



# Metal Processing Module

User's Guide

# Metal Processing Module User's Guide

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# Introduction

This guide describes the Metal Processing Module, an optional add-on package for the COMSOL Multiphysics® simulation software. The module is designed to perform transient analyses of processes involving metallurgical (solid-solid) phase transformations in, mainly, steels. This chapter introduces you to the capabilities of the Metal Processing Module and includes a summary of the physics interfaces and where you can find the documentation.

In this chapter:

- [About the Metal Processing Module](#)

# About the Metal Processing Module

In this section:

- [What Can the Metal Processing Module Do?](#)
- [Where Do I Access the Documentation and Application Libraries?](#)

## *What Can the Metal Processing Module Do?*

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The Metal Processing Module can be used to model different physical phenomena related to heat treatment of metals. Using this module, you can study how metallurgical phase transformations change the microstructure of a metallic material during a heating or cooling process. One example is the quenching of automotive steel transmission components, where the resulting microstructure is tailored to meet specific demands on strength and durability. Other examples include the study of phase transformations that occur during additive manufacturing of metal components and phase transformations in the heat-affected zone during welding.

There are four physics interfaces in the Metal Processing Module:

- The *Metal Phase Transformation* interface for studying diffusive and displacive metallurgical phase transformations in steels.
- The *Austenite Decomposition* interface for specifically studying the cooling of steel from an austenitic state.
- The *Heat Transfer with Phase Transformations* interface for modeling thermal processes involving metallurgical phase transformations.
- The *Steel Quenching* interface for modeling coupled thermal and mechanical processes involving metallurgical phase transformations.

Throughout the *Metal Processing User's Guide*, the Metal Phase Transformation and Austenite Decomposition physics interfaces are collectively referred to as *phase transformation* physics interfaces.

The physics interfaces in the Metal Processing Module can be added from the Model Wizard's **Select Physics** page under **Heat Transfer>Metal Processing**. The physics interfaces can also be added by right-clicking a **Component** node and selecting **Add Physics**.



## *Where Do I Access the Documentation and Application Libraries?*

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### **ACCESSING THE METAL PROCESSING MODULE DOCUMENTATION**

The Metal Processing Module feature information, including theory and modeling details, is included in the *Metal Processing Module User's Guide*.

When you install COMSOL Multiphysics, the documentation sets are installed in several locations, both on your computer and most easily accessible while you are working in COMSOL Multiphysics. The next section details where to access it.

### **ACCESSING COMSOL DOCUMENTATION AND APPLICATION LIBRARIES**

A number of internet resources have more information about COMSOL, including licensing and technical information. The electronic documentation, topic-based (or context-based) help, and the application libraries are all accessed through the COMSOL Desktop.



If you are reading the documentation as a PDF file on your computer, the [blue links](#) do not work to open an application or content referenced in a different guide. However, if you are using the Help system in COMSOL Multiphysics, these links work to open other modules, application examples, and documentation sets.

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# Overview of the User's Guide

## **TABLE OF CONTENTS AND INDEX**

To help you navigate this guide, see the Contents and Index sections.

## **MODELING WITH THE METAL PROCESSING MODULE**

The Metal Processing Modeling chapter discusses how to model different problems involving phase transformations. The content covers the topics Selecting Physics Interfaces, Study Types, Modeling Phase Transformations, Defining Multiphysics Models, Selecting Discretizations, and Using Effective Material Properties.

## **METAL PROCESSING THEORY**

The Metal Processing Theory chapters outlines the theory for the interfaces present in the Metal Processing Module. The chapter covers the topics Metallurgical Phase Transformations, Compound Material Properties, Phase Transformation Strains, and Phase Transformation Latent Heat.

## **THE METAL PHASE TRANSFORMATION INTERFACE**

The Metal Phase Transformation chapter describes the Metal Phase Transformation interface and its feature nodes.

## **THE AUSTENITE DECOMPOSITION INTERFACE**

The Austenite Decomposition chapter describes the Austenite Decomposition interface and how it is based on the Metal Phase Transformation Interface.

## **MULTIPHYSICS INTERFACES AND COUPLINGS**

The Multiphysics Interfaces and Couplings chapter describes two multiphysics interfaces found under the Metal Processing branch when adding a physics interface:

- The Heat Transfer with Phase Transformations interface combines a Metal Phase Transformation interface with a Heat Transfer in Solids interface. The coupling of the interfaces appears on a domain level, where produced latent heat from the (temperature-dependent) phase transformations gives rise to a heat source in the heat equation. Optionally, phase-composition-dependent thermal material properties can be used in the heat transfer analysis.
- The Steel Quenching Interface combines an Austenite Decomposition interface with a Heat Transfer in Solids interface and a Solid Mechanics interface. There are two domain-level multiphysics couplings: In the first coupling, produced latent heat

from the (temperature-dependent) phase transformations gives rise to a heat source in the heat equation. In the second coupling, phase transformation strains that result from thermal expansion or transformation-induced plasticity (TRIP) are transferred to the Solid Mechanics interface as inelastic strain contributions for the computation of stresses. In the case of plasticity, the coupling also involves equivalent plastic strains and hardening functions. Optionally, phase-composition-dependent thermal and mechanical properties can be used in the heat transfer and solid mechanics analyses.

- The Phase Transformation Latent Heat multiphysics coupling adds the latent heat that is produced during phase transformations, as a heat source term, to the heat equation in a Heat Transfer interface.
- The Phase Transformation multiphysics coupling adds the transformation strains that are produced during phase transformations, as an inelastic strain contribution, to the equation for stress in a Solid Mechanics interface. The coupling also transfers stresses and the equivalent plastic strain from a Solid Mechanics interface to the coupled phase transformation interface.

# Metal Processing Modeling

The goal of this chapter is to show you how to model different problems involving phase transformations in steels and how to include various physical phenomena that may be relevant in specific situations.

In this chapter:

- [Selecting Physics Interfaces](#)
- [Study Types](#)
- [Modeling Phase Transformations](#)
- [Defining Multiphysics Models](#)
- [Selecting Discretizations](#)
- [Using Effective Material Properties](#)

# Selecting Physics Interfaces

The Metal Processing Module contains two basic physics interfaces and two multiphysics interfaces:

- [Metal Phase Transformation](#) — For modeling general metallurgical phase transformations
- [Austenite Decomposition](#) — For modeling the specific case of austenite decomposing into a combination of destination phases, on cooling

## *Metal Phase Transformation*

---

The Metal Phase Transformation interface provides a basic way to model phase transformations in metals. Three common models for phase transformations in steels are provided. The Leblond–Devaux and Johnson–Mehl–Avrami–Kolmogorov (JMAK) models are used to model time-dependent (diffusion-controlled) phase transformations, such as the transformation of austenite into pearlite during steel hardening. In contrast, the Koistinen–Marburger model is used to model the transformation of austenite into martensite, where the amount of undercooling below the so-called martensite start temperature controls the formation of martensite. In addition to these three types of phase transformations, you can define your own phase transformation models and let them coexist with other active phase transformations in your analysis. You can use an arbitrary number of phase transformations in a model. The Metal Phase Transformation interface lets you generate a compound material whose properties are phase composition dependent. This material can be used by other physics interfaces, such as Solid Mechanics and Heat Transfer in Solids.



- [Modeling Phase Transformations](#)
  - [Metallurgical Phase Transformations](#)
- 

## *Austenite Decomposition*

---

The Austenite Decomposition interface is a specialized interface that considers hardening of steel from an austenitic state. During hardening of steels, the material is heated above the austenitizing temperature. It is then cooled, and depending on the rate of cooling, a combination of destination phases such as ferrite, pearlite, bainite, and martensite can form. The Austenite Decomposition interface automatically creates

corresponding phase nodes and phase transformation nodes. You can also define an arbitrary number of additional phases and phase transformations. Optionally, you can define your own phase transformation models and let them coexist with other active phase transformations in the analysis. The Austenite Decomposition interface lets you generate a compound material whose properties are phase-composition dependent. This material can be used by other physics interfaces, such as Solid Mechanics and Heat Transfer in Solids.



