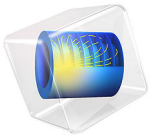

Welding of a Titanium Plate

Introduction

During welding of metals, the material will undergo phase transformations due to the thermal transients around the moving melt pool. In this example, welding of a titanium plate is considered. The titanium material is a heat treatable alpha-beta alloy, and the welding process is modeled using a double-ellipsoidal Goldak heat source (Ref. 1). The model shows how to define the temperature-dependent metallurgical phase transformations that are involved in this process, and how to compute the heterogeneous phase composition in the plate subsequent to a single weld pass.

Model Definition

The plate is 5 cm in length, 3.5 cm in width, and with a thickness of 5 mm. In this example, the plate is to be welded to a second, identical plate, along their lengths. Because of symmetry, only one plate is modeled. The plate is made from an alpha-beta titanium alloy. This is a class of materials that can be found in for example automotive and aerospace applications. The material modeled here represents a fictitious alloy, however the material properties and the phase transformation kinetics are representative of commercial alpha-beta titanium alloys.

MATERIAL PROPERTIES

The material properties of the alpha-beta alloy are temperature-dependent, and also phase composition dependent. The Alpha-Beta Phase Transformation physics interface automatically averages these properties into effective properties that define a compound material. The compound material is used in the thermal analysis.

PHASE TRANSFORMATION ANALYSIS

Thermal transients involving heating and cooling can give rise to different phase transformations in an alpha-beta titanium alloy. The Alpha-Beta Phase Transformation physics interface automatically sets up a beta phase and two alpha phases — Widmanstätten alpha, and Martensitic alpha, and then defines phase transformations relevant to cooling and to heating. The physics interface also generates several model parameters, such as transformation temperatures. As this model concerns a fictitious alpha-beta titanium alloy, these default values are used without modification. The phase transformations that need to be supplemented with phase transformation data are:

- Beta to Widmanstätten alpha
- Alpha (Widmanstätten alpha and Martensitic alpha) to beta
- Martensitic alpha to beta

- Martensitic alpha to Widmanstätten alpha
- Beta re-formation

In addition, the temperature dependent equilibrium fraction of alpha phase is required. The phase transformation data and the data for the equilibrium fraction of alpha phase are defined in text files that can be loaded as interpolation functions.

Beta to Widmanstätten Alpha

The transformation of beta phase into Widmanstätten alpha phase during cooling below the beta transus temperature is modeled using the JMAK phase transformation model. It is characterized using TTT data for the 1% and 50% transformation levels, here given as interpolation functions. The equilibrium phase fraction of the alpha phase is also given as an interpolation function. The TTT data and the equilibrium phase fraction data are taken from Salsi and others (Ref. 2); see Figure 1 and Figure 2

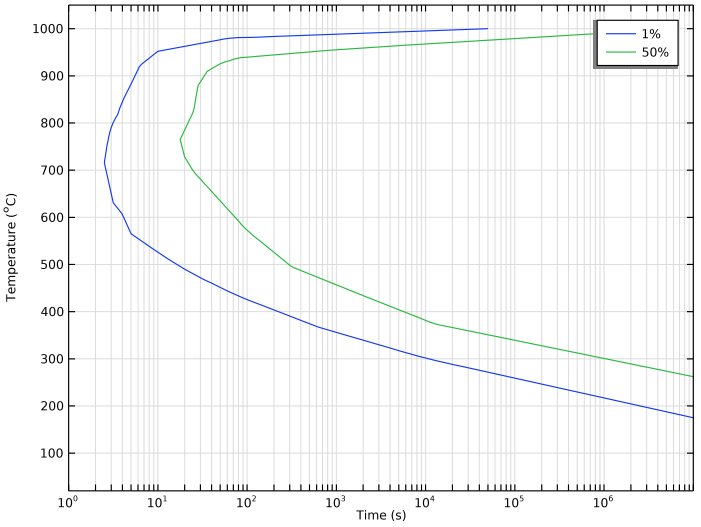

Figure 1: TTT data for the Beta to Widmanstätten alpha phase transformation.

