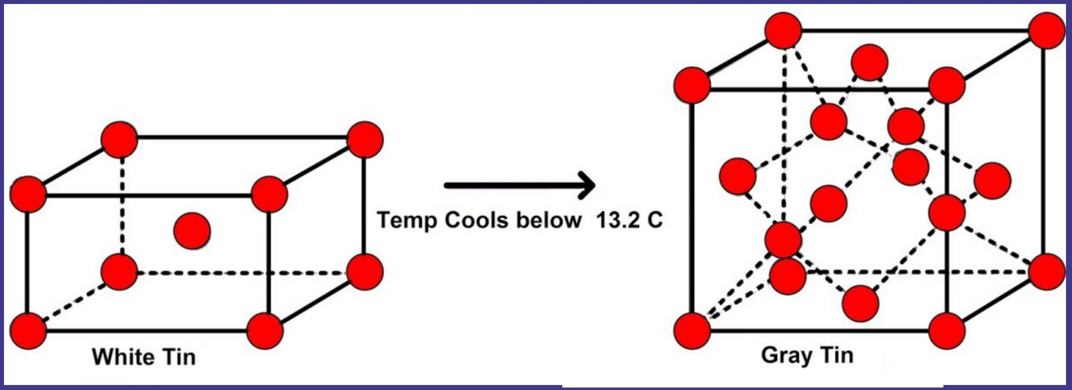
Imperial College London

Materials and Manufacturing



https://www.youtube.com/watch?v=FUoVEmHuykM

Metals and engineering alloys I

