Created in COMSOL Multiphysics 6.2

Carburization and Quenching of a Steel Gear

Introduction

In this model, a steel gear is first carburized in a carbon rich atmosphere. Diffusion of carbon into the surface lowers the martensite start temperature, and thereby delays the onset of transformation. Quenching of the carburized gear is then performed. The quenching simulation includes heat transport in the gear, phase transformations, and computation of residual stresses.

Model Definition

A 2D spur gear is used to build a model for the carburization and quenching processes. The spur gear has a pitch diameter of 100 mm and twenty teeth, see Figure 1. Because of symmetries, half a gear segment is included in the model, and corresponding boundary conditions are applied. The 2D model is meant to represent a center cut of the spur gear. A generalized plane strain assumption is used.

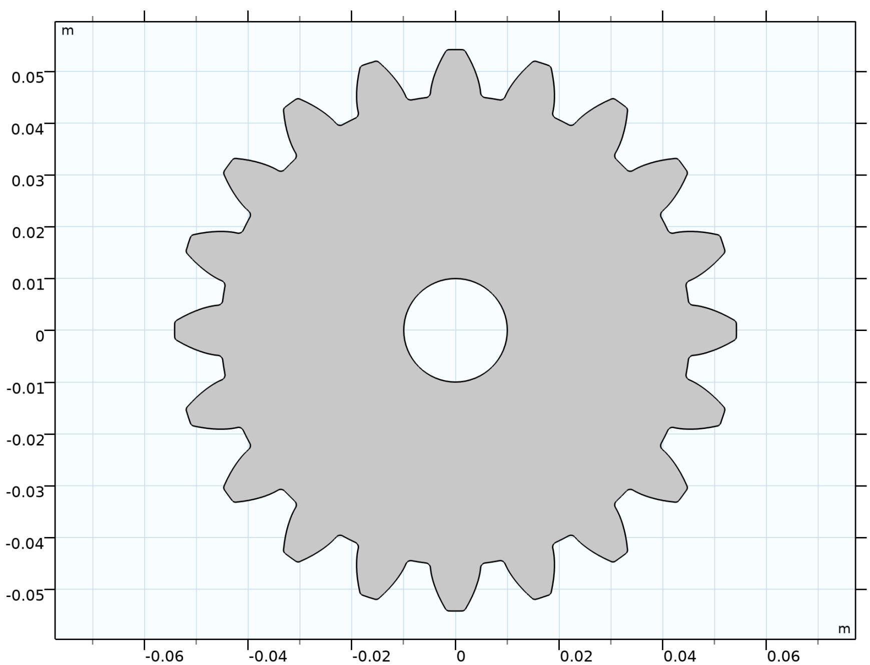

Figure 1: The 2D spur gear.

Figure 2 shows the geometry of the gear segment. During carburization, flux of carbon is possible along the tooth surface and along the center hole (dashed, blue lines). Along the symmetry planes, there is zero carbon flux. During quenching, the rollers shown in the figure indicate applied displacement symmetry boundary conditions. Heat flux to the surrounding quenching oil is possible though the tooth surface, and along the center hole (dashed, blue lines).

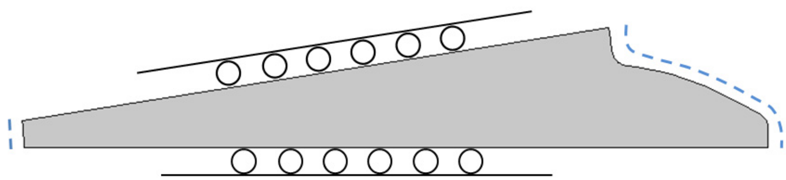

Figure 2: Boundary condition regions: Rollers indicate displacement symmetry boundary conditions. The dashed lines in blue indicate boundaries on which flux boundary conditions are applied.

MATERIAL PROPERTIES

The material properties of the gear are temperature-dependent, and also depend on phase composition. The Austenite Decomposition physics interface automatically averages these properties into effective properties that define a compound material. The compound material is used in the thermal and mechanical analyses.