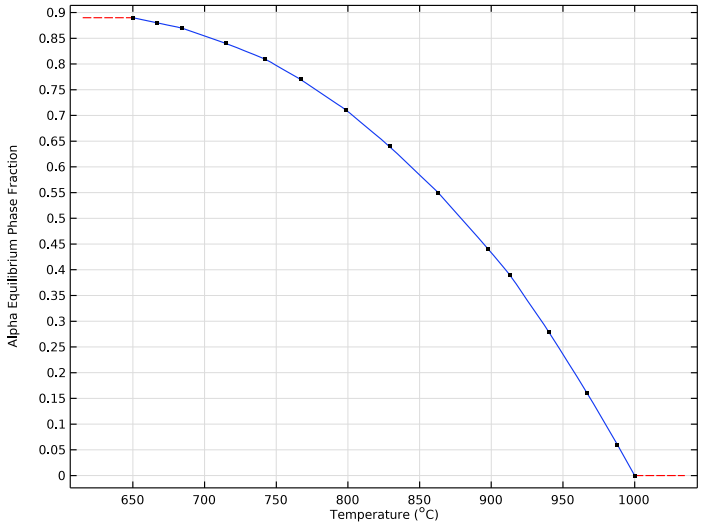

Figure 2: Equilibrium phase fraction for the alpha phase.

Alpha to Beta

The dissolution of alpha phase is modeled using the Hyperbolic rate phase transformation model. The temperature dependent data for the alpha dissolution is taken from Kelly (Ref. 3), where a power-law expression was used to describe a so-called parabolic thickening:

$$\alpha_{1,\,\mathrm{H},\,\mathrm{SS}}(T) \;=\; 2.20655 \times 10^{-31} \times T^{9.88821}$$

with the implied unit of $1/\mathrm{s}^{1/2}$, and the temperature in Kelvin. This analytical form for the data is converted into a numerically less challenging interpolation function $\mathrm{f}_{\mathrm{Diss}}(T)$, and when it is used to model the phase transformation using the Hyperbolic rate phase transformation model, the rate term becomes:

$$P_{\mathrm{s}\,\rightarrow\,\mathrm{d}} \;=\; \frac{1}{2} f_{\mathrm{Diss}}(T)^2$$

This phase transformation represents the simultaneous dissolution of Widmanstätten alpha and Martensitic alpha. This is accomplished using the **Additional source phase** subnode.

Martensitic Alpha to Beta & Martensitic Alpha to Widmanstätten Alpha

Above the martensite dissolution temperature, the Martensitic alpha phase dissolves into a combination of Widmanstätten alpha and beta phase. This transformation is modeled

using two separate **Phase transformation** nodes. The JMAK phase transformation model is used for each phase transformation, and TTT data is used to characterize the rate of dissolution. The amount of available data in the literature is scarce. Guided by the experimental work in Qazi and others (Ref. 4), the transformation is approximated with TTT data for 1% and 99% transformation levels, see Figure 3.

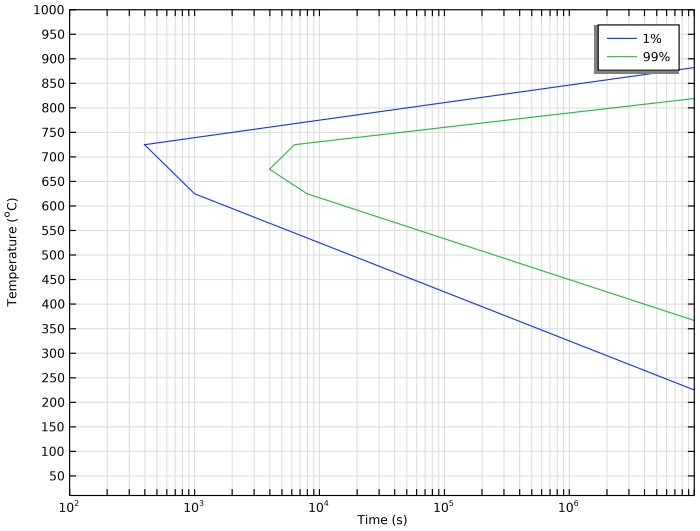

Figure 3: TTT data for the dissolution of Martensitic alpha.