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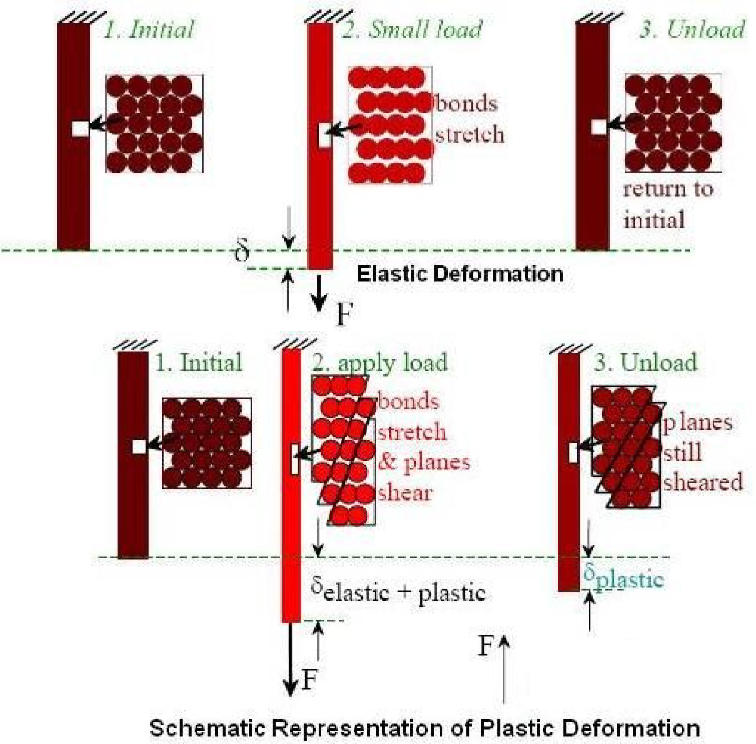
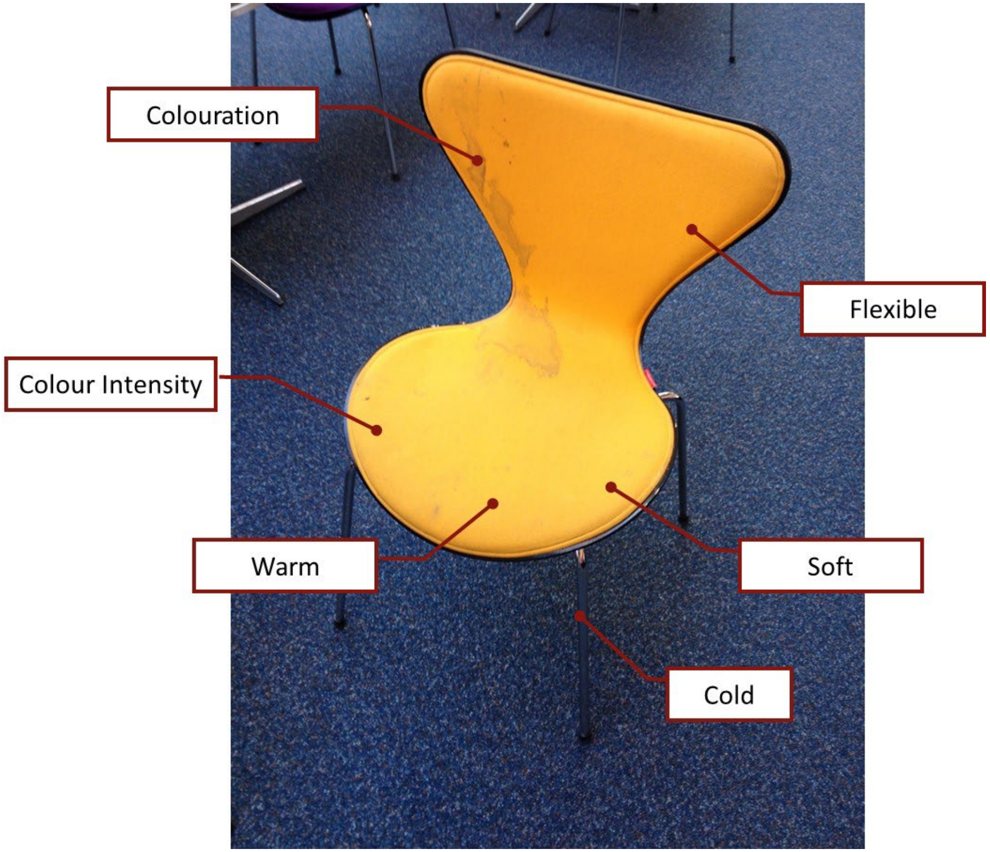
Dyson School of Design Engineering