CARBURIZATION ANALYSIS

The process of carburization involves heating a steel component and exposing it to a carbon rich environment, such as carbon monoxide. When done correctly, carburization followed by quenching can produce compressive stresses at the surface of a component, which is beneficial from a fatigue standpoint. In this model, it is assumed that the carbon content of the austenite is c = 0.2%, and that the so-called carbon potential of the surrounding atmosphere is c_{env} = 0.75%. A simple carburization process is modeled using the transient Fick's law:

$$\frac{\partial c}{\partial t} + (-D_{\mathrm{c}}\nabla^2 c) = 0$$

where the diffusion constant is $D_{\mathrm{c}} = 2 \cdot 10^{-7}\ \mathrm{cm}^2/\mathrm{s}$.

Boundary Conditions

Diffusion of carbon from the surrounding environment occurs through a boundary flux of the form

$$\mathbf{n} \cdot (D_c \nabla c) = k_c (c_{env} - c)$$

with the assumed mass transfer coefficient $k_c = 2 \cdot 10^{-5}$ cm/s. The carburization process is taken to occur over a period of twelve hours, during which carbon diffuses from the surface and into the material.

PHASE TRANSFORMATION ANALYSIS

In this analysis, it is assumed that austenite decomposes into martensite only. This phase transformation is displacive and described by the Koistinen–Marburger model. The model states that the amount of martensite formed at the expense of austenite depends on the fraction of available austenite, and under-cooling below the so-called martensite start temperature M_s. On differential form, the model is given by

$$\dot{\xi}^d = -\xi^s \beta \dot{T}$$

where the rate at which the destination phase (martensite) forms is proportional to the temperature rate and the instantaneous fraction of the source phase (austenite), through a the Koistinen–Marburger coefficient β. The start temperature M_s depends on the carbon content. Here a simple linear relationship is assumed:

$$M_s = (560 - 470 \times c)°\mathrm{C}$$

where the carbon concentration is c. The Koistinen–Marburger coefficient is given as β=0.011/K. Note that the start temperature decreases with increasing carbon content, which means that martensite may well begin to form inside the surface of the gear, as a result of the carburization.

THERMAL ANALYSIS

The heat transport in the bar is described by the heat equation:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = 0$$

where T is the temperature, k represents the thermal conductivity, ρ denotes the density, C_p denotes the specific heat capacity. In the equation above, the effect of latent heat of phase transformation has been neglected. The thermal conductivity, the density, and the specific heat capacity are in general temperature dependent, and in the presence of metallurgical phase transformations, they also depend on the current phase composition.

Material Properties

The densities, specific heat capacities and heat conductivities of austenite and martensite are given in Table 1. It is assumed that densities are not temperature dependent.

TABLE 1: TEMPERATURE-DEPENDENT THERMAL MATERIAL PROPERTIES.

Temperature (°C)	**ρ (kg/m^3)**	**C_p (J/(kg·K))**	**k (W/(m·K))**
Austenite			
0	7930	520	15
300		560	20
600		590	22
900		620	25
Martensite			
0	7850	480	44
300		570	38
600		640	30
900		650	24

Boundary Conditions

The quenching oil is not modeled explicitly, but it is replaced by a temperature-dependent heat-transfer coefficient h that is used to prescribe a heat flux as

$$q_0 = h(T)(T_{\mathrm{ext}} - T)$$

where T_{ext} = 80°C is the temperature of the quenching oil. The heat-transfer properties of the quenching oil are shown in Table 2.

TABLE 2: HEAT-TRANSFER COEFFICIENT OF THE QUENCHING OIL.

Temperature (°C)	**h (W/(m^2·K))**
0	200
300	200
500	2800
650	750
1300	750

MECHANICAL ANALYSIS

The quenching process is time dependent, but from a structural-mechanics point of view it is quasi static, and modeled as such. Stresses and strains are computed using material properties of the compound material defined by the phase composition and the constitutive behavior of the individual phases, here austenite and martensite.

Material Properties

As in the thermal analysis, the mechanical analysis involves material properties that are temperature as well as phase composition dependent. In this model, the elastoplastic behavior of austenite and martensite is taken to be linear elastic with linear hardening. The properties for austenite and martensite are shown in Table 3. The linear elastic behavior is given by the Young's moduli (E) and Poisson's ratios (ν) of the phases, and the plastic behavior is given by initial yield stresses (σ_{ys0}) and isotropic hardening moduli (h). In this model, the elastic behavior of austenite and martensite is assumed equal. Note that the secant coefficients of thermal expansion (α) are not averaged into a compound material property, but are instead used to compute the thermal strain tensor of each metallurgical phase. The thermal strain tensors are averaged into a thermal strain of the compound material.