- [Modeling Phase Transformations](#)
  - [Metallurgical Phase Transformations](#)
-

# Study Types

Metallurgical Phase transformations are inherently time dependent. Phase transformations are defined by a set of ordinary differential equations in time, and the only supported study type is therefore Time Dependent.



In the *COMSOL Multiphysics Reference Manual*:

- [Time-Dependent Solver](#)
- [Studies and Solvers](#)



# Modeling Phase Transformations

This section describes how to model metallurgical solid-solid phase transformations. When you simulate processes such as hardening of steel, these phase transformations are fundamental because they ultimately determine the final properties of the material. In the Metal Phase Transformation and Austenite Decomposition interfaces, each phase transformation is defined by a certain evolution equation that defines the time rate of change of the algebraic proportion of a destination phase at the expense of a source phase. In the following, the two modeling concepts of phases and phase transformations are discussed.

## *Metallurgical Phases*

---

When you model phase transformations in a material, each transformation defines how a source phase transforms into a destination phase as a function of time. When you create a metallurgical phase node, you have to define its initial phase fraction. This is the value from which the phase fraction evolves during the analysis.

You have the option, at the physics interface level, to compute effective thermal and mechanical properties for the compound material. If you have opted to do this, you also need to define the corresponding properties of each phase. At each phase node, you can choose to create a component-level phase material. This material can be populated with properties that define the behavior of the phase. The phase material properties are averaged (phase-fraction averaged) into effective material properties of a compound material that can be used in other physics interfaces. This is described in [Using Effective Material Properties](#).

## *Phase Transformations*

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When you have created a phase transformation node, you have to choose a source phase and a destination phase. These are the two phases that are involved in the phase transformation. You then have to define a phase transformation model which defines the underlying type of phase transformation. The phase transformation models are described below.

### **THE LEBLOND-DEVAUX MODEL**

Phase transformations in steels are based on diffusion of carbon, and the Leblond-Devaux phase transformation model is suitable to model this. You can choose between

two formulations for the model — **General coefficients** or **Time and equilibrium**. Both these formulations require generally temperature-dependent functions that determine the characteristics of the phase transformation. The functions will be different for different phase transformations.



#### The Leblond-Devaux Model

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#### THE JOHNSON-MEHL-AVRAMI-KOLMOGOROV (JMAK) MODEL

This model can be viewed as a generalization of the **Time and equilibrium** form of the Leblond-Devaux model. In addition to the generally time-dependent functions describing the equilibrium phase fraction and the time constant, a time-dependent exponent is used. The exponent is called the Avrami exponent, and it alters the characteristic of the phase transformation.



#### The Johnson-Mehl-Avrami-Kolmogorov (JMAK) Model

---

#### THE KOISTINEN-MARBURGER MODEL

This phase transformation model is suitable to model the displacive martensitic transformation in steel, on rapid cooling. The **Martensite start temperature**  $M_s$  can be experimentally obtained from dilatometry experiments. If the integrated form of the phase transformation model is used ([Equation 3-7](#)), a value for the **Koistinen-Marburger coefficient**  $\beta$  can be correlated to the temperature at which the martensitic transformation is considered complete (see, for example, [Ref. 8](#)). The **Martensite start temperature smoothing** is used to numerically smoothen the otherwise sudden onset of the martensitic transformation.



#### The Koistinen-Marburger Model

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For an example how to model phase transformations, see *Phase Transformations in a Round Bar*: Application Library path **Metal\_Processing\_Module/Tutorial\_Examples/phase\_transformations\_in\_a\_round\_bar**.

### *Calibration of Phase Transformation Models*

During a thermal transient, a material point may undergo varying rates of cooling and heating. During this transient, several phase transformations can be active at the same time. This suggests that it is difficult to calibrate phase transformation models individually, as they tend to affect one another. It is common in practice to present the complicated nature of the austenite decomposition as continuous cooling transformation (CCT) or time-temperature transformation (TTT) diagrams; see [Figure 2-1](#) and [Figure 2-2](#) for schematic examples. Both diagrams show the start temperatures for the formation of a small fraction of different phases ( $F_s$  for the start temperature of ferrite, and so on). The fraction can be chosen arbitrarily but is often 0.1% or 1%. The difference between the two diagram types, as their names imply, is the following:

- A CCT diagram is constructed by performing experiments where a small specimen is cooled at a specified, constant, *temperature rate*.
- A TTT diagram is constructed by performing experiments where a small specimen is rapidly cooled to a temperature  $T_0$  that is subsequently kept constant.

One method to measure the actual start temperatures required to draw each diagram is to use dilatometry experiments. Metallurgical phase transformations are accompanied by a change in volume, owing to the density difference between phases. In a dilatometer, a specimen is cooled (or heated), and its length is monitored. The specimen length will change according to basic thermal expansion, but phase transformations will induce additional length changes that can be measured.

In a real quenching situation, it is clear that material points do not experience either of the two extremes represented by the CCT and TTT diagrams (constant temperature rate versus constant temperature). Nevertheless, because experimentally obtained CCT and TTT diagrams are very common in the heat treatment community, phase transformation models must in practice be calibrated using them.

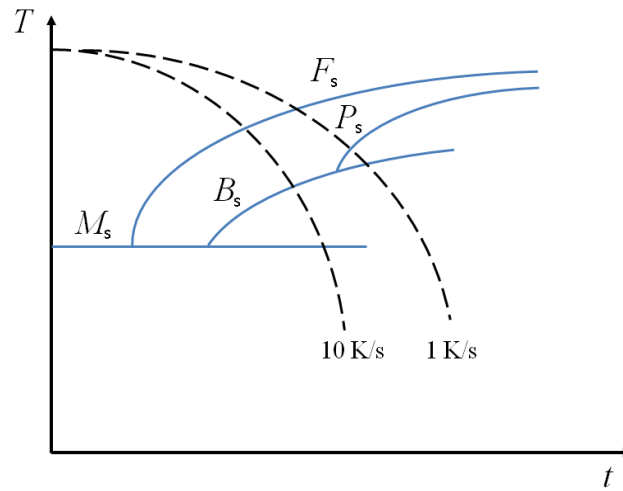
It is here useful to examine one form for the Leblond–Devaux model:

$$\xi^d = \frac{\xi_{eq}^d - \xi^d}{\tau_{s \rightarrow d}}$$

In this equation, the phase fraction for the destination phase tends toward an equilibrium value  $\xi_{eq}^d$ , and the rate at which this occurs is characterized by the time constant  $\tau_{s \rightarrow d}$ . Note here that the equilibrium phase fraction and the time constant are in general both temperature dependent, and that temperature in turn varies with time. At constant temperature, the equation can be integrated analytically, giving

$$\xi^d = \xi_{eq}^d \left( 1 - \exp\left(-\frac{t}{\tau_{s \rightarrow d}}\right) \right)$$

The equilibrium phase fraction can be deduced from an (equilibrium) iron-carbon diagram (Ref. 1) or from dilatometry experiments at a very low temperature rate (or at constant temperature after a rapid temperature drop). If the equilibrium phase fraction is known at a certain temperature, the TTT diagram can be used to compute the time constant at that temperature because it shows the time required to form a known small fraction (0.1% or 1%) of the phase. In this sense, a TTT diagram is easier to use for phase transformation model calibration than a CCT diagram. However, given a set of phase transformation model data, it is straightforward to compute both types of diagrams and to make adjustments to the data based on the computed diagrams. It is sometimes necessary to iterate in this manner to find a sufficiently accurate set of data.



