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ENR116 Engineering Materials

Module 3 Metals

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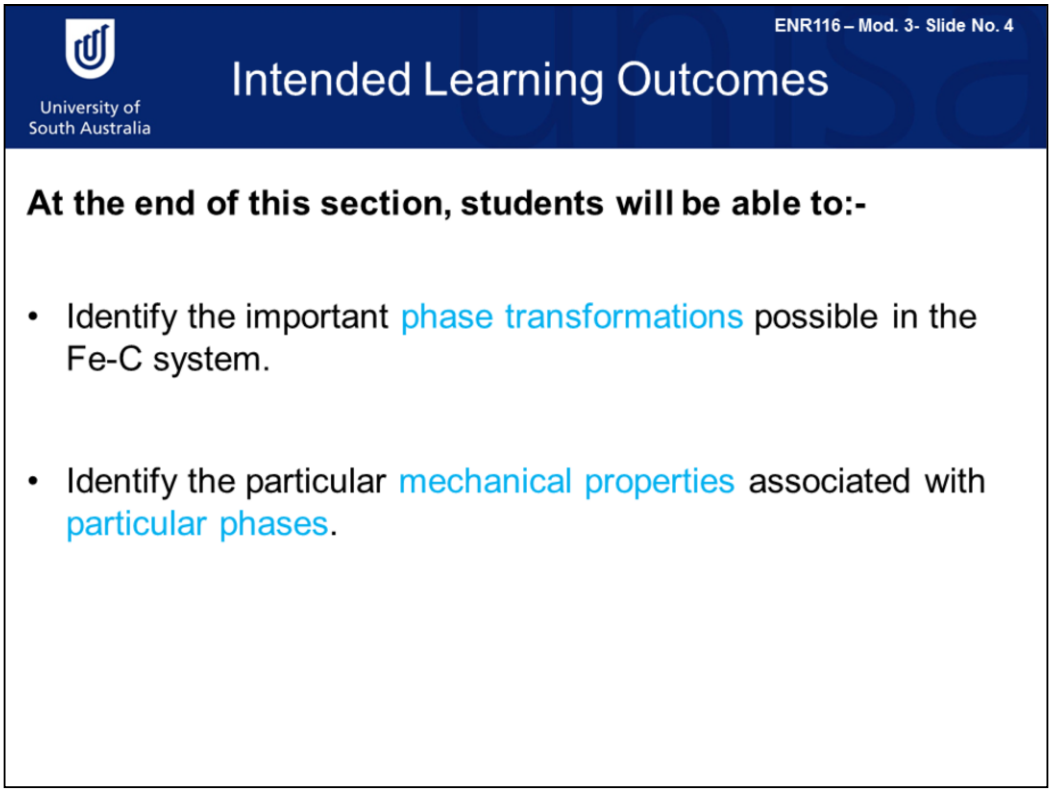
Iron-Carbon alloys



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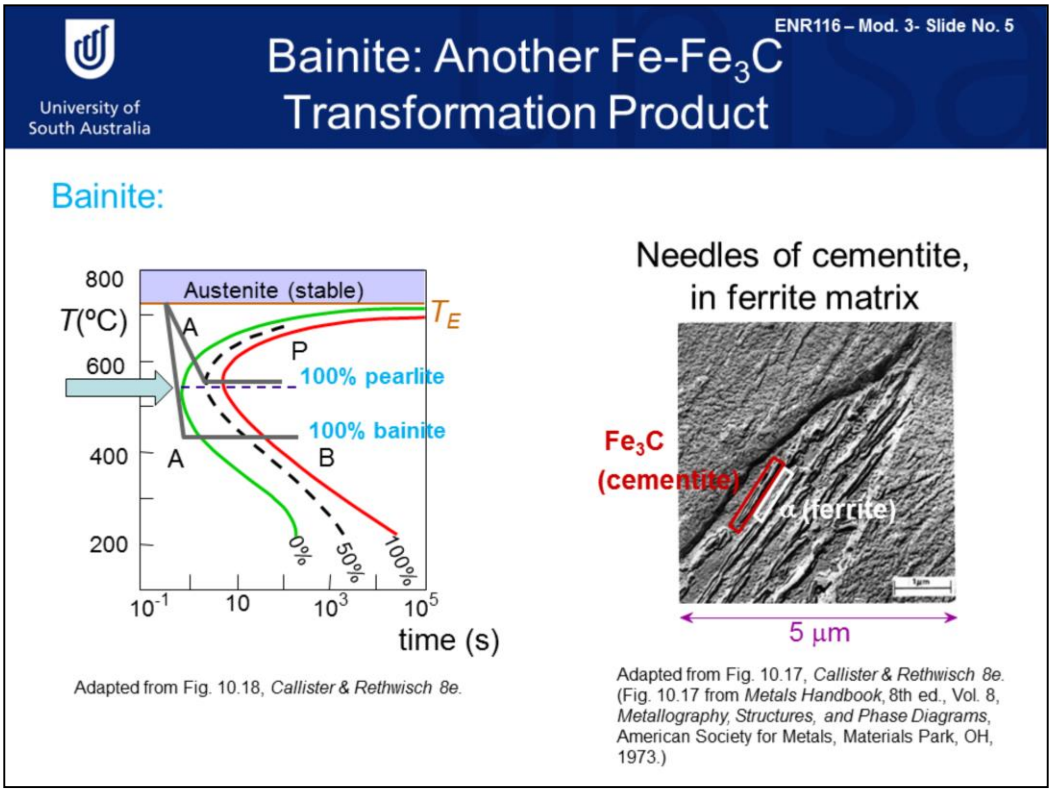
Intended Learning Outcomes

At the end of this section, students will be able to:-

- Identify the important phase transformations possible in the Fe-C system.
- Identify the particular mechanical properties associated with particular phases.

At the end of this lecture summary you will be able to identify the important phase transformations of the iron – iron carbide system. You will also be able to recognise the particular mechanical properties associated with the different phases.