TABLE 3: TEMPERATURE-DEPENDENT MECHANICAL MATERIAL PROPERTIES.

Temperature (°C)	**E (GPa)**	ν	σ_{ys0} **(MPa)**	**h (GPa)**	α **(1/K)**
Austenite					
0	210	0.3	200	1	$22 \cdot 10^{-6}$
300	180		135	15	
600	165		40	11	
900	120		36	0.6	
Martensite					$14 \cdot 10^{-6}$
0	210	0.3	1600	1	
300	180		1500	15	
600	165		1400	11	
900	120		100	0.6	

To complete the description of the phase properties, a volume reference temperature T_{ref} has to be defined for the phases. In this model, the heating stage (austenitization) is not considered explicitly, so the volume reference temperature is set to the austenitization temperature (900°C). This means that the gear is strain free at this temperature.

Boundary Conditions and Constraints

Because of symmetries, displacement boundary conditions are applied according to Figure 2, where the rollers indicate that displacements normal to the surface are prescribed to be zero. The gear segment is modeled using generalized plane strain to allow for out-of-plane strains. Only normal out-of-plane strains are allowed.

Initial Strains from Heating and Austenitization

To account for the strains that follow from thermal expansion and austenitization of the (unknown) base phase composition, an initial strain is applied. The initial strain is given by

$$\varepsilon_0 = 5 \cdot 10^{-3} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Transformation Induced Plasticity (TRIP)

In general, phase transformations occur while the material is subjected to a mechanical stress. This gives rise to so-called transformation induced plasticity, or TRIP. In essence, an inelastic straining of the material results from stresses that are below the yield stress, and would not cause plastic flow in a classical plasticity sense. In this model, the TRIP effect is included in the transformation from austenite to martensite. Two parameters are required to describe the effect: the parameter $K_{\mathrm{s} \to \mathrm{d}}^{\mathrm{TRIP}}$ and the saturation function Φ. For the present model, the default parameter value is used, and the Desalos saturation function is used.

Phase Plasticity

During a quenching process, each phase may undergo plastic straining. By default, the equivalent plastic strain of the individual phases follows that of the compound material. That is to say, the equivalent plastic strain of a given phase in the Austenite Decomposition interface is equal to the equivalent plastic strain of a Plasticity node under Solid Mechanics. This equivalence is established through the Phase Transformation Strain multiphysics coupling. For the vanishing austenite, this is a reasonable modeling assumption. However, for phases that appear gradually and devoid of prior plastic straining, this assumption is questionable. This deficiency can be remedied by allowing for plastic recovery of the destination phase. In this model, the plastic recovery option is therefore used for the martensite. In the computation of an initial yield stress for the compound material, a linear averaging between phases is often adequate as long as the phases are of similar hardness. In the case where one phase is significantly harder than the others, this averaging scheme can be amended by giving the hard phase stronger influence on the compound material behavior. To this end, the description by Geijselaers (Ref. 1) is used to modify the weighting of the martensite initial yield stress.

During carburization, the amount of carbon in the austenite increases because of diffusion into the surface of the gear. After the carburization period of twelve hours, the mass percent of carbon at the surface has almost saturated to the surrounding level, see Figure 3. The influence of the carburization process is mainly affecting the surfaces of the gear, while the interior remains at its initial carbon content.