*Figure 2-1: A CCT diagram showing how phases appear during cooling at two different rates. The temperatures corresponding to 1% formed fraction of ferrite, pearlite, and bainite are shown. The martensite start temperature is shown as a straight line. The time is shown on a logarithmic axis.*

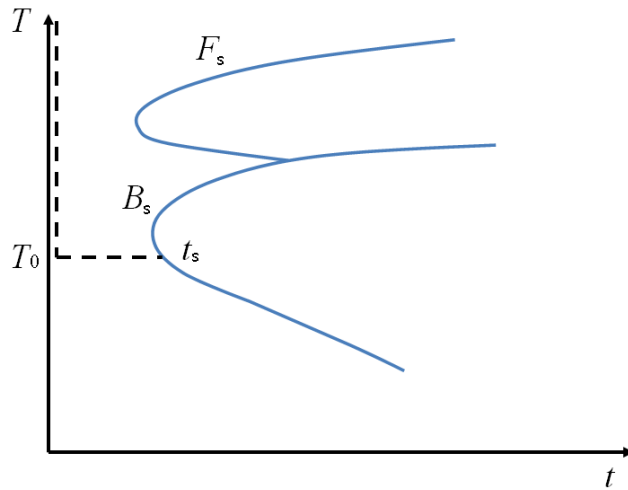


Figure 2-2: A TTT diagram showing how the temperature is rapidly decreased to a fixed value  $T_0$  and then kept constant.



For an example how to compute CCT and TTT diagrams, see *Transformation Diagram Computation*: Application Library path **Metal\_Processing\_Module/Austenite\_Decomposition/transformation\_diagram\_computation**.

# Defining Multiphysics Models

This chapter describes how to couple the phase transformation interfaces to the Heat Transfer in Solids and Solid Mechanics interfaces. A good place to start reading is in [Building a COMSOL Multiphysics Model](#) in the *COMSOL Multiphysics Reference Manual*.

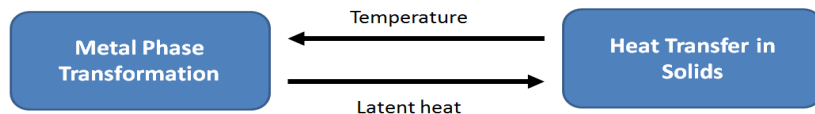
In this chapter:

- [Heat Transfer with Phase Transformations](#) — For modeling phase transformations coupled to heat transfer.
- [Steel Quenching](#) — For modeling the specific case of austenite decomposition coupled to heat transfer and solid mechanics.
- [Phase Transformation Latent Heat](#) — A predefined one-way coupling that adds latent heat from phase transformations as a heat source term in the coupled heat transfer interface.
- [Phase Transformation Strain](#) — A predefined two-way coupling that is used to transfer strains and stresses to, and from, the coupled solid mechanics interface.

## *Heat Transfer with Phase Transformations*

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The Heat Transfer with Phase Transformations multiphysics interface combines the Metal Phase Transformation interface with the Heat Transfer in Solids interface. Phase transformations are generally temperature dependent, and this interface is a suitable starting point for modeling metallurgical phase transformations that occur during a thermal transient. Latent heat is generated during phase transformations, and the interface transfers this generated heat to the heat equation that is used by the Heat Transfer in Solids interface, as shown in [Figure 2-3](#). This is done using the one-way [Phase Transformation Latent Heat](#) multiphysics coupling.



*Figure 2-3: The constituent interfaces of the Heat Transfer with Phase Transformations interface*

## *Steel Quenching*

---

The Steel Quenching multiphysics interface combines the Austenite Decomposition interface with the Heat Transfer in Solids and the Solid Mechanics interfaces. This is the most specialized interface of the Metal Processing Module. It can be used to study heat treatment processes by which steel parts, which have been heated to a fully austenitic state, are quenched. The multiphysics interface couples the constituent interfaces so that effects of latent heat and phase transformation strains can be included in the analysis. Phase compositions, distortions, and residual stresses can be computed using the Steel Quenching multiphysics interface. [Figure 2-4](#) shows how this information is passed to, and from, the Austenite Decomposition interface. Note that, for example, material properties used in Solid Mechanics can be temperature dependent, and that plastic dissipation can act as a heat source in Heat Transfer in Solids (this is not shown in [Figure 2-4](#)). The Steel Quenching multiphysics interface



uses the one-way [Phase Transformation Latent Heat](#) multiphysics coupling and the two-way [Phase Transformation Strain](#) multiphysics coupling.

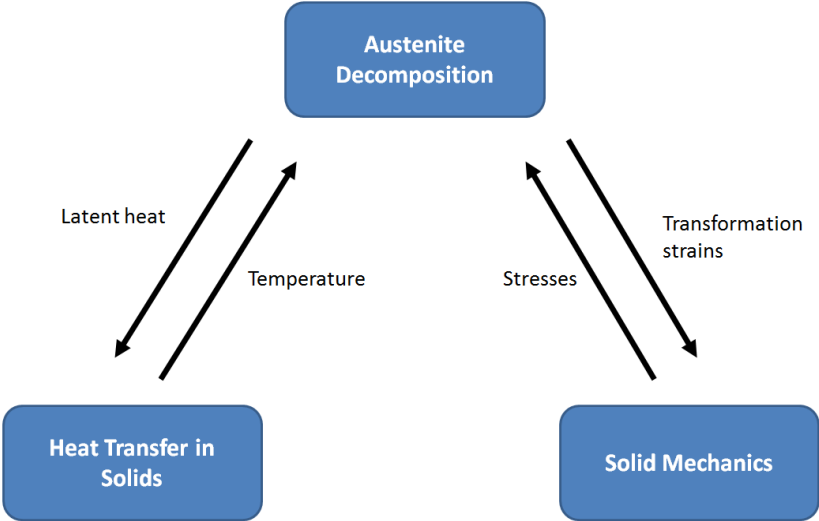


Figure 2-4: The constituent interfaces of the Steel Quenching interface.



For an example how to use the Steel Quenching interface, see *Carburization and Quenching of a Steel Gear*: Application Library path **Metal\_Processing\_Module/Steel\_Quenching/carburization\_and\_quenching\_of\_a\_steel\_gear**.

### *Phase Transformation Latent Heat*

This one-way multiphysics coupling generates a heat source term in the heat equation of the coupled Heat Transfer in Solids interface. The heat source term corresponds to the latent heat produced during phase transformations.



See [Phase Transformation Latent Heat](#) in the Metal Processing Theory.

## *Phase Transformation Strain*

---

This two-way multiphysics coupling is used to transfer strains and stresses to, and from, the coupled Solid Mechanics interface.

- If **Enable transformation-induced plasticity** is selected, the stress tensor from the Solid Mechanics interface is used to compute TRIP strains during phase transformations. These strains are used by the Solid Mechanics interface as an inelastic strain contribution.
- If **Enable thermal strains** is selected, the thermal strains are used by the Solid Mechanics interface as an inelastic contribution.



When you use this coupling, you should not use the [Thermal Expansion](#) node to compute thermal strains to be used in the Solid Mechanics interface.

---

- If **Enable phase plasticity** is selected, and if the **Plasticity** subnode under **Linear Elastic Material** is used by the coupled Solid Mechanics interface, the equivalent plastic strain is transferred to the phase transformation interface. This way, the individual hardening function for each phase can be evaluated.