Beta Re-Formation

When the temperature exceeds the beta transus temperature, the alpha phases dissolve to beta phase. Here, this phase transformation is simplified, as the objective is simply to "reset" the material above the beta transus. The JMAK phase transformation model is used, and a fixed time constant and Avrami constant are used. The **Additional Source Phase** subnode is used to include both alpha phases as source phases. If a more detailed description of the alpha dissolution is required, the phase transformation data would need a more careful definition.

THERMAL ANALYSIS

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

$$\rho C_p \dot{T} + \nabla \cdot (-k \nabla T) = Q$$

where T is the temperature, k represents the thermal conductivity, ρ denotes the density, C_p denotes the specific heat capacity, and Q is a heat source. The thermal conductivity, the density, and the specific heat capacity are in general temperature dependent, but in the presence of metallurgical phase transformations, they also depend on the current phase composition. In the present thermal analysis, phase transformation latent heat is neglected. Thus, the only heat source that contributes is that of the externally applied weld arc. The densities, specific heat capacities and heat conductivities of the individual phases are defined below. Note that the equations are solved on the material frame, meaning that the density of each phase is constant, corresponding to the density at the volume reference temperature. With regard to thermal conductivities, they are taken as linear functions of temperature. The specific heat is assumed to be equal across all three phases. Table 1 lists the thermal properties for the three phases. The temperature T is assumed to be in Kelvin.

TABLE 1: TEMPERATURE-DEPENDENT THERMAL MATERIAL PROPERTIES.

Phase	ρ	$\mathbf{C_p}$	**k**
Beta	4700kg/m^3	480J/(kg·K) + 0.24m/W · T	0.3W/(m·K) + 0.021m/W · T
Widmanstätten Alpha	4400kg/m^3	480J/(kg·K) + 0.24m/W · T	0.1W/(m·K) + 0.016m/W · T
Martensitic Alpha	4400kg/m^3	480J/(kg·K) + 0.24m/W · T	0.1W/(m·K) + 0.016m/W · T

During welding, the plate is subjected to a moving heat source that represents the weld arc. As the plate heats up, it also releases heat to the exterior through natural convection and thermal radiation.

The Goldak Double-Ellipsoid Heat Source

The center point of the weld arc moves along the X axis, at a velocity vel = 1 mm/s. Its current position is thus given by X_0 = vel·t. The heat source by Goldak is defined by two regions that join at X_0, and whose shapes are ellipsoidal. The widths a and depths b of these regions are equal, but the front and rear lengths, c_f and c_r, may differ, see Figure 4. The heat source is given by:

$$Q = \begin{cases} q_0 \exp\left(-3\left(\left(\frac{X-X_0}{c_f}\right)^2 + \left(\frac{Y}{a}\right)^2 + \left(\frac{Z}{b}\right)^2\right)\right) & X \geq X_0 \\ q_0 \exp\left(-3\left(\left(\frac{X-X_0}{c_r}\right)^2 + \left(\frac{Y}{a}\right)^2 + \left(\frac{Z}{b}\right)^2\right)\right) & X < X0 \end{cases}$$

where q_0 is the power density of the weld, given by

$$q_0 = Q_w \frac{6\sqrt{3} \cdot f_r}{a \cdot b \cdot c_r \cdot \pi\sqrt{\pi}} = Q_w \frac{6\sqrt{3} \cdot f_f}{a \cdot b \cdot c_f \cdot \pi\sqrt{\pi}}$$

where the weld power is Q_w = 800 W, a = 4 mm, b = 4 mm, cr = 8 mm, cf = 4 mm, and the condition that $f_r + f_f = 2$ gives $f_r = 4/3$ and $f_f = 2/3$.