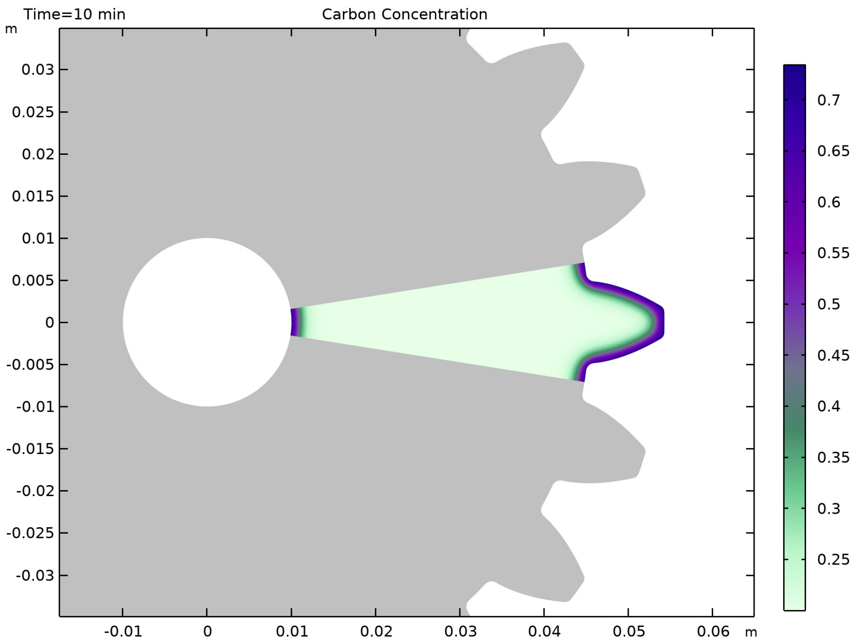

Figure 3: Carbon content in the gear after carburization.

One reason for performing the carburization is to alter the phase transformation characteristics by changing the carbon content. Figure 4 shows how the martensite start temperature has been affected by the carburization process. In the vicinity of the surfaces, where the carbon content is the highest, the martensite start temperature is lower than in the interior. During cooling, it is therefore likely that austenite on the inside of the gear transforms to martensite before the surface does.

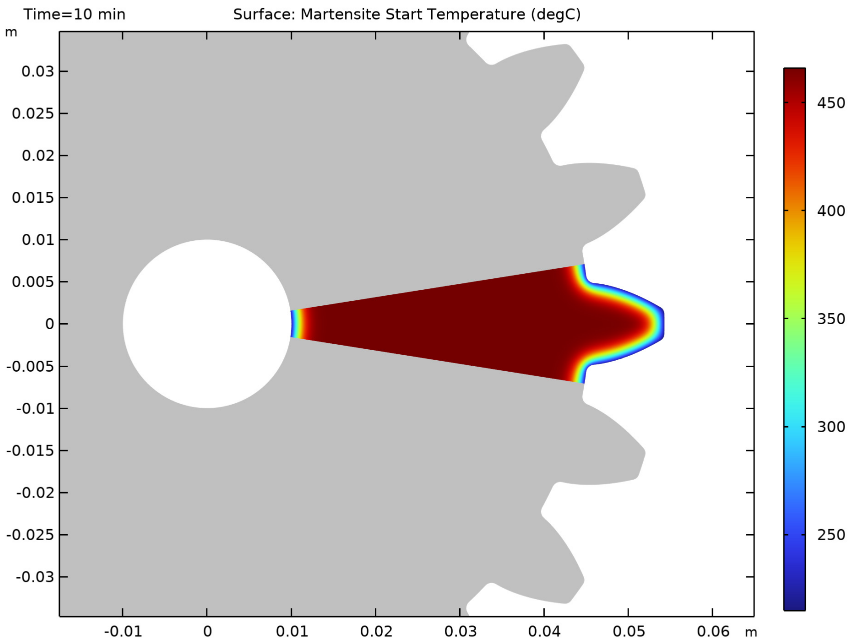

Figure 4: Computed martensite start temperature resulting from the carburization.

During quenching, the austenite is cooled, and the onset of martensitic transformation is determined by the computed start temperatures. From a fatigue standpoint, it is well known that residual compressive stresses are beneficial. During service, gear teeth will experience high cycle fatigue loading, and a critical location is often near the root of each gear tooth, where tensile stresses may cause fatigue. In Figure 5, the second principal stress is displayed. High compressive stresses appear at the root of the tooth, and the entire gear tooth surface experiences compressive stresses.