# Selecting Discretizations

The Metal Phase Transformation and Austenite Decomposition interfaces provide discretization settings — **Discretization for phase fractions** and **Discretization for displacements**. The former sets the shape function order for the phase fractions, and it should match the settings for the temperature field used by the Heat Transfer in Solids interface. The latter sets the shape function order for strains. There are two types of strains that this setting affects:

- Phase transformation strains (that is, the thermal strains and TRIP strains)
- Equivalent plastic strains of the phases

Both of these strains are intrinsically related to strains used by a coupled Solid Mechanics interface. The **Discretization for displacements** setting should therefore match the discretization order for the displacement field used in the Solid Mechanics interface. For example, if the Solid Mechanics interface uses a quadratic shape function order for its displacement field, the **Discretization for displacements** should be quadratic.

Both discretization types are set to quadratic by default to match the default settings of the Heat Transfer in Solids and Solid Mechanics interfaces.

# Using Effective Material Properties

When a material undergoes phase transformations during a thermal transient, its material properties will change. The properties are typically temperature dependent and tend to be phase dependent, too. For example, the initial yield stress at a given temperature will be higher in martensite than in ferrite — two metallurgical phases that appear during hardening of steel. When the Metal Phase Transformation or Austenite Decomposition interface is used with Heat Transfer in Solids or Solid Mechanics, it can compute effective material properties that can be utilized by these interfaces. The benefit is that the Heat Transfer in Solids and Solid Mechanics interfaces themselves do not need to perform phase averaging of the material properties that are used.

You can generate a compound material that can be used by other physics interfaces as a domain material. The compound material is created if you use the **Create Compound Material** option at the physics interface level. This material contains effective material properties that are computed from the corresponding material properties defined for each phase.



## Compound Material Properties



Note that if **Enable phase plasticity** has been selected at the physics interface level, the **User defined** option should be used for the **Isotropic hardening model** in the **Plasticity** node in Solid Mechanics.

# References

1. T. Holm, P. Olsson, and E. Troell (Eds.), “Steel and its heat treatment — A handbook”, *Swerea IVE*, Mölndal, 2012.



# Metal Processing Theory

This chapter introduces you to the theory for the Metal Processing Module.

In this chapter:

- Metallurgical Phase Transformations
- Phase Transformation Strains
- Phase Transformation Latent Heat
- Compound Material Properties

# Metal Phase Transformation Theory

In the following, the theory for the Metal Phase Transformation physics interface is described. This section also covers the theory for the Austenite Decomposition physics interface. These physics interfaces can be used to model metallurgical phase transformations in metals. They can be coupled to Heat Transfer in Solids and Solid Mechanics, where, for example, quenching of steel components can be performed.



# Metallurgical Phase Transformations

## Definitions

The material consists of a number of metallurgical phases. The fraction of each phase  $i$  is denoted  $\xi^i$ . There are in general  $N$  phases, where

$$\sum_{i=1}^N \xi^i = 1$$

The initial phase fraction must be defined for each phase, and the sum of initial phase fractions should be one. At the onset of an analysis, some phases may not be present, and have zero initial phase fraction.



- The phase fractions are defined in the material frame.
- Because of the employed weighting scheme for the effective mass density of the compound material, the phase fractions become algebraic fractions.
- See [Compound Material Properties](#).

Each phase transformation describes how a source phase  $s$  transforms into a destination phase  $d$ . A phase transformation is formally defined by the rate  $A_{s \rightarrow d}$  at which the destination phase  $d$  forms at the expense of the source phase  $s$ . This can be expressed as

$$A_{s \rightarrow d} = \dot{\xi}^d = -\dot{\xi}^s \quad (3-1)$$

Note that this equation describes only a single contribution to the total rates at which the destination phase forms, and the source phase decomposes. With several simultaneous phase transformations, some phases may receive more than one contribution. As an example, consider the case of three phases and two phase transformations, where phase 1 transforms into phases 2 and 3. Using the terminology above, the total rate equations for the three phases can be expressed as

$$\dot{\xi}^1 = -A_{1 \rightarrow 2} - A_{1 \rightarrow 3}$$

$$\dot{\xi}^2 = A_{1 \rightarrow 2}$$

$$\dot{\xi}^3 = A_{1 \rightarrow 3}$$

Note that these rate equations satisfy

$$\sum_{i=1}^N \dot{\xi}^i = 0$$

In COMSOL Multiphysics, a weak contribution is generated for each phase  $i$ :

$$\left( \dot{\xi}^i - \sum_j A_{j \rightarrow i} \right) \delta \xi^i$$

where the summation is done over every phase transformation for which phase  $j$  transforms into phase  $i$ .

### *Phase Transformation Models*

---

In this section, the different types of phase transformations are described.

#### **THE LEBLOND–DEVAUX MODEL**

This phase transformation model is based on the work of Leblond and Devaux (Ref. 1). The model primarily considers carbon-diffusion-based phase transformations that occur in steels during heat treatment. Such transformations include austenite to ferrite, and austenite to bainite. There are two forms for the Leblond–Devaux model:

- General coefficients
- Time and equilibrium

#### *General coefficients*

Using this form, the transformation of a source phase into a destination phase is given by

$$\dot{\xi}^d = K_{s \rightarrow d} \xi^s - L_{s \rightarrow d} \xi^d \quad (3-2)$$

where the phase transformation is active only when  $\dot{\xi}^d > 0$ ; that is, when the right-hand side of Equation 3-2 is strictly positive. In general, the functions  $K_{s \rightarrow d}$  and  $L_{s \rightarrow d}$  are functions of temperature  $T$ . It was shown in Ref. 1 that the bainitic

transformation additionally depends on the rate of cooling,  $\dot{T}$ . In this case, the functions  $K_{s \rightarrow d}$  and  $L_{s \rightarrow d}$  are functions of both  $T$  and  $\dot{T}$ .

#### Time and equilibrium

This form is a special case of the general-coefficients form. The phase transformation is defined by an equilibrium phase fraction for the destination phase  $\xi_{eq}^d$  and a time constant  $\tau_{s \rightarrow d}$ . The phase transformation is given by

$$\xi^d = \frac{\xi_{eq}^d - \xi^d}{\tau_{s \rightarrow d}} \quad (3-3)$$

where the phase transformation is active only when  $\xi^d > 0$ ; that is, when the right side of Equation 3-3 is strictly positive. The equilibrium phase fraction  $\xi_{eq}^d$  and the time constant  $\tau_{s \rightarrow d}$  are typically functions of temperature.

#### THE JOHNSON-MEHL-AVRAMI-KOLMOGOROV (JMAK) MODEL

This phase transformation model is based on the work by Leblond and others (Ref. 3). This model can be viewed as a generalization of the Leblond-Devaux model. It is based on an Avrami law of the form

$$\xi^d = \xi_{eq}^d \left( 1 - \exp \left( - \left( \frac{t}{\tau_{s \rightarrow d}} \right)^{n_{s \rightarrow d}} \right) \right) \quad (3-4)$$

The equilibrium phase fraction  $\xi_{eq}^d$ , the time constant  $\tau_{s \rightarrow d}$  and the Avrami constant  $n_{s \rightarrow d}$  are typically functions of temperature. On rate form, Equation 3-4 can be expressed as

$$\xi^d = \frac{\xi_{eq}^d - \xi^d}{\tau_{s \rightarrow d}} n_{s \rightarrow d} \left( - \ln \left( 1 - \frac{\xi^d}{\xi_{eq}^d} \right) \right)^{1 - \frac{1}{n_{s \rightarrow d}}} \quad (3-5)$$

where the explicit time dependence has been eliminated. The phase transformation is active only when  $\xi^d > 0$ ; that is, when the right side of Equation 3-5 is strictly positive. For the special case of  $n_{s \rightarrow d} = 1$ , the equation reduces to the time-and-equilibrium form of the Leblond-Devaux model (Equation 3-3). The JMAK phase transformation model in Equation 3-5 has a mathematical disadvantage in that an initial destination phase fraction equal to zero will yield a trivial zero solution, as the logarithm will evaluate to zero. There are different ways to circumvent this problem. One way is to require the initial phase fraction be assigned a small, but finite, value. Another way is to modify the rate equation itself, so that a zero initial phase fraction does not yield a

trivial zero solution. In the phase transformation interfaces, the JMAK phase transformation model in Equation 3-5 is modified for small values on the phase fraction  $\xi^d$ . Below a certain threshold, the argument for the logarithm is modified so that the logarithm does not produce a zero value. This threshold phase fraction is set to  $10^{-6}$  by default.