Last time on M&M…

Materials properties and experience

- Stress-strain diagrams
- Elastic-plastic deformation
- Young's Modulus, Poisson's ratio, ductility, hardness, yielding





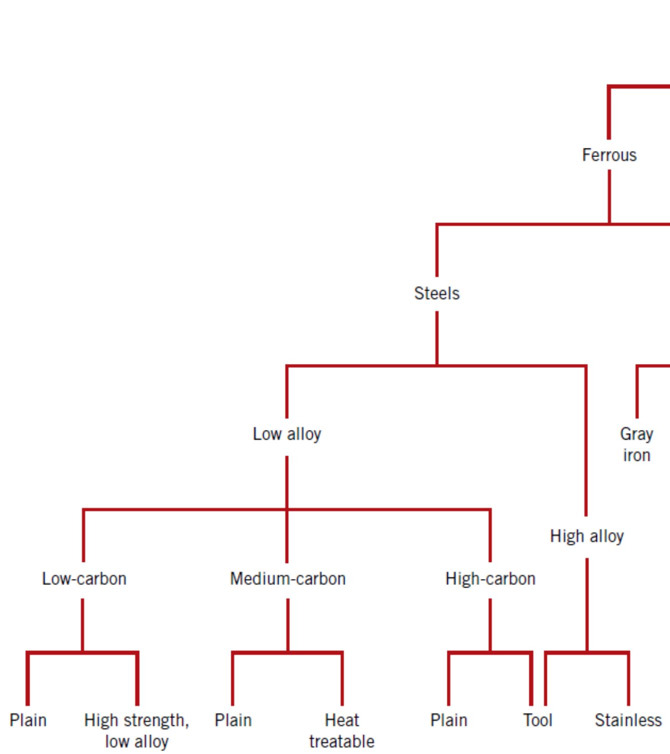
Learning objectives

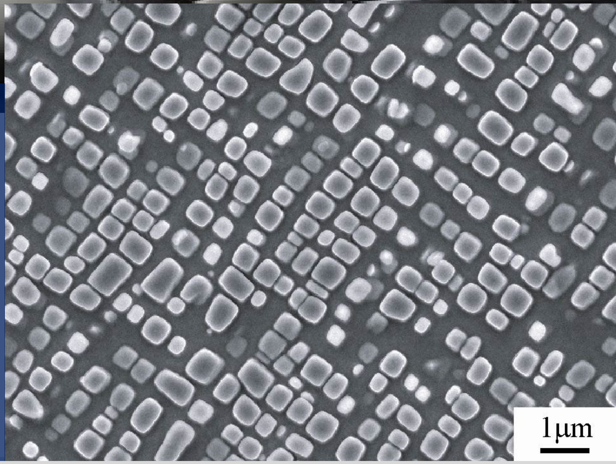
- Describe why alloys are used and be able to define the terms used for their description
- Evaluate an equilibrium phase diagram and be able to label the various lines and regions present
- Apply the lever rule to determine key characteristics of a phase diagram
- Analyse and describe the microstructural changes which occur when cooling an alloy of given composition from the liquid phase

Why is this important?

Often a materials problem is really one of selecting the material that has the right combination of characteristics for a specific application. Therefore, the people who are involved in the decision making should have some knowledge of the available options.

By combining different metals to create alloys we can create unique properties





Nickel superalloy

- Excellent mechanical strength
- High resistance to creep
- Good resistance to corrosion

It’s all about the money…

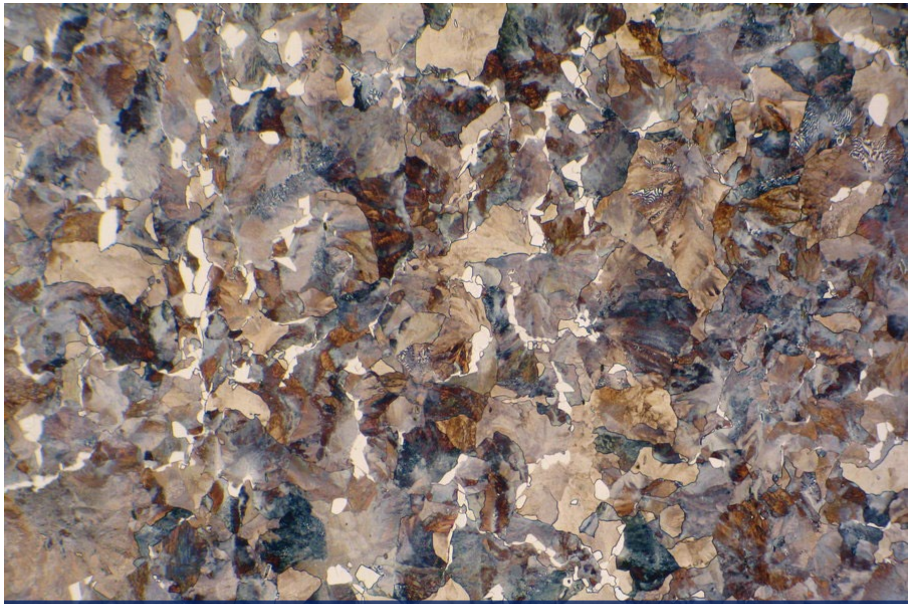
Euro coin requirements

- Ability to distinguish one denomination from the other (colour)
- Security – difficult to counterfeit – Vending machines use conductivity
- Easy to manufacture – soft and ductile so can be stamped
- Wear resistant
- High corrosion resistance
- Anti-bacterial characteristics

Copper (base metal)

- €2 – bimetallic – Outer ring 75Cu-25Ni (silver colour) – Inner ring 75Cu-20Zn-5Ni (gold colour)
- €1 – bimetallic – Reverse of €2
- 50, 20 and 10 cent – Nordic gold alloy – 89Cu-5Al-5Zn-1Sn
- 5, 2 and 1 cent – Copper plated steels

Basic concepts



Optical micrograph of Pearlite

Alloy

A mixture of a metal with one or more other metals or non-metals (binary, ternary etc)

