 From the **Phase material** list, choose **General Steel, Austenite (mat1)**.
- 3 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Hardening function**.

#### *Ferrite*

- 1 In the **Model Builder** window, click **Ferrite**.
- 2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.
- 3 From the **Phase material** list, choose **General Steel, Ferrite (mat2)**.
- 4 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Hardening function**.

#### *Pearlite*

- 1 In the **Model Builder** window, click **Pearlite**.
- 2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.
- 3 From the **Phase material** list, choose **General Steel, Pearlite (mat3)**.
- 4 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Hardening function**.

#### *Bainite*


- 1 In the **Model Builder** window, click **Bainite**.
- 2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.
- 3 From the **Phase material** list, choose **General Steel, Bainite (mat4)**.

- 4 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Hardening function**.

#### *Martensite*

- 1 In the **Model Builder** window, click **Martensite**.
- 2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.
- 3 From the **Phase material** list, choose **General Steel, Martensite (mat5)**.
- 4 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Hardening function**.

Set the Volume strain reference temperature. It should be equal across metallurgical phases.

- 5 Locate the **Model Input** section. Click  **Go to Source** for **Volume reference temperature**.

### **GLOBAL DEFINITIONS**

#### *Default Model Inputs*

- 1 In the **Model Builder** window, under **Global Definitions** click **Default Model Inputs**.
- 2 In the **Settings** window for **Default Model Inputs**, locate the **Browse Model Inputs** section.
- 3 Find the **Expression for remaining selection** subsection. In the **Volume reference temperature** text field, type `Tinit`.

### **AUSTENITE DECOMPOSITION (AUDC)**

#### *General Steel, Austenite to Ferrite*

- 1 In the **Model Builder** window, under **Component 1 (comp1)** > **Austenite Decomposition (audc)** click **General Steel, Austenite to Ferrite**.
- 2 In the **Settings** window for **Phase Transformation**, locate the **Phase Transformation** section.
- 3 From the  $\xi^S$  list, choose **Austenite**.
- 4 From the  $\xi^d$  list, choose **Ferrite**.

#### *General Steel, Austenite to Pearlite*

- 1 In the **Model Builder** window, click **General Steel, Austenite to Pearlite**.
- 2 In the **Settings** window for **Phase Transformation**, locate the **Phase Transformation** section.
- 3 From the  $\xi^S$  list, choose **Austenite**.

- 4 From the  $\xi^d$  list, choose **Pearlite**.

*General Steel, Austenite to Bainite*

- 1 In the **Model Builder** window, click **General Steel, Austenite to Bainite**.
- 2 In the **Settings** window for **Phase Transformation**, locate the **Phase Transformation** section.
- 3 From the  $\xi^s$  list, choose **Austenite**.
- 4 From the  $\xi^d$  list, choose **Bainite**.

*General Steel, Austenite to Martensite*

- 1 In the **Model Builder** window, click **General Steel, Austenite to Martensite**.
- 2 In the **Settings** window for **Phase Transformation**, locate the **Phase Transformation** section.
- 3 From the  $\xi^s$  list, choose **Austenite**.
- 4 From the  $\xi^d$  list, choose **Martensite**.


## STUDY I

*Step I: Time Dependent*

- 1 In the **Model Builder** window, expand the **Study I** node, then click **Step I: Time Dependent**.
- 2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
- 3 In the **Output times** text field, type range (0,30,240).

## RESULTS

*Preferred Units I*

- 1 In the **Results** toolbar, click  **Configurations** and choose **Preferred Units**.  
Set preferred units for result presentation.
- 2 In the **Settings** window for **Preferred Units**, locate the **Units** section.
- 3 Click **+ Add Physical Quantity**.
- 4 In the **Physical Quantity** dialog, select **General > Temperature (K)** in the tree.
- 5 Click **OK**.
- 6 In the **Settings** window for **Preferred Units**, locate the **Units** section.

7 In the table, enter the following settings:

Quantity	Unit	Preferred unit
Temperature	K	°C

8 Click  **Add Physical Quantity**.

9 In the **Physical Quantity** dialog, select **Solid Mechanics > Stress tensor (N/m<sup>2</sup>)** in the tree.


10 Click **OK**.

11 In the **Settings** window for **Preferred Units**, locate the **Units** section.

12 In the table, enter the following settings:

Quantity	Unit	Preferred unit
Stress tensor	N/m <sup>2</sup>	MPa

#### STUDY I

In the **Study** toolbar, click  **Compute**.