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Bainite: Another Fe-Fe$_3$C Transformation Product

Bainite:

Adapted from Fig. 10.18, *Callister & Rethwisch 8e.*

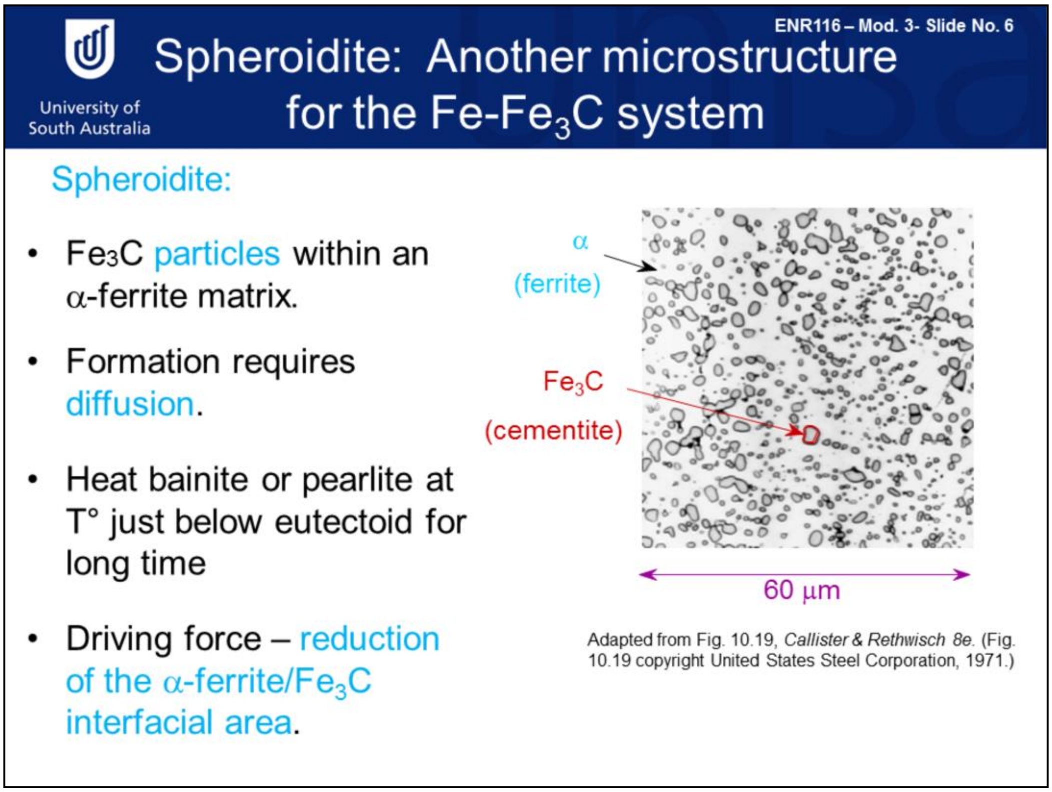
Needles of cementite, in ferrite matrix

Adapted from Fig. 10.17, *Callister & Rethwisch 8e.* (Fig. 10.17 from *Metals Handbook*, 8th ed., Vol. 8, *Metallography, Structures, and Phase Diagrams*, American Society for Metals, Materials Park, OH, 1973.)

We've seen in previous lecture summaries that there are a number of microstructural features associated with the iron- iron carbide system. As if austenite, cementite, ferrite and pearlite weren't enough, there are others!

The first of these is bainite. Bainite is formed by a rapid quenching rate to avoid the nose of the isothermal transformation curve. The nose of the transformation curve is this section here. You can in this illustration that with a relatively slow cooling rate to a temperature above 550 degrees C, we get 100% pearlite. But if we cool the system faster, to a temperature below 550 degrees C, we get bainite. As with pearlite, the formation of bainite is diffusion dependant.

At the microscopic level, bainite appears as elongated particles or needles of cementite, embedded in an alpha ferrite matrix. You can this structure in this image. In terms of relative mechanical properties, bainite is harder and stronger than both coarse and fine pearlite.



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Spheroidite: Another microstructure for the Fe-Fe_3C system

Spheroidite:

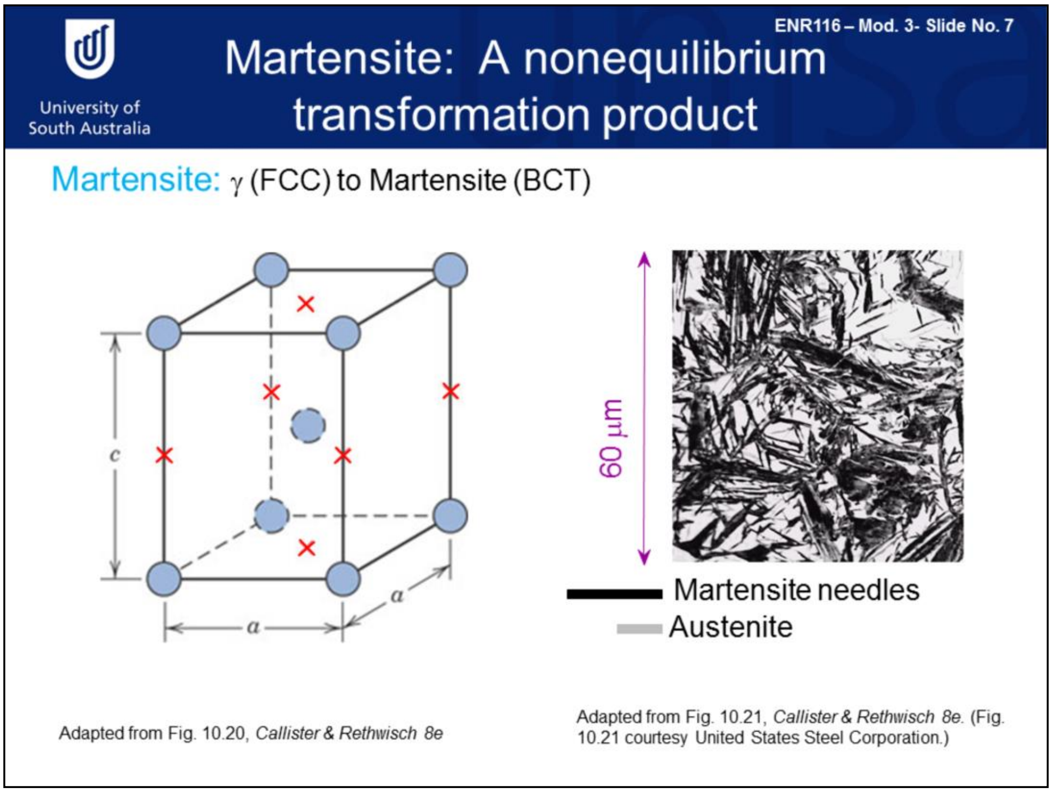
- Fe_3C particles within an α-ferrite matrix.
- Formation requires diffusion.
- Heat bainite or pearlite at T° just below eutectoid for long time
- Driving force – reduction of the α-ferrite/Fe_3C interfacial area.