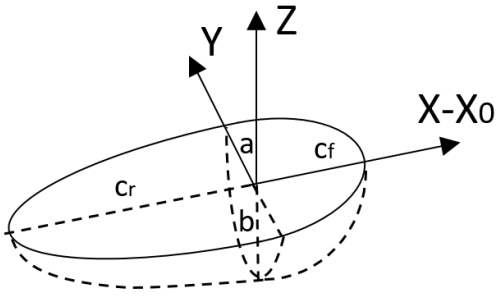

Figure 4: The Goldak double-ellipsoid.

Natural Convection

The convection of heat to the exterior is characterized by an assumed constant heat transfer coefficient of 10 W/(m^2·K).

Thermal Radiation

Thermal radiation is modeled using a surface emissivity of 0.4.

Results and Discussion

As the weld arc moves along the plate, it heats up the material. In reality, a melt pool forms, but this is not modeled here. Instead, we concern ourselves with solid state phase transformations that result from heating the material, and subsequently when the material cools. Figure 5 shows the phase composition evolution over time, halfway along the weld path. The initial composition is 89% Widmanstätten alpha phase, and 11% beta phase. As the temperature increases past the beta transus, the alpha phase dissolves into beta phase. As the weld arc passes, the material cools below the beta transus, and the beta phase transforms into Widmanstätten alpha. On further cooling below the Martensite start temperature, Martensitic alpha phase forms. This example involves a single weld pass. In a

situation of multiple weld passes, the phase composition will change with each weld pass. By performing simulations of so-called multi-pass welding, it is possible to gain insight into how the material develops in the heat affected zone (HAZ).

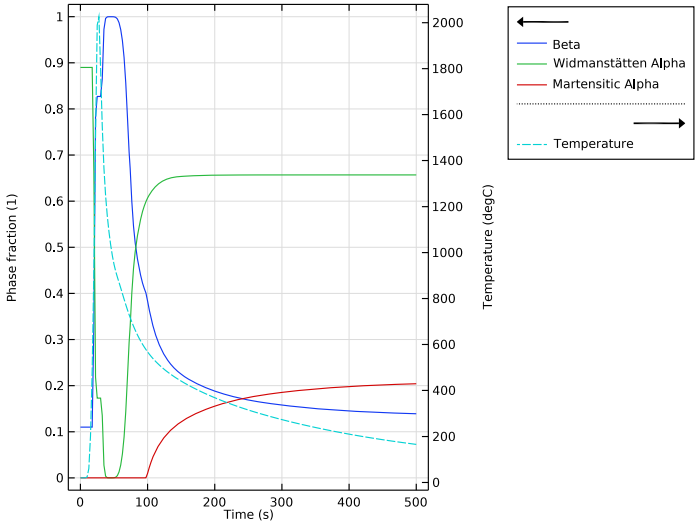

Figure 5: Phase composition evolution over time.

References

1. J. Goldak, A. Chakravarti, and M. Bibby, "A New Finite Element Model for Welding Heat Sources," *Metall. Trans. B*, vol. 15, pp. 299–305, 1984.

2. E. Salsi, M. Chiumenti, and M. Cervera, "Modeling of Microstructure Evolution of Ti6Al4V for Additive Manufacturing," *Metals*, vol. 8, pp. 633–657, 2018.

3. S.M. Kelly, *Thermal and Microstructure Modeling of Metal Deposition Processes with Application to Ti-6Al-4V*, PhD Thesis, Virginia Tech, 2004.

4. J.I. Qazi, O.N. Senkov, J. Rahim, and F.H. (Sam) Froes, "Kinetics of Martensite Decomposition in Ti-6Al-4V-xH alloys," *Mat. Sci. Engng.*, vol. A359, pp. 137–149, 2003.

Application Library path: `Metal_Processing_Module/Titanium_Phase_Transformations/welding_of_a_titanium_plate`

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 **3D**.

2 In the **Select Physics** tree, select **Heat Transfer>Heat Transfer in Solids (ht)** and **Heat Transfer>Metal Processing>Alpha-Beta Phase Transformation (abp)**.