Component

An element included in an alloy

Phase

A region of material having uniform physical and chemical characteristics

Composition

The mass of each component present in an alloy or phase

Constitution

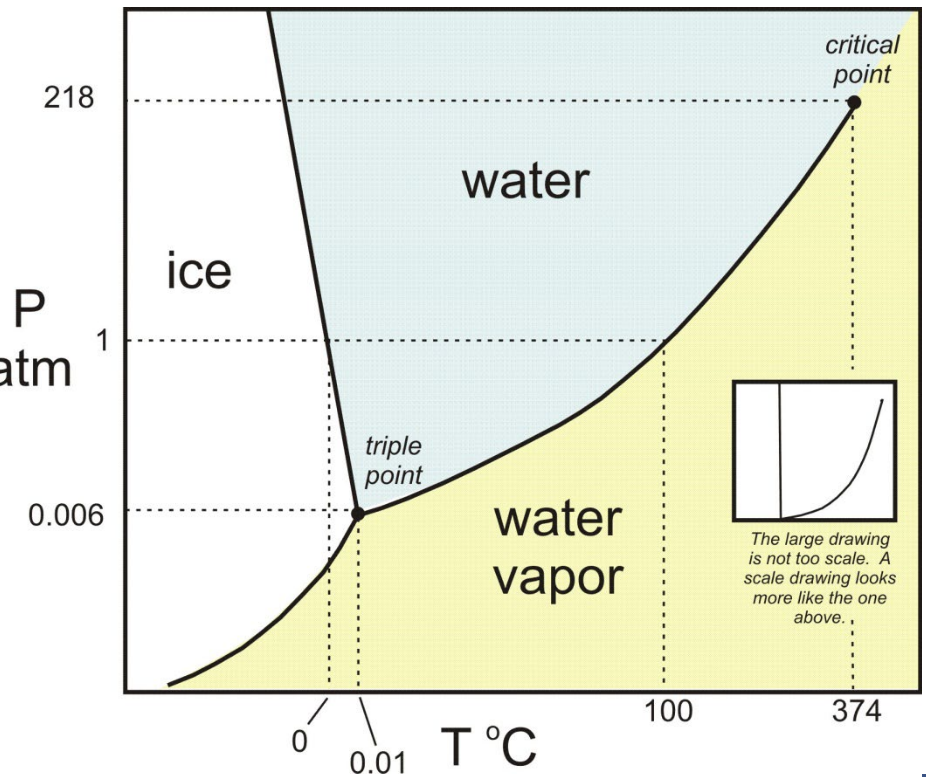
The sum of the phases, the mass of each phase and the composition

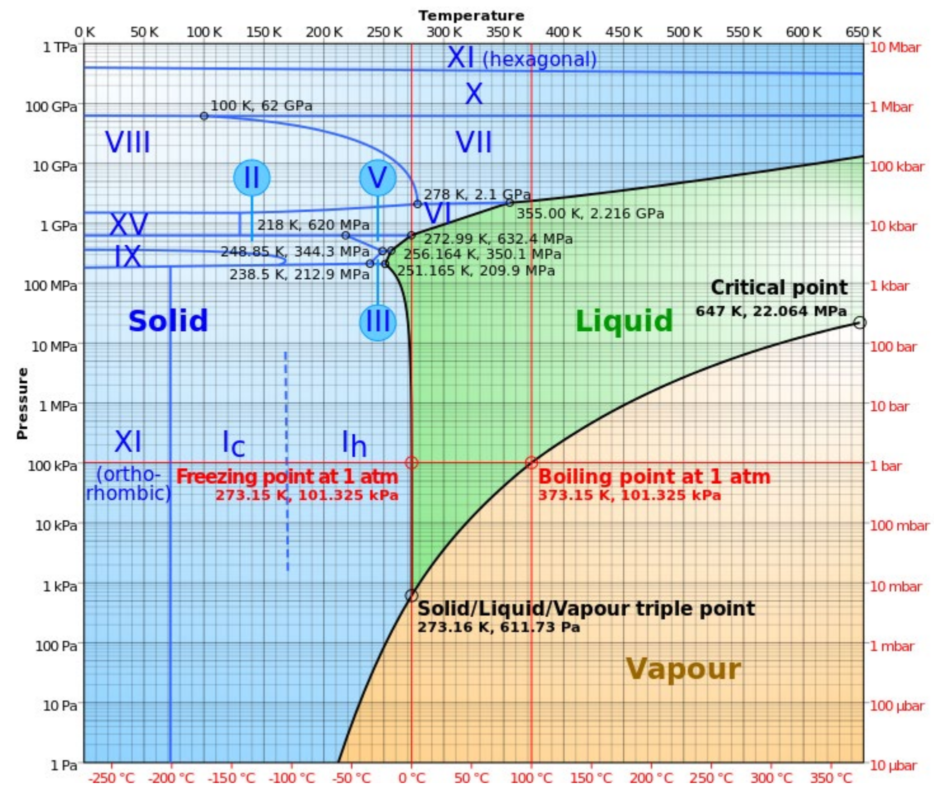
Phase diagram

The equilibrium constitution of all combinations of temperature and composition

Phases

A phase is a region of material having uniform physical and chemical characteristics