Adapted from Fig. 10.19, *Callister & Rethwisch 8e.* (Fig. 10.19 copyright United States Steel Corporation, 1971.)

Spheroidite is another microstructure. Here cementite particles appear as small spheres within an alpha ferrite matrix.

Spheroidite is formed by heating either bainite or pearlite at a temperature just below the eutectoid for a extended period. The transformation process is diffusion controlled and is driven by the reduction in interfacial area between the cementite and ferrite that occurs upon going from the layer structure or needles, to spheres.

Spheroidite is softer and more ductile than either pearlite or bainite.



Martensite: A nonequilibrium transformation product

Martensite: γ (FCC) to Martensite (BCT)

▬ Martensite needles
▬ Austenite

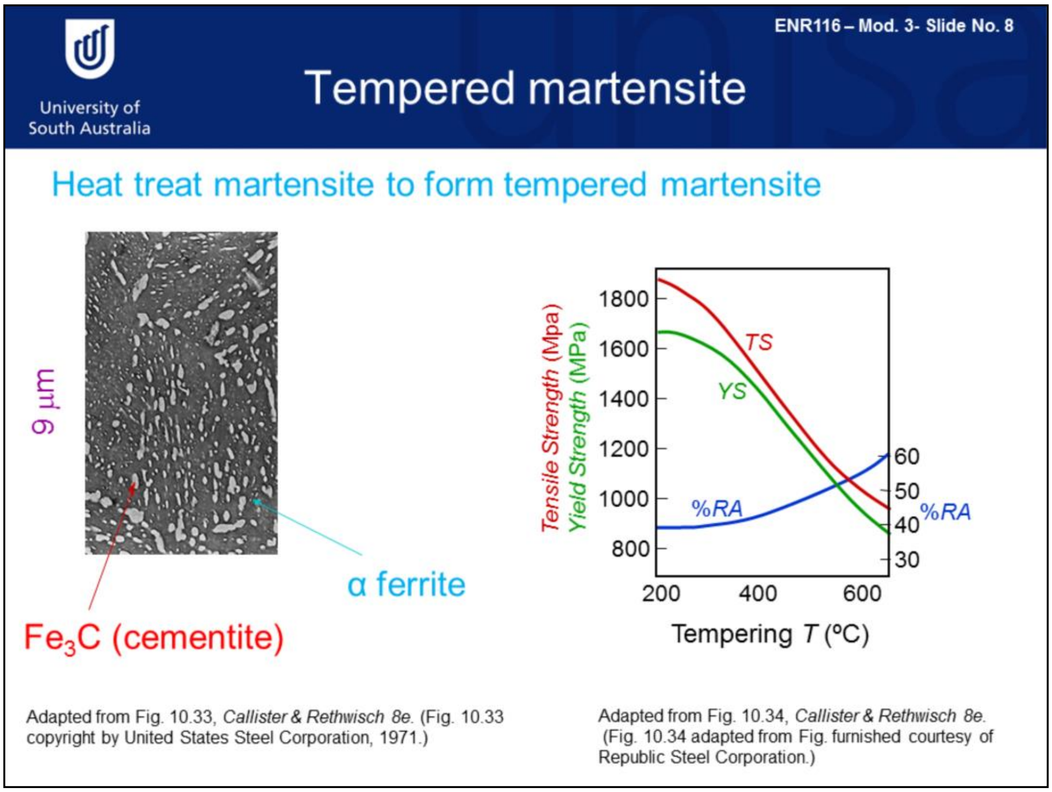
Adapted from Fig. 10.20, *Callister & Rethwisch 8e*

Adapted from Fig. 10.21, *Callister & Rethwisch 8e*. (Fig. 10.21 courtesy United States Steel Corporation.)

All of the microstructures we have discussed so far, pearlite, bainite and spheriodite, have depended upon diffusion for their formation. This last microstructure, Martensite, is different.

Martensite is a metastable product, formed when an austenitised alloy is rapidly cooled (quenched) to room temperature. This cooling is so rapid that it effectively prevents diffusion. The carbon atoms therefore are locked into place as interstitial impurities in face centered cubic austentite. The atoms are then thought to move together from the face centered structure to a body centered tetragonal arrangement that is supersaturated with carbon. In the illustration on your left of your screen you can see potential carbon sites within the body centered tetragonal cell highlighted in red. The body centered tetragonal structure has very few slip planes, and as a result Martensite is extremely hard and brittle. It is harder and stronger than spheroidite, pearlite or bainite.

Whilst the actual mechanism of the Martensite transformation is really still very poorly understood, but we do know that microstructurally, Martensite appears as long needles within the austenite phase. You can see this in the photograph of Martensite on the right here.