3 Click **Add**.

4 Click **Study**.

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

6 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
Lx	5[cm]	0.05 m	Plate length
Ly	3.5[cm]	0.035 m	Plate width
Lz	5[mm]	0.005 m	Plate thickness
Qw	800[W]	800 W	Weld power
vel	1[mm/s]	0.001 m/s	Welding speed
a	4[mm]	0.004 m	Goldak ellipsoid width

Name	Expression	Value	Description
b	4[mm]	0.004 m	Goldak ellipsoid depth
cr	8[mm]	0.008 m	Goldak ellipsoid length, rear
cf	4[mm]	0.004 m	Goldak ellipsoid, front
fr	2/(cf/cr+1)	1.3333	Goldak parameter
ff	2-fr	0.66667	Goldak parameter
q0	6*sqrt(3)*fr*Qw/a/b/cr/pi/sqrt(pi)	1.5553E10 W/m³	Goldak power density

DEFINITIONS

Variables 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

2 Right-click **Definitions** and choose **Variables**.

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

4 In the table, enter the following settings:

Name	Expression	Unit	Description
X0	vel*t	m	Current weld arc position

Analytic 1 (an1)

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

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

3 In the **Expression** text field, type q0*exp(-3*(dX^2/C^2 + dY^2/A^2 + dZ^2/B^2)).

4 In the **Arguments** text field, type dX, dY, dZ, q0, A, B, C.

5 Locate the **Units** section. In the **Function** text field, type W/m^3.

6 In the table, enter the following settings:

Argument	Unit
dX	m
dY	m
dZ	m
q0	W/m^3

Argument	Unit
A	m
B	m
C	m

Interpolation 1 (int1)

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

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

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

4 Click **Load from File**.

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

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

Function	Unit
xieqAlpha	1

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

Argument	Unit
t	degC

Interpolation 2 (int2)

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

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

3 In the **Function name** text field, type `ttt1`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `welding_of_a_titanium_plate_ttt1.txt`.

6 Locate the **Interpolation and Extrapolation** section. From the **Extrapolation** list, choose **Linear**.

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

Function	Unit
ttt1	1

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

Argument	Unit
t	degC

Interpolation 3 (int3)

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

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

3 In the **Function name** text field, type `ttt50`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `welding_of_a_titanium_plate_ttt50.txt`.

6 Locate the **Interpolation and Extrapolation** section. From the **Extrapolation** list, choose **Linear**.

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

Function	Unit
ttt50	1

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

Argument	Unit
t	degC

Interpolation 4 (int4)

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

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

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

4 Click **Load from File**.

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

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

Function	Unit
fDiss	1

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

Argument	Unit
t	K

Interpolation 5 (int5)

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

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

3 In the **Function name** text field, type `ttt1m`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `welding_of_a_titanium_plate_ttt1m.txt`.

6 Locate the **Interpolation and Extrapolation** section. From the **Extrapolation** list, choose **Linear**.

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

Function	Unit
ttt1m	1

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

Argument	Unit
t	degC

Interpolation 6 (int6)

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

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

3 In the **Function name** text field, type `ttt99m`.

4 Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `welding_of_a_titanium_plate_ttt99m.txt`.

6 Locate the **Interpolation and Extrapolation** section. From the **Extrapolation** list, choose **Linear**.

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

Function	Unit
ttt99m	1

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

Argument	Unit
t	degC

The imported TTT data uses a logarithmic time axis, so we need to convert the data to use it in the phase transformation modeling.

Analytic 2 (an2)

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

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

3 In the **Expression** text field, type `10^ttt1(x)`.

4 Locate the **Units** section. In the **Function** text field, type `s`.

5 In the table, enter the following settings:

Argument	Unit
x	K

Analytic 3 (an3)

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

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

3 In the **Expression** text field, type `10^ttt50(x)`.

4 Locate the **Units** section. In the **Function** text field, type `s`.

5 In the table, enter the following settings:

Argument	Unit
x	K

Analytic 4 (an4)

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

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

3 In the **Expression** text field, type `10^ttt1m(x)`.

4 Locate the **Units** section. In the **Function** text field, type `s`.

5 In the table, enter the following settings:

Argument	Unit
x	K

Analytic 5 (an5)

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

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

3 In the **Expression** text field, type `10^ttt99m(x)`.

4 Locate the **Units** section. In the **Function** text field, type `s`.

5 In the table, enter the following settings:

Argument	Unit
x	K

GEOMETRY 1

Block 1 (blk1)

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Geometry 1** node.