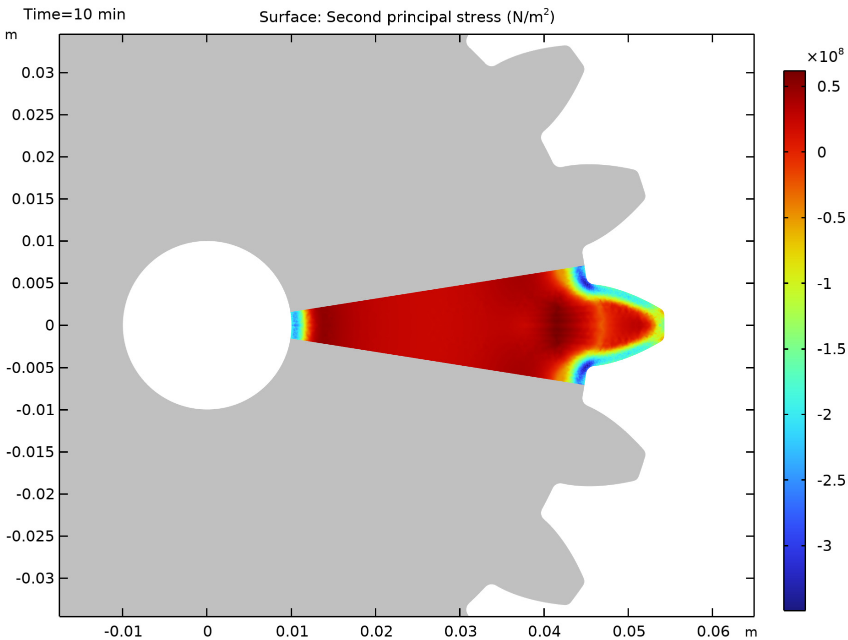

Figure 5: Residual stress state in the gear after quenching.

Reference

1. H.J.M. Geijselaers, *Numerical simulation of stresses due to solid state transformations: The simulation of laser hardening*, doctoral dissertation, Univ. of Twente, Enschede, 2003.

Application Library path: `Metal_Processing_Module/Steel_Quenching/carburization_and_quenching_of_a_steel_gear`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **Heat Transfer>Metal Processing>Steel Quenching**.

3 Click **Add**.

4 In the **Select Physics** tree, select **Heat Transfer>Metal Processing>Carburization (carb)**.

5 Click **Add**.

6 Click **Study**.

7 In the **Select Study** tree, select **General Studies>Time Dependent**.

8 Click **Done**.

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
cenv	0.75	0.75	Carbon potential
c0	0.2	0.2	Initial carbon concentration
Dc	2e-7[cm^2/s]	2E-11 m²/s	Carbon diffusion coefficient
kc	2e-5[cm/s]	2E-7 m/s	Mass transfer coefficient

PART LIBRARIES

1 In the **Home** toolbar, click **Windows** and choose **Part Libraries**.

2 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

3 In the **Part Libraries** window, select **Multibody Dynamics Module>2D>External Gears>spur_gear_2d** in the tree.

4 Click **Add to Geometry**.

GEOMETRY 1

Spur Gear (2D) 1 (pi1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Spur Gear (2D) 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, click **Build All Objects**.

Square 1 (sq1)

1 In the **Geometry** toolbar, click **Square**.

2 In the **Settings** window for **Square**, locate the **Size** section.

3 In the **Side length** text field, type `0.06`.

Square 2 (sq2)

1 In the **Geometry** toolbar, click **Square**.

2 In the **Settings** window for **Square**, locate the **Size** section.

3 In the **Side length** text field, type `0.06`.

4 Locate the **Rotation Angle** section. In the **Rotation** text field, type `9`.

Intersection 1 (int1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Intersection**.

2 Select the objects **pi1** and **sq1** only.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **int1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **sq2** only.

6 Click **Build All Objects**.

CARBURIZATION (CARB)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Carburization (carb)**.

2 In the **Settings** window for **Carburization**, locate the **Carburizing Cycle** section.

3 From the **Carbon potential model** list, choose **User defined**.

4 In the c_{pot} text field, type `cenv`.

Carbon Flux 1

In the **Physics** toolbar, click **Boundaries** and choose **Carbon Flux**.

Carburization 1

1 In the **Model Builder** window, click **Carburization 1**.

2 In the **Settings** window for **Carburization**, locate the **Carbon Diffusion** section.

3 In the D_0 text field, type `Dc`.

4 From the **Diffusion coefficient** list, choose **User defined**.

5 In the D text field, type `Dc`.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the c text field, type `c0`.

Carbon Flux 1

1 In the **Model Builder** window, click **Carbon Flux 1**.

2 Select Boundaries 3–8 only.

3 In the **Settings** window for **Carbon Flux**, locate the **Carbon Mass Transfer** section.

4 From the **Mass transfer coefficient** list, choose **User defined**.

5 In the b text field, type `kc`.

MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Predefined** list, choose **Extra fine**.

Size 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.