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Tempered martensite

Heat treat martensite to form tempered martensite

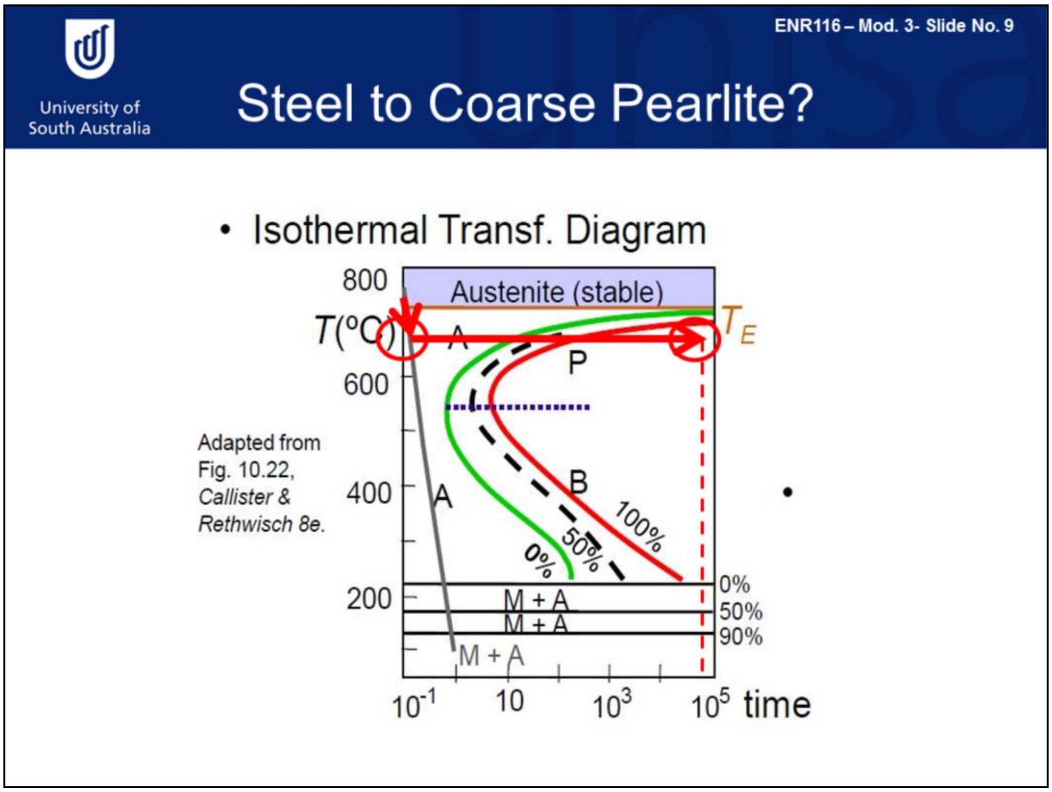
Adapted from Fig. 10.33, *Callister & Rethwisch 8e.* (Fig. 10.33 copyright by United States Steel Corporation, 1971.)

Adapted from Fig. 10.34, *Callister & Rethwisch 8e.* (Fig. 10.34 adapted from Fig. furnished courtesy of Republic Steel Corporation.)

As I mentioned in the previous slide, of all the iron-iron carbide microstructures martensite is the hardest but also the most brittle and as-formed it’s essentially unusable.

However, if we take the as-quenched martensite and then heat treat, or ‘temper’ it, we can further modify the microstructure. Typically this process involves heating the martensite to a temperature below the eutectoid, somewhere in the range of 250 degrees C to 650 degrees C and holding it at this temperature. Diffusional processes then allow transformation of the super saturated body centered tetragonal structure to extremely small spheres of cementite in an alpha ferrite matrix.

Tempered martensite is not quite as strong as as-formed martensite, but it is considerably tougher and more ductile. By carefully selecting the tempering tempwrature, we can control the final values for the tensile strength, yield strength and ductility of the new material. This graph here shows how the tensile strength, yield strength and toughness vary with temperature. In all cases the tempering time is the same.



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Steel to Coarse Pearlite?

- Isothermal Transf. Diagram

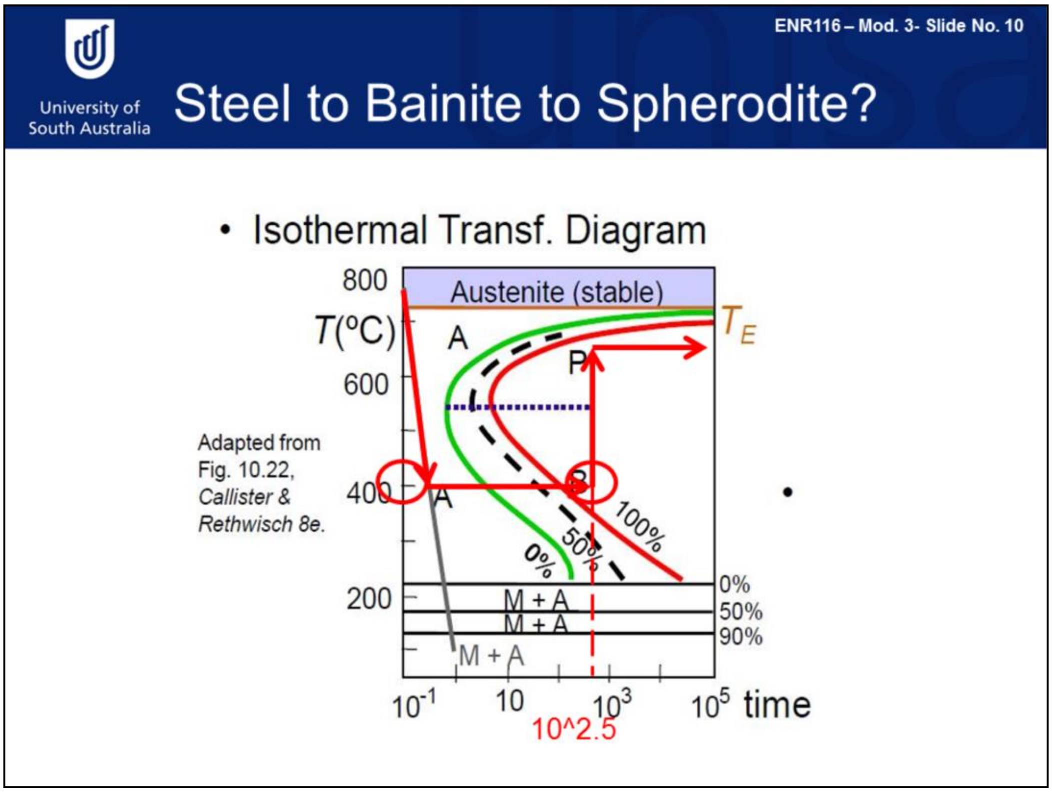
Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

Now that we have introduced all of the possible microstructures for the iron-iron carbide system, it would be useful to revisit the isothermal transformation graphs from the previous lecture, and explore how we can use these to determine a pathway from austenite to a particular microstructure. In this first example we want to generate one hundred percent coarse pearlite.

Coarse pearlite is formed at temperatures just below the eutectoid, so we need to end up about here. This point corresponds to a temperature of about 670 degrees C, as you can see here.

So the first thing we need to do is cool the sample from the eutectoid temperature to 670C. Then, in order to end up in the coarse pearlite region, here, we need to hold the sample at that temperature as shown here. Checking against the x axis shows that we need to hold at 670 degrees C for about 10^5 seconds.

So to summarise the procedure we've determined – first we cool the sample to 670 degrees C. We then hold the sample at this temperature for 10^5 seconds, before cooling to room temperature. This results in 100% coarse pearlite.