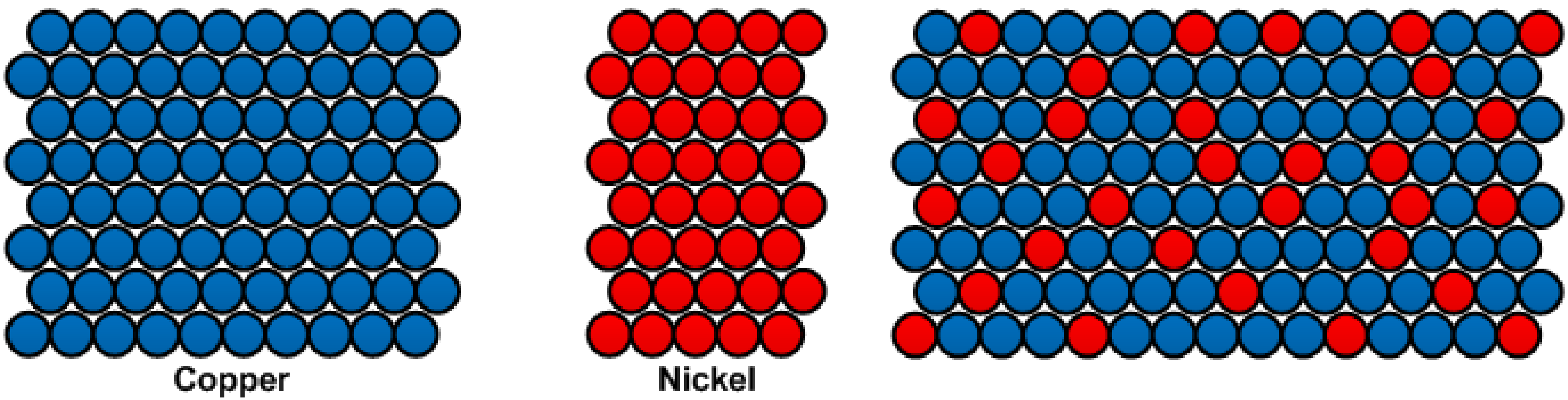


There are actually many phases of H_2O

Complete solid solubility

A **solid solution** is a single phase region in which solute atoms have mixed with solvent atoms to form a homogeneous composition

Complete solid solubility means that the solute atoms are completely soluble in the solvent atoms for any composition of solute and solvent. Thus, a second phase does not form if complete solid solubility exists.