2 Drag and drop **Size 1** below **Size**.

3 In the **Settings** window for **Size**, locate the **Element Size** section.

4 Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** check box. In the associated text field, type `0.3[mm]`.

7 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.

8 Select Boundaries 3–8 only.

9 Click **Build All**.

CARBURIZATION

1 In the **Model Builder** window, click **Study 1**.

2 In the **Settings** window for **Study**, type `Carburization` in the **Label** text field.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Carburization** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **h**.

4 In the **Output times** text field, type `range(0,0.1,12)`.

5 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check boxes for **Heat Transfer in Solids (ht)**, **Solid Mechanics (solid)**, and **Austenite Decomposition (audc)**.

6 In the table, clear the **Solve for** check boxes for **Phase Transformation Latent Heat 1 (lht1)** and **Phase Transformation Strain 1 (ptstr1)**.

7 In the **Home** toolbar, click **Compute**.

GLOBAL DEFINITIONS

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `htc`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_htc.txt`.

6 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	degC

7 In the **Function** table, enter the following settings:

Function	Unit
htc	`W/(m^2*K)`

Analytic 1 (an1)

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global>Analytic**.

2 In the **Settings** window for **Analytic**, type `Ms` in the **Function name** text field.

3 Locate the **Definition** section. In the **Expression** text field, type `560-470*carb.c`.

4 In the **Arguments** text field, type `carb.c`.

5 Locate the **Units** section. In the table, enter the following settings:

Argument	Unit
carb.c	1

6 In the **Function** text field, type `degC`.

Interpolation 2 (int2)

1 In the **Home** toolbar, click f(x) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `EYoung`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_EYoung.txt`.

6 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	`degC`

7 In the **Function** table, enter the following settings:

Function	Unit
EYoung	`GPa`

HEAT TRANSFER IN SOLIDS (HT)

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Heat Transfer in Solids (ht)** click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the T text field, type `900[degC]`.

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 Select Boundaries 1 and 2 only.

Heat Flux 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Heat Flux**.

2 Select Boundaries 3–8 only.

3 In the **Settings** window for **Heat Flux**, locate the **Heat Flux** section.

4 From the **Flux type** list, choose **Convective heat flux**.

5 In the h text field, type `htc(T)`.

6 In the T_{ext} text field, type `80[degC]`.

SOLID MECHANICS (SOLID)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Solid Mechanics (solid)**.

2 In the **Settings** window for **Solid Mechanics**, locate the **2D Approximation** section.

3 From the list, choose **Generalized plane strain**.

4 Clear the **Enable out-of-plane bending** check box.

Linear Elastic Material 1

In the **Model Builder** window, under **Component 1 (comp1)>Solid Mechanics (solid)** click **Linear Elastic Material 1**.

Plasticity 1

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**.

Linear Elastic Material 1

In the **Model Builder** window, click **Linear Elastic Material 1**.

Initial Stress and Strain 1

1 In the **Physics** toolbar, click **Attributes** and choose **Initial Stress and Strain**.

2 In the **Settings** window for **Initial Stress and Strain**, locate the **Initial Stress and Strain** section.

3 In the ε_0 table, enter the following settings:

0.005	0	0
0	0.005	0
0	0	0.005

Symmetry 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Symmetry**.

2 Select Boundaries 1 and 2 only.

Disable phases and phase transformations that are not present in the analysis.

AUSTENITE DECOMPOSITION (AUDC)

Austenite to Bainite, Austenite to Ferrite, Austenite to Pearlite, Bainite, Ferrite, Pearlite

1 In the **Model Builder** window, under **Component 1 (comp1)>Austenite Decomposition (audc)**, Ctrl-click to select **Ferrite**, **Pearlite**, **Bainite**, **Austenite to Ferrite**, **Austenite to Pearlite**, and **Austenite to Bainite**.

2 Right-click and choose **Disable**.

Austenite

1 In the **Model Builder** window, click **Austenite**.

2 In the **Settings** window for **Metallurgical Phase**, locate the **Model Input** section.

3 Click **Create Model Input** for **Volume reference temperature**.

SHARED PROPERTIES

Model Input 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Definitions>Shared Properties** click **Model Input 1**.

2 In the **Settings** window for **Model Input**, locate the **Definition** section.

3 In the text field, type `900[degC]`.

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 **Heat Transfer** section. Clear the **Enable phase transformation latent heat** check box.