2 Right-click **Geometry 1** and choose **Block**.

3 In the **Settings** window for **Block**, locate the **Size and Shape** section.

4 In the **Width** text field, type `Lx`.

5 In the **Depth** text field, type `Ly`.

6 In the **Height** text field, type `Lz`.

7 Locate the **Position** section. In the **z** text field, type `-Lz`.

8 Click to expand the **Layers** section. Find the **Layer position** subsection. Select the **Front** check box.

9 Clear the **Bottom** check box.

10 In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	0.2*Ly

11 Click **Build Selected**.

HEAT TRANSFER IN SOLIDS (HT)

Heat Source 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Heat Transfer in Solids (ht)** and choose **Heat Source**.

2 In the **Settings** window for **Heat Source**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All domains**.

4 Locate the **Heat Source** section. In the Q_0 text field, type `(X>=X0)*an1(X-X0,Y,Z,q0,a,b,cf) + (X<X0)*an1(X-X0,Y,Z,q0,a,b,cr)`.

Heat Flux 1

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

2 Select Boundaries 1, 3–5, and 7–11 only.

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

4 From the **Material type** list, choose **Solid**.

5 Locate the **Heat Flux** section. From the **Flux type** list, choose **Convective heat flux**.

6 In the h text field, type `10`.

Surface-to-Ambient Radiation 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Surface-to-Ambient Radiation**.

2 Select Boundaries 1, 3–5, and 7–11 only.

3 In the **Settings** window for **Surface-to-Ambient Radiation**, locate the **Surface-to-Ambient Radiation** section.

4 From the ε list, choose **User defined**. In the associated text field, type `0.4`.

ALPHA-BETA PHASE TRANSFORMATION (ABP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Alpha-Beta Phase Transformation (abp)**.

2 In the **Settings** window for **Alpha-Beta Phase Transformation**, locate the **Material Properties** section.

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

Beta

1 In the **Model Builder** window, under **Component 1 (comp1)>Alpha-Beta Phase Transformation (abp)** click **Beta**.

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.

Widmanstätten Alpha

1 In the **Model Builder** window, click **Widmanstätten Alpha**.

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.

Martensitic Alpha

1 In the **Model Builder** window, click **Martensitic Alpha**.

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.