The phase fraction threshold variable used by the JMAK phase transformation model can be modified in the **Equation View** of the **Phase Transformation** node. Typically, the default value of  $10^{-6}$  should not have to be changed.

### THE KOISTINEN–MARBURGER MODEL

This phase transformation model was developed by Koistinen and Marburger (Ref. 2) to model the diffusionless (displacive) austenite-martensite transformation in iron-carbon alloys and carbon steels. The onset of the transformation, which only occurs on cooling, is characterized by a critical start temperature — the martensite start temperature  $M_s$ . Above this temperature, no transformation from austenite (the source phase) to martensite (the destination phase) occurs. Below  $M_s$ , the amount of formed martensite is proportional to the undercooling below  $M_s$ , given by  $M_s - T$ . On rate form, the Koistinen–Marburger equation can be written

$$\dot{\xi}^d = -\xi^s \beta \dot{T} \quad (3-6)$$

where  $\beta$  is the Koistinen–Marburger coefficient. Note that the transformation of austenite into martensite only occurs below  $M_s$  and only during cooling (that is, when  $\dot{T} < 0$ ). To make the onset of martensitic transformation numerically smooth, a parameter  $\Delta M_s$  is used. The smoothing parameter defines a smoothed Heaviside function that makes the onset of martensitic transformation gradual. The parameter should be chosen small enough that the start temperature characteristic is retained. Assuming a constant cooling rate and that the phase fraction of austenite at  $M_s$  is  $\xi_0^s$ , the rate equation can be integrated to

$$\xi^d = \xi_0^s (1 - \exp(-\beta(M_s - T))) \quad (3-7)$$

This integrated form is commonly found in the literature. The rate form of Equation 3-6 is more general, and from a computational standpoint it is more suitable for implementation. The rate form is therefore used in the phase transformation interfaces.

### **USER DEFINED**

Using this option, other types of phase transformations can be defined. A user-defined phase transformation assumes that a source phase decomposes into a destination phase according to [Equation 3-1](#).

# Compound Material Properties

The material consists of a mixture of metallurgical phases, each with a phase fraction that is evolving during the analysis. When the Metal Processing Module is used together with the Heat Transfer in Solids and Solid Mechanics interfaces, it is of interest to compute effective material properties so that a compound material can be defined and used by these physics interfaces. This chapter describes how various thermal and mechanical properties are averaged in terms of the phase fractions of the material.

## *Heat Transfer Properties*

---

The thermal conductivity and mass density of the compound material are computed using linear weighting by the phase fractions. The properties are given by

$$k = \sum_{i=1}^N \xi^i k^i$$

$$\rho = \sum_{i=1}^N \xi^i \rho^i$$

The thermal conductivity of the compound material uses a full tensor description. The heat capacity at constant pressure is computed by using a linear weighting of the volumetric heat capacity  $\rho C_p$ , having already computed  $\rho$ :

$$C_p = \frac{1}{\rho} \sum_{i=1}^N \xi^i \rho^i C_p^i$$



If geometric nonlinearity is used,  $k$  and  $\rho C_p$  are convected to the spatial frame in the Heat Transfer in Solids physics interface.

---

The mechanical properties for the compound material are generally computed using linear weighting by the phase fractions. The exception is in the case where phase plasticity is modeled, where other types of weighting schemes can be used for the initial yield strength of the compound material.

### **ELASTICITY**

The elastic behavior of the compound material is assumed to be isotropic and defined by a linear weighting of the Young's moduli and Poisson's ratios of the phases. This is reasonable because the elastic properties for the different phases are similar at a given temperature.

$$E = \sum_{i=1}^N \xi^i E^i$$
$$\nu = \sum_{i=1}^N \xi^i \nu^i$$

### **PLASTICITY**

It is not obvious what weighting scheme should be used to define an effective initial yield strength because the initial yield strengths of the phases will differ. The following weighting scheme is used:

$$\sigma_{ys0} = \sum_{i=1}^N g_i(\xi^i) \sigma_{ys0}^i$$

The simplest model for the initial yield strength of the compound material uses a linear weighting

$$g_i(\xi^i) = \xi^i$$

This scheme is reasonable when the initial yield strengths are similar. However, it is well known that the yield strength of some metallurgical phases can differ significantly. Most notably, martensite is typically an order of magnitude harder than austenite, and a linear mixture rule is unsuitable. Geijselaers ([Ref. 7](#)) developed a weighting scheme that is suitable in this situation. In this model, it is assumed that the hardest phase is

considerably harder than the softest phase. Assuming that the hard phase is  $m$  and the soft phase is  $\gamma$ , the Geijselaers weighting scheme is given by

$$g_i(\xi^i) = \begin{cases} \xi^i, & i \neq m \\ f_i(\xi^i), & i = m \end{cases}$$

with

$$f_m(\xi^m) = \xi^m (C + 2(1 - C)\xi^m - (1 - C)(\xi^m)^2)$$

$$C = 1.383 \frac{\sigma_{ys0}^\gamma}{\sigma_{ys0}^m}$$

The hardening function for the compound material is defined using the linear weighting

$$\sigma_h = \sum_{i=1}^N \xi^i \sigma_h^i(\epsilon_{pe}^i) \quad (3-8)$$

where  $\epsilon_{pe}^i$  is the equivalent plastic strain of the phase.

### EQUIVALENT PLASTIC STRAINS

In [Equation 3-8](#), the hardening function for each individual phase depends on equivalent plastic strain. If we denote the equivalent plastic strain of the compound material  $\epsilon_{pe}$ , we must define how the equivalent of each phase  $\epsilon_{pe}^i$  evolves with this strain. The simplest assumption is to use the evolution equation

$$\dot{\epsilon}_{pe}^i = \dot{\epsilon}_{pe}$$

which is to say that the equivalent plastic strain of phase  $i$  follows that of the compound material. If phase transformation and mechanical straining occur simultaneously, the equivalent plastic strain of the diminishing source phase of the phase transformation can be taken to follow that of the compound material, and this is the behavior in the phase transformation physics interfaces. However, for a phase which is increasing in fraction during plastic straining, this assumption is questionable. Leblond ([Ref. 6](#)) derived an evolution equation for the equivalent plastic strain, which is suitable for the



forming destination phase. The evolution equations for the source and destination phases are

$$\dot{\varepsilon}_{pe}^s = \dot{\varepsilon}_{pe}$$

$$\dot{\varepsilon}_{pe}^d = \dot{\varepsilon}_{pe} - \frac{\dot{\xi}^d}{\xi} (\varepsilon_{pe}^d - \Theta_{s \rightarrow d} \varepsilon_{pe}^s)$$

where the plasticity memory coefficient  $\Theta_{s \rightarrow d}$  was introduced to model that some plastic straining present in the source phase at the instant of transformation will be carried over to the forming destination phase. A zero plasticity memory coefficient means that no plastic straining will be remembered.

# Phase Transformation Strains

We consider two types of strains that appear during a thermal transient involving metallurgical phase transformations. These strains originate from:

- Thermal expansion
- Transformation induced plasticity (TRIP)

Other inelastic strains may also be present during a thermal transient, such as plastic strains or creep strains.