5 Locate the **Solid Mechanics** section. Select the **Enable phase plasticity** check box.

Austenite

1 In the **Model Builder** window, under **Component 1 (comp1)>Austenite Decomposition (audc)** click **Austenite**.

2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.

3 Click **Create Phase Material** in the upper-right corner of the section.

4 Locate the **Mechanical Properties** section. From the **Isotropic hardening model** list, choose **Linear**.

Martensite

1 In the **Model Builder** window, click **Martensite**.

2 In the **Settings** window for **Metallurgical Phase**, locate the **Phase Material** section.

3 Click **Create Phase Material** in the upper-right corner of the section.

4 Locate the **Mechanical Properties** section. From the $g(\xi)$ list, choose **Geijselaers**.

5 From the **Soft phase** list, choose **Austenite**.

6 From the **Isotropic hardening model** list, choose **Linear**.

Austenite to Martensite

1 In the **Model Builder** window, click **Austenite to Martensite**.

2 In the **Settings** window for **Phase Transformation**, locate the **Phase Transformation** section.

3 In the M_s text field, type `Ms(carb.c)`.

4 Locate the **Phase Transformation Strain** section. Select the **Transformation induced plasticity** check box.

5 From the Φ list, choose **Desalos**.

6 Select the **Plastic recovery for destination phase** check box.

GLOBAL DEFINITIONS

Austenite (audcphase1mat)

In the **Model Builder** window, expand the **Global Definitions>Materials** node.

Interpolation 1 (int1)

1 In the **Model Builder** window, expand the **Austenite (audcphase1mat)** node.

2 Right-click **Global Definitions>Materials>Austenite (audcphase1mat)>Basic (def)** and choose **Functions>Interpolation**.
3 In the **Settings** window for **Interpolation**, locate the **Definition** section.
4 In the **Function name** text field, type `k`.
5 Click **Load from File**.
6 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_kAustenite.txt`.
7 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	degC

8 In the **Function** table, enter the following settings:

Function	Unit
k	W/(m*K)

Austenite (audcphase1mat)

1 In the **Model Builder** window, under **Global Definitions>Materials>Austenite (audcphase1mat)** click **Basic (def)**.
2 In the **Settings** window for **Basic**, locate the **Model Inputs** section.
3 Click **Select Quantity**.
4 In the **Physical Quantity** dialog box, select **General>Temperature (K)** in the tree.
5 Click **OK**.

Interpolation 2 (int2)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.
2 In the **Settings** window for **Interpolation**, locate the **Definition** section.
3 In the **Function name** text field, type `Cp`.
4 Click **Load from File**.
5 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_CpAustenite.txt`.
6 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	degC

7 In the **Function** table, enter the following settings:

Function	Unit
Cp	`J/(kg*K)`

Austenite (audcphase1mat)

1 In the **Model Builder** window, under **Global Definitions>Materials> Austenite (audcphase1mat)** click **Basic (def)**.

2 In the **Settings** window for **Basic**, locate the **Output Properties** section.

3 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	`k(T)`	W/(m·K)	3x3
Density	rho	`7930`	kg/m³	1x1
Heat capacity at constant pressure	Cp	`Cp(T)`	J/(kg·K)	1x1

4 In the **Model Builder** window, under **Global Definitions>Materials> Austenite (audcphase1mat)** click **Thermal expansion (ThermalExpansion)**.

5 In the **Settings** window for **Thermal Expansion**, locate the **Output Properties** section.

6 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Coefficient of thermal expansion	alpha_iso ; alphaii = alpha_iso, alphaij = 0	`2.2e-5`	1/K	3x3

7 In the **Model Builder** window, under **Global Definitions>Materials> Austenite (audcphase1mat)** click **Young's modulus and Poisson's ratio (Enu)**.

8 In the **Settings** window for **Young's Modulus and Poisson's Ratio**, locate the **Model Inputs** section.

9 Click + **Select Quantity**.

10 In the **Physical Quantity** dialog box, select **General>Temperature (K)** in the tree.

11 Click **OK**.

12 In the **Settings** window for **Young's Modulus and Poisson's Ratio**, locate the **Output Properties** section.

13 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Young's modulus	E	EYoung(T)	Pa	1x1
Poisson's ratio	nu	0.3	1	1x1

14 In the **Model Builder** window, under **Global Definitions>Materials>Austenite (audcphase1mat)** click **Elastoplastic material model (ElastoplasticModel)**.