Beta to Widmanstätten Alpha

1 In the **Model Builder** window, click **Beta to Widmanstätten Alpha**.

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

3 From the **Formulation** list, choose **TTT diagram data**.

4 In the ξ_{eq}^{d} text field, type `xieqAlpha(abp.T)`.

5 Find the **TTT curve 1** subsection. In the X_1 text field, type `0.01`.

6 In the t_1 text field, type `an2(abp.T)`.

7 Find the **TTT curve 2** subsection. In the X_2 text field, type `0.5`.

8 In the t_2 text field, type `an3(abp.T)`.

Alpha to Beta

1 In the **Model Builder** window, click **Alpha to Beta**.

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

3 In the $P_{s->d}$ text field, type `0.5*fDiss(abp.T)^2 * 1[1/s]`.

Martensitic Alpha to Beta

1 In the **Model Builder** window, click **Martensitic Alpha to Beta**.

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

3 From the **Formulation** list, choose **TTT diagram data**.

4 Find the **TTT curve 1** subsection. In the X_1 text field, type `0.01`.

5 In the t_1 text field, type `an4(abp.T)`.

6 Find the **TTT curve 2** subsection. In the X_2 text field, type `0.99`.

7 In the t_2 text field, type `an5(abp.T)`.

Martensitic Alpha to Widmanstätten Alpha

1 In the **Model Builder** window, click **Martensitic Alpha to Widmanstätten Alpha**.

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

3 From the **Formulation** list, choose **TTT diagram data**.

4 Find the **TTT curve 1** subsection. In the X_1 text field, type `0.01`.

5 In the t_1 text field, type `an4(abp.T)`.

6 Find the **TTT curve 2** subsection. In the X_2 text field, type `0.99`.

7 In the t_2 text field, type `an5(abp.T)`.

Beta Re-Formation

1 In the **Model Builder** window, click **Beta Re-Formation**.

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

3 From the **Phase transformation model** list, choose **Johnson-Mehl-Avrami-Kolmogorov (JMAK)**.

4 In the $\tau_{s \rightarrow d}$ text field, type `5`.

5 In the $n_{s \rightarrow d}$ text field, type `2`.

GLOBAL DEFINITIONS

Beta (abpphase1mat)

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

Analytic 1 (an1)

1 In the **Model Builder** window, expand the **Beta (abpphase1mat)** node.

2 Right-click **Global Definitions>Materials>Beta (abpphase1mat)>Basic (def)** and choose **Functions>Analytic**.

3 In the **Settings** window for **Analytic**, locate the **Definition** section.

4 In the **Arguments** text field, type `T`.

5 In the **Expression** text field, type `0.3+0.021*T`.

6 Locate the **Units** section. In the **Function** text field, type `W/m/K`.

7 In the table, enter the following settings:

Argument	Unit
T	K

8 In the **Function name** text field, type `k`.

Beta (abpphase1mat)

1 In the **Model Builder** window, under **Global Definitions>Materials>Beta (abpphase1mat)** 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

4 Locate the **Model Inputs** section. Click + **Select Quantity**.

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

6 Click **OK**.

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

8 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Density	rho	4700	kg/m³	1x1

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

2 In the **Settings** window for **Analytic**, type in the **Label** text field.

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

4 Locate the **Definition** section. In the **Arguments** text field, type `T`.

5 In the **Expression** text field, type `480+0.24*T`.

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

Argument	Unit
T	K

7 In the **Function** text field, type `J/kg/K`.

Beta (abpphase1mat)

1 In the **Model Builder** window, under **Global Definitions>Materials>Beta (abpphase1mat)** 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
Heat capacity at constant pressure	Cp	C(T)	J/(kg·K)	1x1

Analytic 1 (an1)

1 In the **Model Builder** window, expand the **Widmanstätten Alpha (abpphase2mat)** node.

2 Right-click **Global Definitions>Materials>Widmanstätten Alpha (abpphase2mat)> Basic (def)** and choose **Functions>Analytic**.

3 In the **Settings** window for **Analytic**, locate the **Definition** section.

4 In the **Arguments** text field, type `T`.

5 In the **Expression** text field, type `0.1+0.016*T`.

6 Locate the **Units** section. In the **Function** text field, type `W/m/K`.

7 In the table, enter the following settings:

Argument	Unit
T	K

8 In the **Function name** text field, type `k`.

Widmanstätten Alpha (abpphase2mat)

1 In the **Model Builder** window, under **Global Definitions>Materials> Widmanstätten Alpha (abpphase2mat)** 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

4 Locate the **Model Inputs** section. Click + **Select Quantity**.

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

6 Click **OK**.

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

8 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Density	rho	4400	kg/m³	1x1

Analytic 2 (an2)

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

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

3 Locate the **Definition** section. In the **Arguments** text field, type `T`.

4 In the **Expression** text field, type `480+0.24*T`.

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

Argument	Unit
T	K

6 In the **Function** text field, type `J/kg/K`.

Widmanstätten Alpha (abpphase2mat)

1 In the **Model Builder** window, under **Global Definitions>Materials> Widmanstätten Alpha (abpphase2mat)** 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
Heat capacity at constant pressure	Cp	`C(T)`	J/(kg·K)	Ix1

Analytic 1 (an1)

1 In the **Model Builder** window, expand the **Martensitic Alpha (abpphase3mat)** node.

2 Right-click **Global Definitions>Materials>Martensitic Alpha (abpphase3mat)>Basic (def)** and choose **Functions>Analytic**.