## *Thermal Expansion*

---

Thermal expansion for the compound material is given by a phase fraction weighted sum of the thermal expansion of each phase:

$$\epsilon_{\text{th}} = \sum_{i=1}^N \xi^i \epsilon_{\text{th}}^i$$

It is well known that different metallurgical phases occupy different volumes at a given temperature. For example, when austenite transforms into martensite, the thermal contraction due to cooling is accompanied by a volumetric expansion when the martensite begins to form. Consider a simple case where phase 1 transforms into phase 2. In 1D, and using a secant definition of the thermal expansion coefficient, the thermal strain is

$$\epsilon_{\text{th}} = \xi^I \alpha^I(T)(T - T_{\text{ref}}^I) + \xi^{II} \alpha^{II}(T)(T - T_{\text{ref}}^{II})$$

where  $\alpha(T)$  and  $T_{\text{ref}}$  are the secant coefficient of thermal expansion and strain volume reference temperature, for the respective phases *I* and *II*. [Figure 3-1](#) shows the thermal strain. For simplicity, the coefficients of thermal expansion for the two phases in the figure are constant (but different). In the figure, a fictitious phase transformation has been used to illustrate when phase *I* transforms completely into phase *II* as the temperature is lowered. No separate volumetric term is required to model this type of phase transformation strain, as it is included in the definition of the thermal expansion itself.

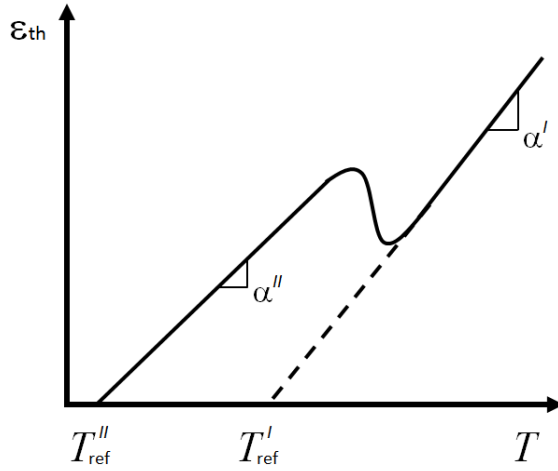


Figure 3-1: Thermal strain during phase transformation.

### Transformation-Induced Plasticity

Plastic strains in metals result from deviatoric stresses that exceed the yield strength of the material. However, during phase transformations, inelastic strains may appear already at very small stress levels. This transformation-induced plasticity (TRIP) is therefore different from classical plasticity in that it does not involve a yield criterion and that it appears at stress levels that would otherwise be insufficient to cause plastic straining even in the softest of the phases. A description of TRIP strain rate, common in the literature (see, for example, [Ref. 3](#)), is

$$\dot{\varepsilon}_{\text{tp, s} \rightarrow \text{d}} = \frac{3}{2} K_{\text{s} \rightarrow \text{d}}^{\text{TRIP}} \cdot \frac{\text{d}\Phi(\xi^{\text{d}})}{\text{d}\xi^{\text{d}}} \dot{\xi}^{\text{d}} \cdot \text{dev}(\mathbf{S})$$

where the strain rate is proportional to the deviatoric part of the second Piola–Kirchhoff stress tensor  $\mathbf{S}$  through the transformation induced plasticity parameter  $K_{\text{s} \rightarrow \text{d}}^{\text{TRIP}}$ , the derivative of the saturation function  $\Phi(\xi^{\text{d}})$ , and the rate of the destination phase  $\dot{\xi}^{\text{d}}$ . Values for the transformation-induced plasticity parameter  $K_{\text{s} \rightarrow \text{d}}^{\text{TRIP}}$  will depend on the type of phase transformation. It can depend on, for example, carbon content and temperature (see [Ref. 4](#)). Several propositions exist for the saturation

functions; see [Table 3-1](#) and [Ref. 9](#). Through the user-defined option, you can define the derivative of the saturation function.

TABLE 3-1: SATURATION FUNCTIONS FOR THE TRIP STRAIN RATE

TYPE	EXPRESSION
Abrassart	$\xi^d(3 - 2\sqrt{\xi^d})$
Desalos	$\xi^d(2 - \xi^d)$
Leblond	$\xi^d(1 - \ln \xi^d)$ for $\xi^d > 0.03$ , zero otherwise
Tanaka	$\xi^d$

The total TRIP strain rate is given by

$$\dot{\epsilon}_{tp} = \sum_{s \rightarrow d} \dot{\epsilon}_{tp, s \rightarrow d}$$

*Total Strain Contribution*

When thermal and TRIP strains are computed, they can be used in a Solid Mechanics interface as an inelastic strain contribution. The contributions from thermal and TRIP strains are added to form a total strain contribution. In the Solid Mechanics interface, this contribution is used additively in the case of a additive strain definition or used to form an inelastic-deformation-gradient contribution in the case of geometric nonlinearity with nonlinear strains; see [Inelastic Strain Contributions](#). In the latter case, the contribution is used multiplicatively.

# Phase Transformation Latent Heat

The heat rate  $Q_0$  that is released during a phase transformation is characterized by the enthalpy per unit volume  $\Delta H_{s \rightarrow d}$  (see [Ref. 4](#)). The heat rate that is associated with the transformation of a source phase into a destination phase can be expressed as

$$Q_0 = \Delta H_{s \rightarrow d} \dot{\xi}^d \quad (3-9)$$

The heat rates that result from each phase transformation are added, and they can be used as a heat source when solving the heat equation. A weak contribution is added to the weak form of the heat equation:



$$\hat{Q}_0 \delta(T)$$

where  $\hat{Q}_0$  is the sum of the contributions  $Q_0$  from each phase transformation ([Equation 3-9](#)), and  $T$  is the temperature degree of freedom used in the Heat Transfer in Solids interface.



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# Metal Phase Transformation

This chapter describes the Metal Phase Transformation Interface () and its functionality. It is found under the **Heat Transfer>Metal Processing** branch () when adding a physics interface.

# The Metal Phase Transformation Interface

The **Metal Phase Transformation** interface () is found under the **Heat Transfer>Metal Processing** () branch when adding a physics interface. The physics interface is intended for studying metallurgical phase transformations. You can use this interface to study diffusional, displacive, and user-defined (solid state) phase transformations. Physical phenomena, such as latent heat of phase transformation and transformation strains, can be computed and used in Heat Transfer in Solids and Solid Mechanics. With the Nonlinear Structural Materials Module or the Geomechanics Module, plastic strains and hardening behavior of each metallurgical phase can be used in Solid Mechanics.

When the Metal Phase Transformation interface is added, three default nodes are also added to the **Model Builder** — two **Metallurgical Phase** nodes and one **Phase Transformation** node. The phase transformation node will be set to use the two metallurgical phases as source and destination phases, respectively. From the **Physics** toolbar, you can add additional metallurgical phases and phase transformations. You can also right-click **Metal Phase Transformation** to select physics features from the context menu.

## SETTINGS

The **Label** is the default physics interface name.

The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the name string must be unique. Only letters, numbers, and underscores (\_) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `metp`.

## MATERIAL PROPERTIES

You have the option of letting the physics interface compute effective thermal and mechanical material properties, based on the corresponding properties and fractions of the individual metallurgical phases. Select the **Compute effective thermal properties** check box to let the physics interface compute effective thermal properties. Select the **Compute effective mechanical properties** check box to let the physics interface compute



effective mechanical properties. You can use the computed effective material properties to create a compound material that can be used in other physics interfaces as a domain material. Select the **Create Compound Material** to create a compound material. This material is created at the component level.