15 In the **Settings** window for **Elastoplastic Material Model**, locate the **Model Inputs** section.

16 Click **Select Quantity**.

17 In the **Physical Quantity** dialog box, select **General>Temperature (K)** in the tree.

18 Click **OK**.

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `sY`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_sYAustenite.txt`.

6 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	degC

7 In the **Function** table, enter the following settings:

Function	Unit
sY	MPa

Interpolation 2 (int2)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Global>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 In the **Function name** text field, type `h`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `carburization_and_quenching_of_a_steel_gear_hardeningAustenite.txt`.

6 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
t	degC

7 In the **Function** table, enter the following settings:

Function	Unit
h	GPa

Austenite (audcphase1mat)

1 In the **Model Builder** window, under **Global Definitions>Materials> Austenite (audcphase1mat)** click **Elastoplastic material model (ElastoplasticModel)**.

2 In the **Settings** window for **Elastoplastic Material Model**, locate the **Output Properties** section.

3 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Initial yield stress	sigmags	sY(T)	Pa	1x1
Isotropic tangent modulus	Et	h(T)	Pa	1x1

Repeat the definitions of material properties for martensite.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies> Time Dependent**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

QUENCHING

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Quenching` in the **Label** text field.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Quenching** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 From the **Time unit** list, choose **min**.

4 In the **Output times** text field, type `range(0,0.1,10)`.

5 From the **Tolerance** list, choose **User controlled**.

6 In the **Relative tolerance** text field, type `0.001`.

7 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check box for **Carburization (carb)**.

8 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

9 From the **Method** list, choose **Solution**.

10 From the **Study** list, choose **Carburization, Time Dependent**.

11 From the **Time (h)** list, choose **Last**.

12 In the **Home** toolbar, click **Compute**.

RESULTS

Mirror 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Mirror 2D**.

2 In the **Settings** window for **Mirror 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Quenching/Solution 2 (sol2)**.

4 Locate the **Axis Data** section. From the **Axis entry method** list, choose **Point and direction**.

5 Find the **Direction** subsection. In the **Y** text field, type `0`.

6 In the **X** text field, type `1`.

Sector 2D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Sector 2D**.

2 In the **Settings** window for **Sector 2D**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 Locate the **Symmetry** section. In the **Number of sectors** text field, type `20`.

Carbon Concentration (carb)

1 In the **Model Builder** window, expand the **Results>Carbon Concentration (carb)** node, then click **Carbon Concentration (carb)**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

Surface 2

1 Right-click **Carbon Concentration (carb)** and choose **Surface**.

Create a backdrop depicting the whole spur gear.

2 Drag and drop **Surface 2** above **Surface 1**.

3 In the **Settings** window for **Surface**, locate the **Data** section.

4 From the **Dataset** list, choose **Sector 2D 1**.

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

7 From the **Color** list, choose **Gray**.

8 In the **Carbon Concentration (carb)** toolbar, click **Plot**.

Martensite Start Temperature

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 In the **Label** text field, type `Martensite Start Temperature`.

5 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

Surface 1

1 Right-click **Martensite Start Temperature** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Sector 2D 1**.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

6 Locate the **Title** section. From the **Title type** list, choose **None**.

Surface 2

1 In the **Model Builder** window, right-click **Martensite Start Temperature** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `Ms(carb.c)`.

4 From the **Unit** list, choose **degC**.

5 Select the **Description** check box. In the associated text field, type `Martensite Start Temperature`.

6 In the **Martensite Start Temperature** toolbar, click **Plot**.

Residual Stress

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Residual Stress` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Mirror 2D 1**.

4 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

Surface 1

1 Right-click **Residual Stress** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Data** section.

3 From the **Dataset** list, choose **Sector 2D 1**.

4 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

5 From the **Color** list, choose **Gray**.

6 Locate the **Title** section. From the **Title type** list, choose **None**.

Surface 2

1 In the **Model Builder** window, right-click **Residual Stress** and choose **Surface**.

2 In the **Settings** window for **Surface**, locate the **Expression** section.

3 In the **Expression** text field, type `solid.sp2Gp`.

4 In the **Residual Stress** toolbar, click **Plot**.