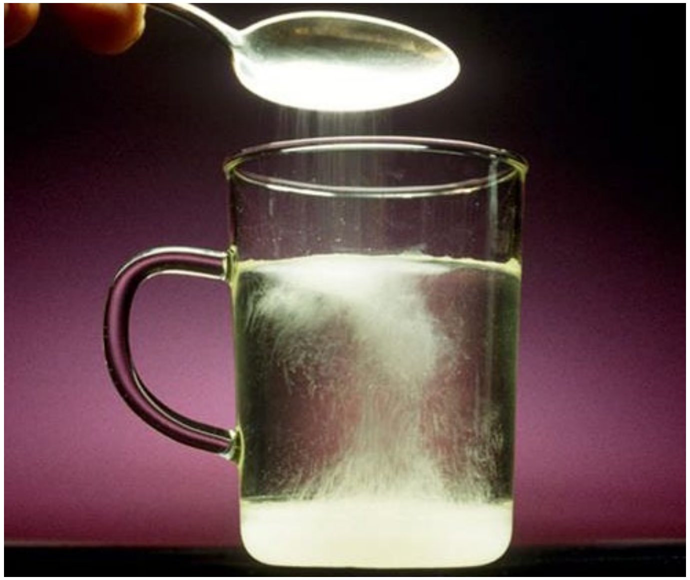


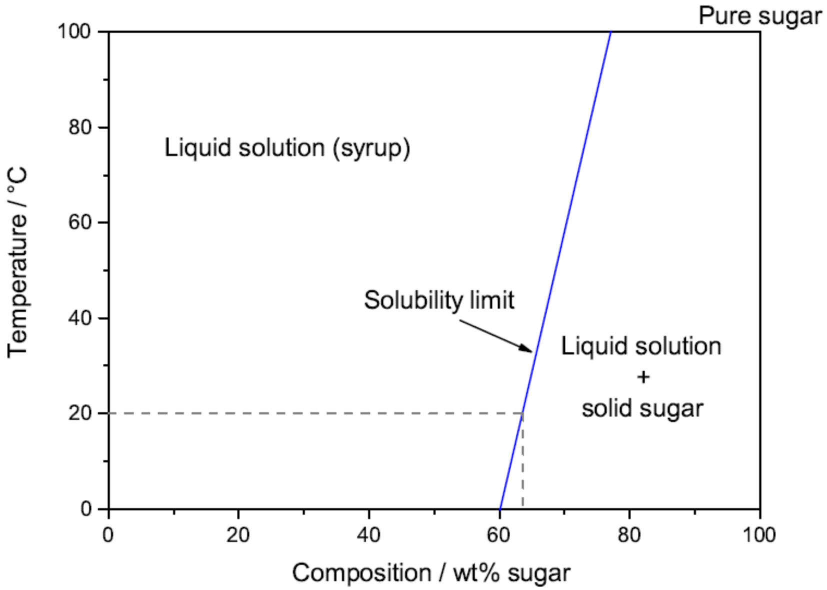
Limited (partial) solid solubility

Limiting the sweetness of your tea

Take for example water at room temperature and add sugar.

- First the sugar dissolves fully in the water to form a syrup solution
- However, if you add more than 65 wt % sugar to water then the solubility limit is reached and solid sugar forms at the bottom
- Below 65 wt% sugar, the mixture was a single phase solution but above 65 wt% sugar, we have two phases.



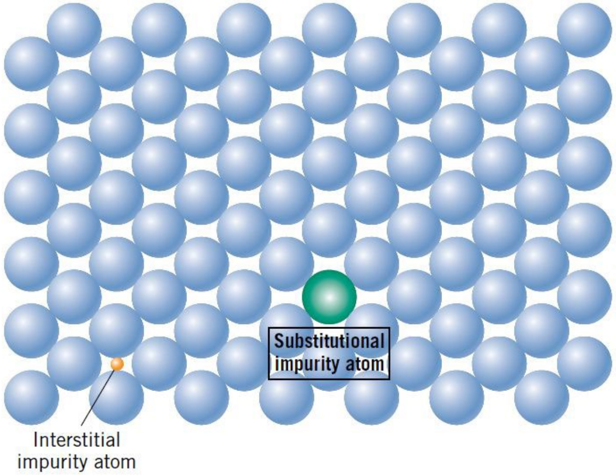


Equilibrium phase diagram

Limited (partial) solid solubility

Factors defining solid solutions

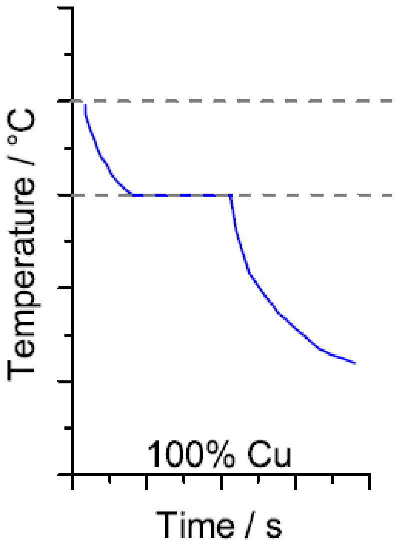
- **Atomic size factor**
  - A solute may be accommodated in this type of solid solution only when the difference in atomic radii between the two atom types is less than about 15%. Otherwise the solute atoms will create substantial lattice distortions and a new phase will form
- **Crystal structure**
  - For appreciable solid solubility the crystal structures for metals of both atom types must be the same
- **Electronegativity**
  - The more electropositive one element and the more electronegative the other, the greater is the likelihood that they will form an intermetallic compound instead of a substitutional solid solution
- **Valences**
  - Other factors being equal, a metal will have more of a tendency to dissolve another metal of higher valency than one of a lower valency.