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Steel to Bainite to Spherodite?

- Isothermal Transf. Diagram

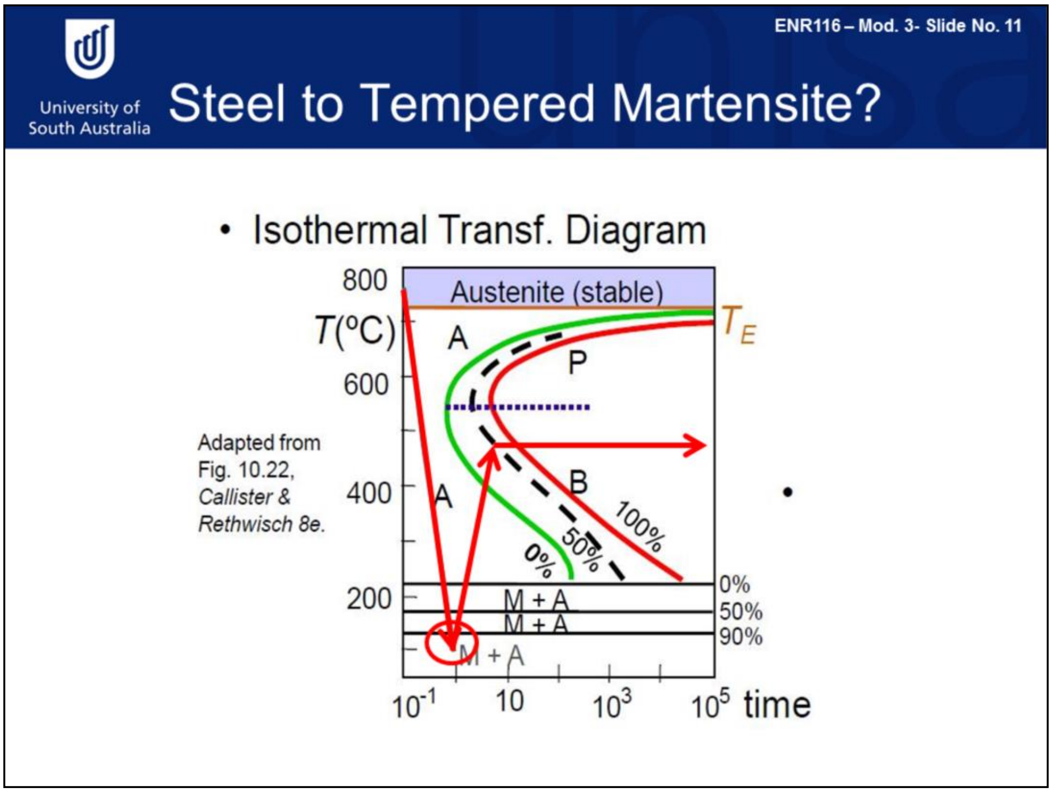
Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

Lets work through a second example. In this case, we want to generate 100% bainite, and subsequently 100% spherodite.

Looking at the diagram, we can see that this point here represents 100% bainite. So this where we need to aim for first. This point corresponds to a temperature of 400 degrees C, so we start by cooling the sample from above the eutectoid to 400 degrees C.

We then need to hold the sample at 400 degrees C, for approximately 10^3 seconds. We now have 100% bainite. You’ll recall that in order to convert bainite or pearlite to spherodite, we need to heat the sample to just below the eutectoid and hold at this raised temperature for an extended time. Lets do this next. So, first, heating the sample to about 670 degrees , and then holding at this temperature. All of the bainite is converted to spherodite.

To summarise the reaction pathway we’ve established – first cool the sample to 400 degrees C. Hold at 400 degrees for about 150s, and then increase the temperature to 670 degrees C. Hold at this temperature in order to convert all of the bainite to spherodite.



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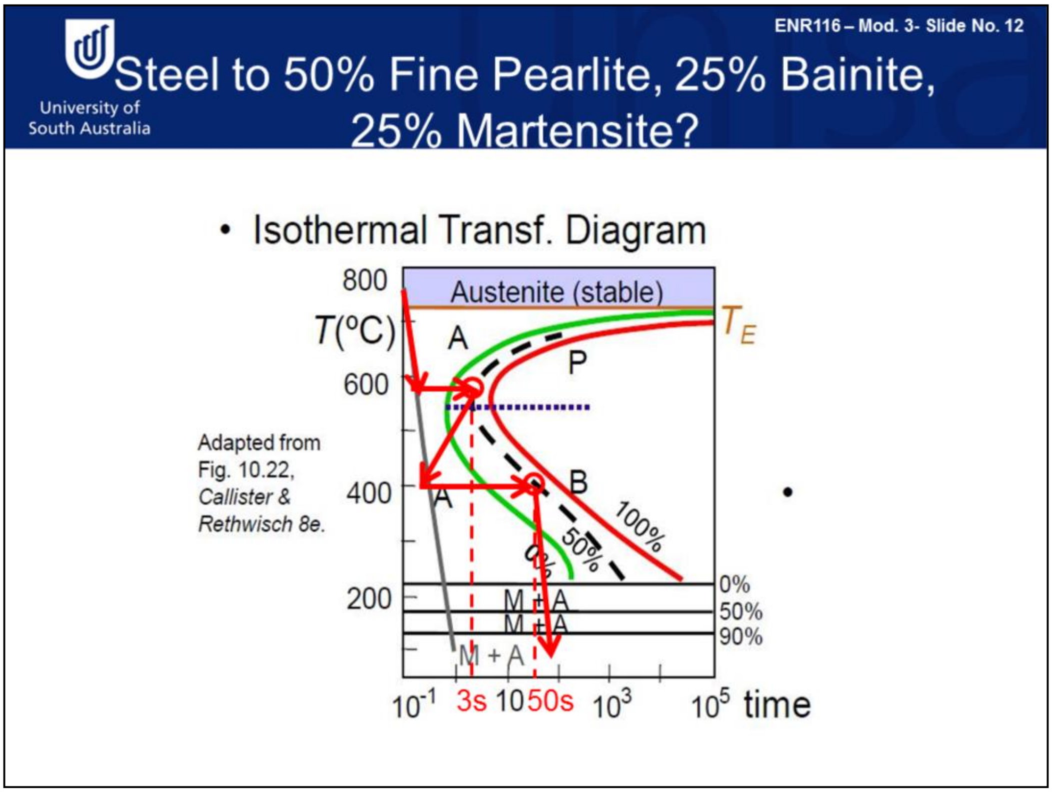
Steel to Tempered Martensite?