A compound material that is generated from an Austenite Decomposition interface (audc) will be given the tag audcmat.

---

## HEAT TRANSFER

Phase transformations are inherently temperature dependent. Select the temperature field to use from the **Temperature** list. If you want to consider the release or absorption of latent heat during phase transformations, select the **Enable phase transformation latent heat** check box. You can then define values for the latent heat at each of the phase transformation nodes. By default, the check box is not selected.

## SOLID MECHANICS

This section contains settings that affect various strains that accompany phase transformations. Select the **Enable transformation-induced plasticity** check box if you want to include this type of transformation strain in your analysis. The **Enable thermal strains** and **Enable phase plasticity** check boxes are visible only if you have selected the **Compute effective mechanical properties** check box in the **Material Properties** section. Select **Enable thermal strains** if you want to include thermal strains in your analysis. Note that the thermal strains will include both pure thermal strains as well as strains that arise from volumetric differences between different metallurgical phases. Select the **Enable phase plasticity** check box if you want to allow for plasticity in the individual phases. By default, none of the three check boxes in this section are selected.

## DISCRETIZATION

The discretizations for phase fractions and displacements can be set independently using the **Discretization for phase fractions** and **Discretization for displacements** lists. In general, the **Discretization for displacements** setting should match the discretization order used for the displacement field in the Solid Mechanics interface. By default, **Linear** is selected for phase fractions and **Quadratic** for displacements.

## *Metallurgical Phase*

---

The **Metallurgical Phase** node defines a phase. Depending on the settings at the physics interface level, the phase node will contain different sections.

## MODEL INPUT

Provide the **Volume reference temperature**  $T_{\text{ref}}$  for the phase. This is the temperature at which the thermal strain is zero for the phase.

## INITIAL PHASE FRACTION

Define the **Initial phase fraction** for the phase. This fraction should be a value between zero and one, and you have to ensure that the initial phase fractions for all the phases in your analysis sum to one.



- The initial fractions for the metallurgical phases are named `metp.phase1.xi0`, `metp.phase2.xi0`, and so on.
- The current phase fractions are correspondingly named `metp.phase1.xi` and `metp.phase2.xi`.

## PHASE MATERIAL

From the **Phase material** list, you select the material that defines the material properties for the phase. This section is visible only if at least one of the **Compute effective thermal properties** or the **Compute effective mechanical properties** check boxes has been selected at the physics interface level. You can create a material at the component level by using **Create Phase Material**. When you define material properties for the phase, **From material** will refer to the material that you have selected from the **Phase material** list.



A phase material that is generated from a Metallurgical Phase (phase2) in an Austenite Decomposition interface (audc) will be given the tag `audcphase2mat`.

## HEAT TRANSFER PROPERTIES

If the **Compute effective thermal properties** has been selected at the physics interface level, you must define the thermal properties for the phase. The default **Thermal conductivity**  $k$ , **Density**  $\rho$ , and **Heat Capacity at constant pressure**  $C_p$ , use values **From material**. The **From material** option refers to the selected material from the **Phase Material** list. For **User defined**, enter values or expressions for these properties.

## MECHANICAL PROPERTIES

If the **Compute effective mechanical properties** has been selected at the physics interface level, you must define mechanical properties for the phase. The default Young's

modulus  $E$  and Poisson's ratio  $\nu$  use values **From material**. For **User defined**, enter values or expressions for these properties.

If **Enable thermal strains** has been selected at the physics interface level, you have to define the **Secant coefficient of thermal expansion**  $\alpha$  for the phase. By default, the value is taken **From material**. For **User defined**, enter a value or expression.

If **Enable phase plasticity** has been selected at the physics interface level, you have to define the plastic behavior of the phase. The default **Initial yield stress**  $\sigma_{ys0}$  uses a value **From material**. For **User defined**, enter another value or expression for initial yield stress. Initial yield stresses for phases can be weighted differently. This is useful when initial yield stresses for the phases in the model are very different. Select a **Weight factor for yield stress** — **Linear**, **Geijselaers**, or **User defined**. If **Geijselaers** is selected, you also need to specify a **Soft phase**, which is considered plastically soft in comparison to this phase. You should typically use this to give a stronger weight to martensite (hard) in relation to austenite (soft).

Select the **Isotropic hardening model** — **Perfectly plastic**, **Linear**, or **User defined** to define the hardening behavior of the phase.

#### *Linear*

Specify the **Isotropic hardening modulus**  $E_{Tiso}$ . The default value is taken **From material**.

#### *User defined*

For **User defined**, enter another value or expression for the modulus. If a **User defined** isotropic hardening modulus is selected, you have to select the **Hardening function**. By default, the value is taken **From material**.

For **User defined**, enter a value or expression for the **hardening function**. The expression can depend, for example, on the equivalent plastic strain in the phase.



In a phase (**phase4**) of an Austenite Decomposition interface (**audc**), the equivalent plastic strain is **audc.phase4.epe**.

### *Phase Transformation*

The Phase Transformation node defines a metallurgical phase transformation. Depending on the settings at the physics interface level, the phase transformation node will contain different sections.

## PHASE TRANSFORMATION

The phase transformation defines how one phase forms (the destination phase) at the expense of another (the source phase). Select **Source phase**  $\xi^s$  and **Destination phase**  $\xi^d$  from the list of defined phases. Select a **Phase transformation model** — **Leblond–Devaux**, **Koistinen–Marburger**, or **User defined**.

### *Leblond–Devaux*

Select **Time and equilibrium** or **General coefficients**. For **Time and equilibrium**, specify the **Equilibrium phase fraction**  $\xi_{eq}^d$  and **Time constant**  $\tau_{s \rightarrow d}$ . For **General coefficients**, specify the expressions for  $K_{s \rightarrow d}$  and  $L_{s \rightarrow d}$ .

### *Johnson–Mehl–Avrami–Kolmogorov*

Specify the **Equilibrium phase fraction**  $\xi_{eq}^d$ , the **Time constant**  $\tau_{s \rightarrow d}$ , and the **Avrami exponent**  $n_{s \rightarrow d}$ .

### *Koistinen–Marburger*

Specify the **Koistinen–Marburger coefficient**  $\beta$ , the **Martensite start temperature**  $M_s$ , and a value for the **Martensite start temperature smoothing**  $\Delta M_s$ .

### *User defined*

Specify the **Phase transformation contribution**  $A_{s \rightarrow d}$ . The expression defines the rate at which the destination phase forms, at the expense of the source phase.

## PHASE TRANSFORMATION LATENT HEAT



This section is active if you have selected **Enable phase transformation latent heat** at the physics interface level. You can specify the latent heat  $\Delta H_{s \rightarrow d}$  that is released during the phase transformation.

## PHASE TRANSFORMATION STRAIN



The **Transformation induced plasticity** check box is available if you have selected **Enable transformation induced plasticity** at the physics interface level. In case of transformation induced plasticity, specify the **Transformation induced plasticity parameter**  $K_{s \rightarrow d}^{TRIP}$  and the **Saturation function**  $\Phi$ .

The **Plastic recovery for destination phase** check box is available if the **Enable thermal strains** has been selected at the physics interface level. If you have selected **Plastic recovery** for destination phase, you can specify the **Plastic memory coefficient**  $\Theta_{s \rightarrow d}$ . The default value is zero, which means that no plastic straining in the source phase will be carried over to the destination phase.

## Austenite Decomposition

This chapter describes the Austenite Decomposition Interface () and its functionality. It is found under the **Heat Transfer>Metal Processing** branch () when adding a physics interface.