Cooling curves

Creating alloys changes their properties

- When cooling a metal from the liquid state the phase transition is related to a latent heat represented by the constant temperature region
- Nickel solidifies at a higher temperature than copper



Equilibrium phase diagram

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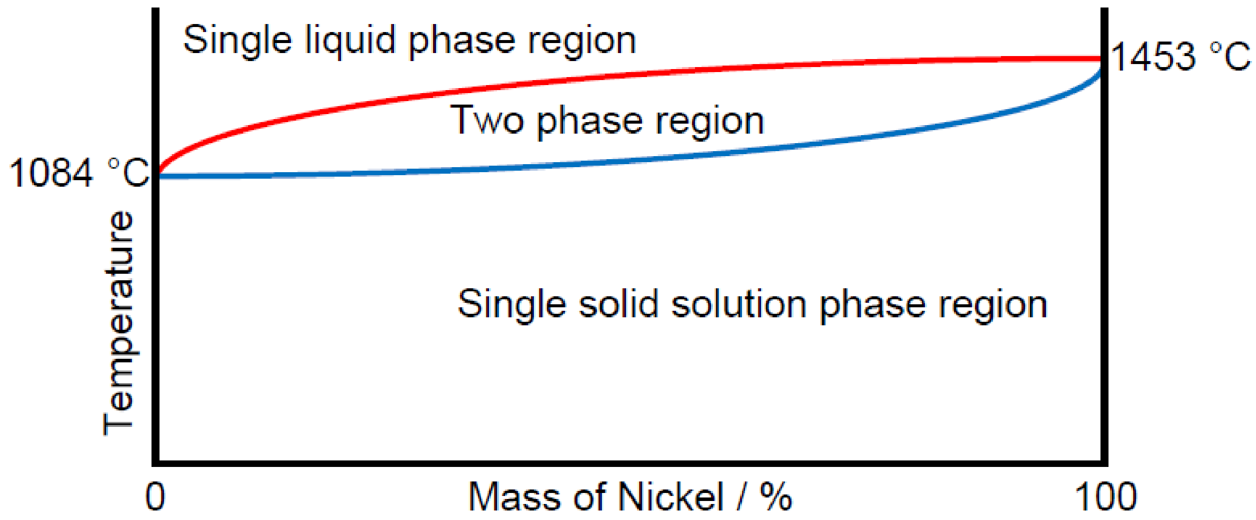
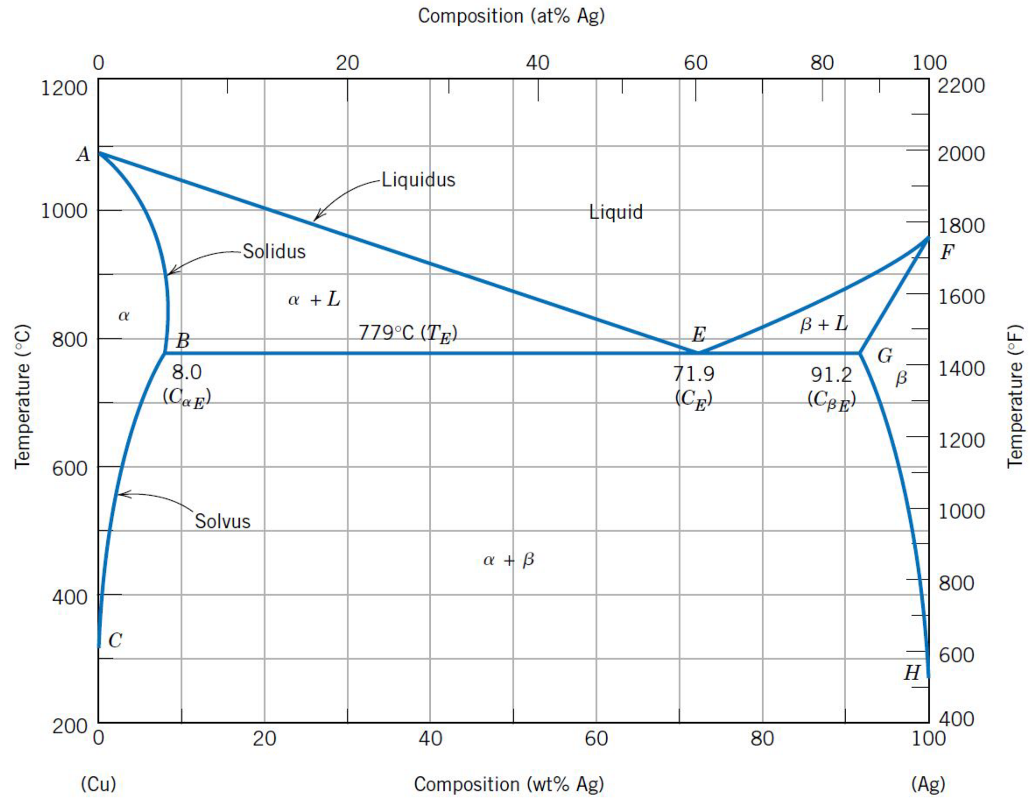