- Isothermal Transf. Diagram

Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

In this case, we want to generated tempered martensite from eutectoid steel. We need to start here by creating 100% martensite, so we need to be here, in this region of the isothermal transformation diagram. To generate martensite, the sample must be rapidly quenched to room temperature, as you can see on your screen now.

In order to temper martensite, we need to heat the sample to about 470 degrees C, and hold at this temperature. The result is 100% tempered martensite.



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Steel to 50% Fine Pearlite, 25% Bainite, 25% Martensite?

- Isothermal Transf. Diagram

Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

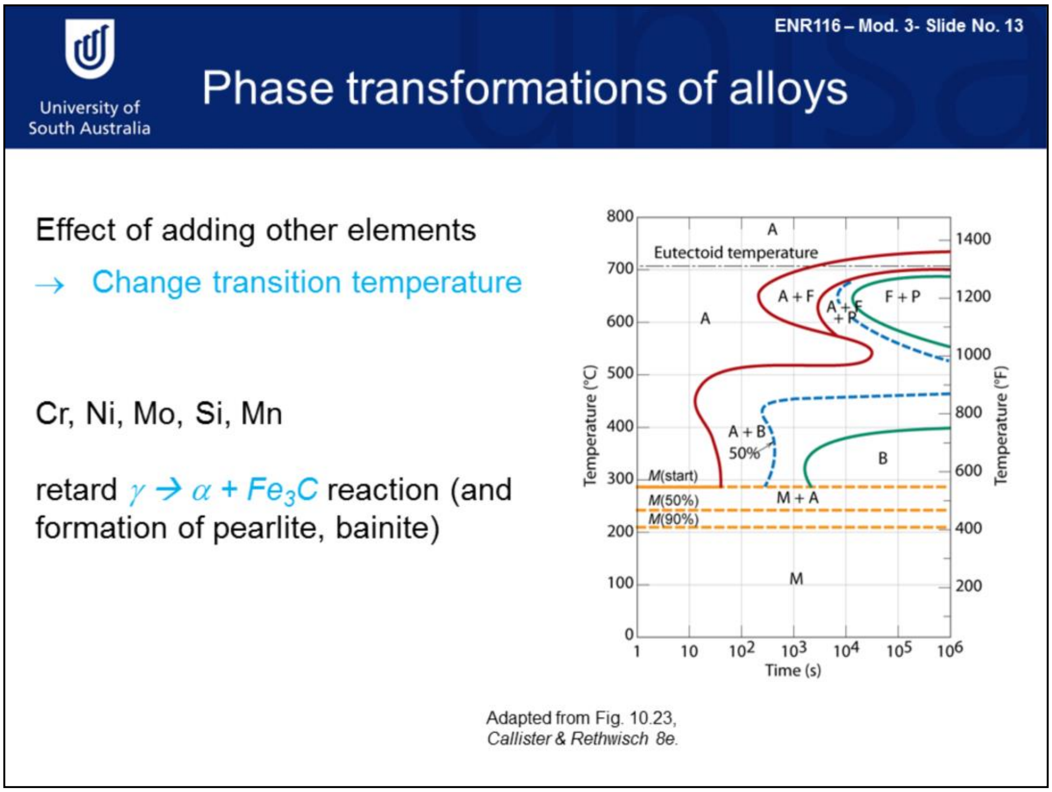
Finally, a slightly more complex example. Here we have been asked to generate 50% fine pearlite, 25% bainite and 25% martensite. When we have a problem that requires multiple microstructures such as this, start by identifying the highest temperature species and determine the reaction pathway to that one first.

Here, the fine pearlite is the highest temperature component. Fine pearlite is formed at temperatures just above the nose. We only want to convert 50% of the sample to pearlite, so we need to stop at this point here, corresponding to a temperature of about 570 degrees C, and 3 seconds. So, cooling to 570 degrees C, and holding for 3 s. We now have 50% fine pearlite, and 50% unmodified austenite.

Next we want to take half of the remaining austenite, and convert it to bainite. As we have 50% austenite remaining, converting just half of this will give us the 25% bainite we need. The fifty percent bainite point is here, corresponding to about 400 degrees C and 50 seconds. So next, we’ll cool the sample to 400 degrees C, and hold it at this temperature for 50 seconds.

OK, now we have 50% fine pearlite, 25% bainite and 25% unmodified austenite. Lets convert that final 25% austenite to martensite, by rapidly cooling to room temperature.

This give us the microstructure we need: 50% fine pearlite, 25% bainite and 25% martensite. Recapping the pathway we determined: we started by cooling to 570 degrees C, and holding at this temperature for 3s. This gave us the 50% fine pearlite. Next we cooled the sample to 400 degrees, and held for 50s. This generated the 25% bainite. Rapid quenching to room temperature converted the remaining 25% austenite to martensite.



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Phase transformations of alloys