3 In the **Settings** window for **Analytic**, locate the **Definition** section.

4 In the **Arguments** text field, type `T`.

5 In the **Expression** text field, type `0.1+0.016*T`.

6 Locate the **Units** section. In the **Function** text field, type `W/m/K`.

7 In the table, enter the following settings:

Argument	Unit
T	K

8 In the **Function name** text field, type `k`.

Martensitic Alpha (abpphase3mat)

1 In the **Model Builder** window, under **Global Definitions>Materials> Martensitic Alpha (abpphase3mat)** 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

4 Locate the **Model Inputs** section. Click + **Select Quantity**.

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

6 Click **OK**.

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

8 In the table, enter the following settings:

Property	Variable	Expression	Unit	Size
Density	rho	4400	kg/m³	1x1

Analytic 2 (an2)

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

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

3 Locate the **Definition** section. In the **Arguments** text field, type `T`.

4 In the **Expression** text field, type `480+0.24*T`.

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

Argument	Unit
T	K

6 In the **Function** text field, type `J/kg/K`.

Martensitic Alpha (abpphase3mat)

1 In the **Model Builder** window, under **Global Definitions>Materials>Martensitic Alpha (abpphase3mat)** 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
Heat capacity at constant pressure	Cp	C(T)	J/(kg·K)	1x1

MESH 1

Mapped 1

1 In the **Mesh** toolbar, click  **Boundary** and choose **Mapped**.

2 Select Boundary 1 only.

Size 1

1 Right-click **Mapped 1** and choose **Size**.

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

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

Free Quad 1

1 In the **Mesh** toolbar, click  **Boundary** and choose **Free Quad**.

2 Select Boundary 5 only.

Size 1

1 Right-click **Free Quad 1** and choose **Size**.

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

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

Swept 1

In the **Mesh** toolbar, click  **Swept**.

Size 1

1 Right-click **Swept 1** and choose **Size**.

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

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

4 Click  **Build All**.

STUDY 1

Step 1: Time Dependent

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

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

3 In the **Output times** text field, type `range(0,2.5,500)`.

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

RESULTS

Cut Point 3D 1

1 In the **Results** toolbar, click **Cut Point 3D**.

2 In the **Settings** window for **Cut Point 3D**, locate the **Point Data** section.

3 In the **X** text field, type `Lx/2`.

4 In the **Y** text field, type `0`.

5 In the **Z** text field, type `0`.

6 From the **Snapping** list, choose **Snap to closest edge**.

7 Click **Plot**.

1D Plot Group 6

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Cut Point 3D 1**.

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

5 Locate the **Plot Settings** section. Select the **Two y-axes** check box.

6 Locate the **Legend** section. From the **Layout** list, choose **Outside graph axis area**.

Point Graph 1

1 Right-click **1D Plot Group 6** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Alpha-Beta Phase Transformation>Phase composition>abp.phase1.xi - Phase fraction**.

3 Click to expand the **Legends** section. Select the **Show legends** check box.

4 From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Beta

Point Graph 2

1 In the **Model Builder** window, right-click **1D Plot Group 6** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Alpha-Beta Phase Transformation>Phase composition>abp.phase2.xi - Phase fraction**.

3 Locate the **Legends** section. Select the **Show legends** check box.

4 From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Widmanstätten Alpha

Point Graph 3

1 Right-click **1D Plot Group 6** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Alpha-Beta Phase Transformation>Phase composition>abp.phase3.xi - Phase fraction**.

3 Locate the **Legends** section. Select the **Show legends** check box.

4 From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Martensitic Alpha

Point Graph 4

1 Right-click **1D Plot Group 6** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **y-Axis** section.

3 Select the **Plot on secondary y-axis** check box.

4 Locate the **y-Axis Data** section. From the **Unit** list, choose **degC**.

5 Locate the **Legends** section. Select the **Show legends** check box.

6 From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
Temperature

8 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

9 In the **1D Plot Group 6** toolbar, click **Plot**.