# The Austenite Decomposition Interface

The **Austenite Decomposition** interface () is found under the **Heat Transfer>Metal Processing** () branch when adding a physics interface. The physics interface is intended for studying metallurgical phase transformations. You can use this interface to study diffusional, displacive, and user-defined (solid-solid) phase transformations. Physical phenomena, such as latent heat of phase transformation and transformation strains can be computed and used in Heat Transfer in Solids and Solid Mechanics. With the Nonlinear Structural Materials Module or the Geomechanics Module, plastic strains and hardening behavior of each metallurgical phase can be used in Solid Mechanics.

This interface is based on the Metal Phase Transformation interface. This chapter will only describe the nodes and settings that set the Austenite Decomposition interface apart from the Metal Phase Transformation interface. With regard to other settings at the physics interface level and feature level, see [The Metal Phase Transformation Interface](#).

When the Austenite Decomposition interface is added, nine nodes are added to the **Model Builder** — five [Metallurgical Phase](#) nodes and four [Phase Transformation](#) nodes. The interface is tailored specifically to the decomposition of austenite into a combination of ferrite, pearlite, bainite, and martensite. The phase nodes are given names to reflect this:

- Austenite
- Ferrite
- Pearlite
- Bainite
- Martensite

The **Initial Phase Fraction** is set to one in the **Austenite** node, and zero in the other metallurgical phase nodes. Four **Phase Transformation** nodes are also created to define the relevant phase transformations:

- Austenite to Ferrite
- Austenite to Pearlite

- Austenite to Bainite
- Austenite to Martensite

The source and destination phases in each phase transformation are set to the corresponding phases that have been created. The **Phase transformation model** is set to **Leblond–Devaux** with **General coefficients**, except in **Austenite to Martensite**, where it is set to **Koistinen–Marburger**.

From the **Physics** toolbar, you can delete or disable metallurgical phases and phase transformations that are irrelevant in a given situation, and you can add additional metallurgical phases and phase transformations. You can also right-click **Metal Phase Transformation** to select physics features from the context menu.

## SETTINGS

The **Label** is the default physics interface name.


The **Name** is used primarily as a scope prefix for variables defined by the physics interface. Refer to such physics interface variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different physics interfaces, the `name` string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first physics interface in the model) is `audc`.






# Multiphysics Interfaces and Couplings

The Metal Processing Module contains predefined multiphysics interfaces to facilitate the coupling to Heat Transfer in Solids and Solid Mechanics interfaces. The physics interfaces are found under the **Heat Transfer>Metal Processing** branch () when adding a physics interface — **Heat Transfer with Phase Transformations** and **Steel Quenching**. Two multiphysics coupling features — **Phase Transformation Latent Heat** and **Phase Transformation Strain**, can be added to facilitate the coupling to Heat Transfer in Solids and Solid Mechanics.

In this chapter:

- [Heat Transfer with Phase Transformations](#)
- [Steel Quenching](#)
- [Phase Transformation Latent Heat Multiphysics Coupling](#)
- [Phase Transformation Strain Multiphysics Coupling](#)

# Heat Transfer with Phase Transformations

The **Heat Transfer with Phase Transformations** multiphysics interface () combines a Heat Transfer in Solids interface with a Metal Phase Transformation interface. When the Heat Transfer with Phase Transformations multiphysics interface is added, the multiphysics coupling **Phase Transformation Latent Heat** is included.

## *On the Constituent Physics Interfaces*


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- The Heat Transfer in Solids interface is described in [The Heat Transfer in Solids Interface](#) of the Heat Transfer Module User's Guide.
- The Metal Phase Transformation interface is described in [The Metal Phase Transformation Interface](#) chapter.

### **SETTINGS FOR PHYSICS INTERFACES AND COUPLING FEATURES**

The **Enable phase transformation latent heat** check box is selected in the Metal Phase Transformation interface.

# Steel Quenching

The **Steel Quenching** multiphysics interface () combines a Heat Transfer in Solids interface with an Austenite Decomposition interface and a Solid Mechanics interface. When the Steel Quenching multiphysics interface is added, the **Phase Transformation Latent Heat** and **Phase Transformation Strain** multiphysics couplings are included.

## *On the Constituent Physics Interfaces*

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- The Heat Transfer in Solids interface is described in [The Heat Transfer in Solids Interface](#).
- The Austenite Decomposition interface is described in [The Austenite Decomposition Interface](#) chapter.
- The Solid Mechanics interface is described in [The Solid Mechanics Interface](#) of the *Structural Mechanics Module User's Guide*.


### **SETTINGS FOR PHYSICS INTERFACES AND COUPLING FEATURES**

The following check boxes are selected in the Austenite Decomposition interface:

- Compute effective thermal properties
- Compute effective mechanical properties
- Enable phase transformation latent heat
- Enable transformation induced plasticity
- Enable thermal strains

The discretization for the temperature field in the Heat Transfer in Solids interface is set to Linear, because thermal strains are typically linear in the Solid Mechanics interface.

# Phase Transformation Latent Heat Multiphysics Coupling

The **Phase Transformation Latent Heat** multiphysics coupling () is used to add the latent heat that is produced by a Metal Phase Transformation interface as a heat source term in the heat equation of the coupled Heat Transfer in Solids interface. When the coupling is used, no separate Heat Source feature in the Heat Transfer interface is required.



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When the **Phase Transformation Latent Heat** multiphysics coupling is used, the effect of latent heat should not be added as a **Heat Source** in the Heat Transfer in Solids interface, as this incorrectly amounts to adding the latent heat contribution twice.

---

## SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the `name` string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is `1ht1`.

## DOMAIN SELECTION

When the coupling is added, selected entities in the coupled Heat Transfer in Solids and Metal Phase Transformation interfaces are included by default.

## COUPLED INTERFACES

This section defines the physics involved in the multiphysics coupling. The **Metal Phase Transformation** and **Heat Transfer** lists include all applicable physics interfaces.

The default values depend on how the coupling node is created.


- If the node is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (Mac and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it the node added automatically when a multiphysics interface is selected in the **Model Wizard** or **Add Physics** window, then the two participating physics interfaces are selected.



See also the Theory for [Phase Transformation Latent Heat](#)

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# Phase Transformation Strain Multiphysics Coupling

The Phase Transformation Strain multiphysics coupling () is used to include phase transformation strains that are produced by a Metal Phase Transformation interface as an inelastic strain contribution to the total strain in the Solid Mechanics interface.



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Note that if **Enable thermal strains** has been selected at the **Metal Phase Transformation** interface level, thermal strain effects are included in the phase transformation strains. In this situation no **Thermal Expansion** coupling should be used between Solid Mechanics and Heat Transfer in Solids.

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## SETTINGS

The **Label** is the default multiphysics coupling feature name.

The **Name** is used primarily as a scope prefix for variables defined by the coupling node. Refer to such variables in expressions using the pattern `<name>.<variable_name>`. In order to distinguish between variables belonging to different coupling nodes or physics interfaces, the name string must be unique. Only letters, numbers, and underscores (`_`) are permitted in the **Name** field. The first character must be a letter.

The default **Name** (for the first multiphysics coupling feature in the model) is `ptstr1`.

## DOMAIN SELECTION

When the coupling is added, selected entities in the coupled Solid Mechanics and Metal Phase Transformation interfaces are included by default.

## COUPLED INTERFACES

This section defines the physics involved in the multiphysics coupling. The **Metal Phase Transformation** and **Solid Mechanics** lists include all applicable physics interfaces.

The default values depend on how the coupling node is created.

- If the node is added from the **Physics** ribbon (Windows users), **Physics** contextual toolbar (macOS and Linux users), or context menu (all users), then the first physics interface of each type in the component is selected as the default.
- If it the node added automatically when a multiphysics interface is selected in the **Model Wizard** or **Add Physics** window, then the two participating physics interfaces are selected.



See also the Theory for [Phase Transformation Strains](#)

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