Effect of adding other elements

→ Change transition temperature

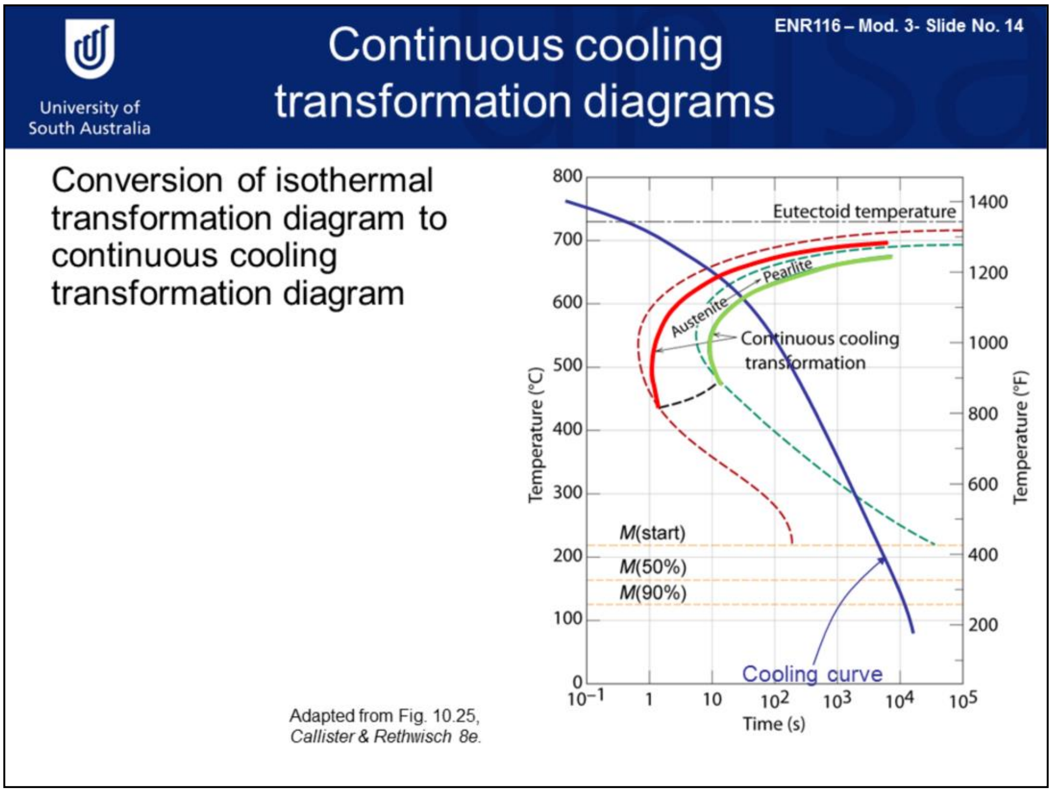
Cr, Ni, Mo, Si, Mn

retard $\gamma \rightarrow \alpha + Fe_3C$ reaction (and formation of pearlite, bainite)

Adapted from Fig. 10.23, *Callister & Rethwisch 8e.*

As a last note, many of the heat treatments for the iron-iron carbide system are energy intensive. They require holding material at high temperatures for extended periods of time. However, by adding alloying elements, other than carbon, we can alter the transformation temperatures to our advantage.

Elements such as chromium, nickel, manganese and others cause the transformation from austenite to pearlite and other microstructural features to be delayed or retarded, and as such the rates at which we need to quench are lower and more energy efficient. It also means we can work with large workpieces.



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Continuous cooling transformation diagrams

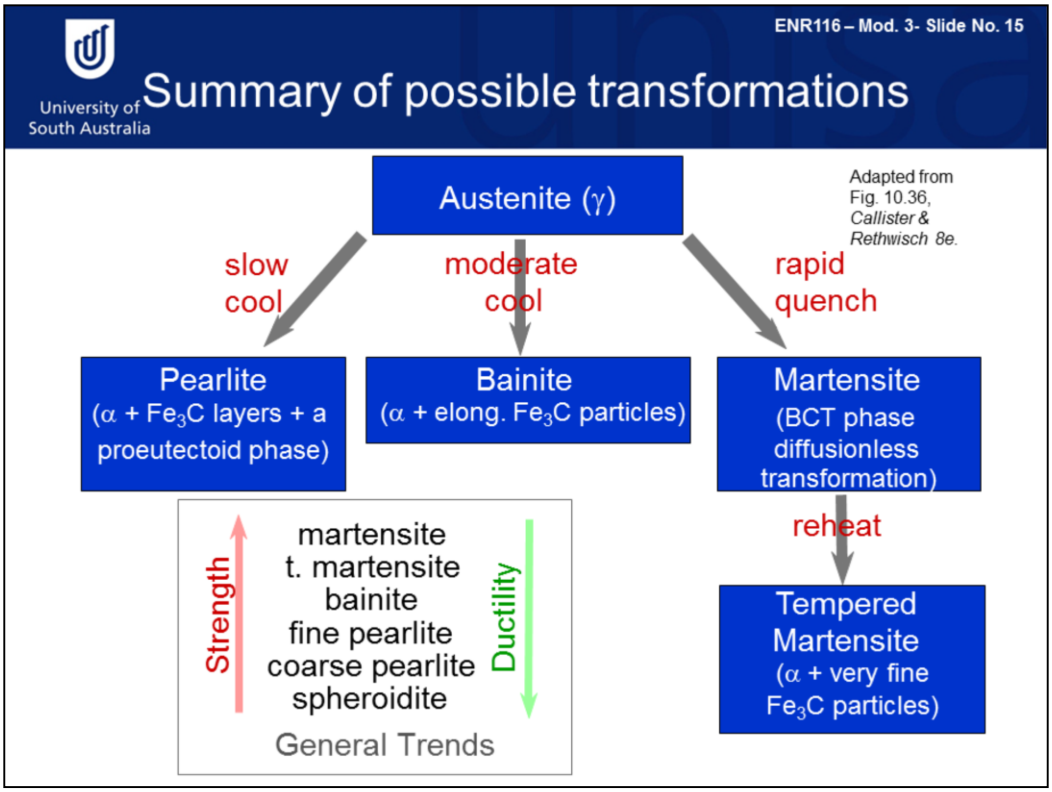
Conversion of isothermal transformation diagram to continuous cooling transformation diagram

Adapted from Fig. 10.25, *Callister & Rethwisch 8e.*

Now, although alloying elements can alter transformation temperatures, many isothermal heat treatments are still impractical, requiring rapid cooling and holding at set temperatures for long periods. In practice we employ a process known as continuous cooling. In this case a workpiece is cast from molten and cools over time. This continuous cooling is seen as the purple cooling curve here.

As a result of continuous cooling, the time required for a reaction to begin and end are shifted to longer times. You can see here in the solid lines on your screen here.

By selecting the correct cooling rate for the appropriate workpiece size/volume we can still keep control of the final microstructure. Note, however, that to form martensite we still need to rapidly quench the sample.



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Summary of possible transformations

Austenite (γ)

Adapted from Fig. 10.36, *Callister & Rethwisch 8e.*

Pearlite (α + Fe_3C layers + a proeutectoid phase)

Bainite (α + elong. Fe_3C particles)

Martensite (BCT phase diffusionless transformation)

Tempered Martensite (α + very fine Fe_3C particles)

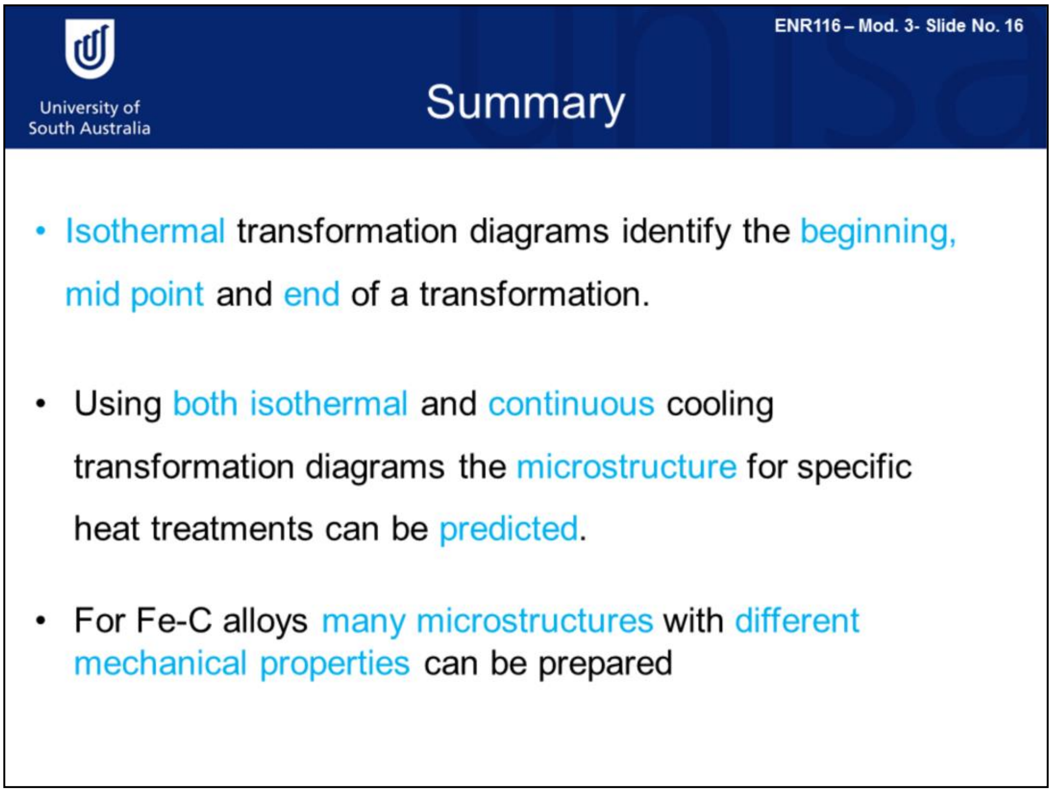
martensite
t. martensite
bainite
fine pearlite
coarse pearlite
spheroidite

General Trends

This slide summarises the possible transformations of the iron-iron carbide system, and shows why iron and steel have such an important place in our technological history and development.

Starting from austenite, we can tailor the processing to generate one of a number of microstructures, such as pearlite, achieved by slow cooling to temperatures near the eutectoid, bainite, the result of moderate cooling, and martensite, which is the product of rapid quenching. Tempered martensite is produced when martensite is reheated.

The flexibility of the iron-iron carbide system gives us, as materials engineers, access to a very large range of mechanical properties.



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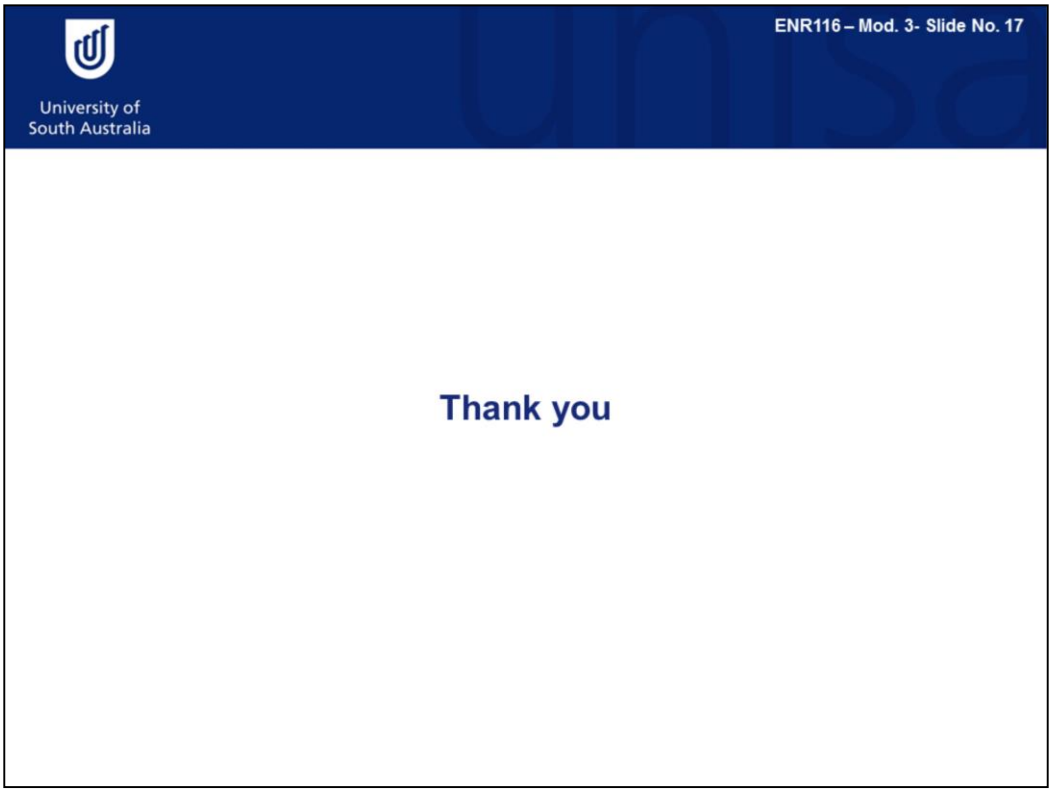
Summary

- Isothermal transformation diagrams identify the beginning, mid point and end of a transformation.
- Using both isothermal and continuous cooling transformation diagrams the microstructure for specific heat treatments can be predicted.
- For Fe-C alloys many microstructures with different mechanical properties can be prepared

So in summary we can use transformation diagrams to follow the start and finish of transformations, to predict the likely microstructures for specific heat treatments and finally, manipulate these to prepare a large range of alloys with many different mechanical properties.



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Thank you

If you have any questions or desire further clarification please post a question or comment on the Engineering Materials Discussion Forum.