Equilibrium phase diagram for a complete solid solution

Phase diagram – Limited solubility

Limited solubility is when the solute atoms do not completely dissolve in the solvent

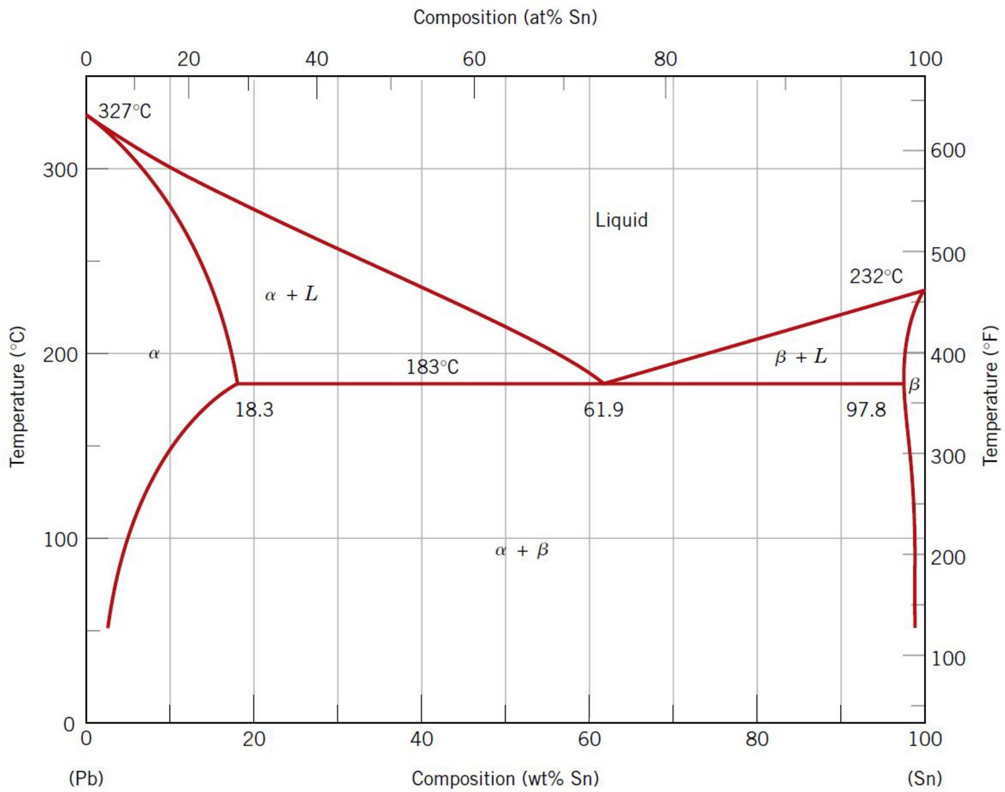
- A common binary phase diagram with limited solubility is silver (Ag)-copper(Cu)
- 3 single phase regions
  - α – solid solution with Ag as the solute
  - β – solid solution but Cu is the solute
  - L - Liquid
- **Solvus line**
  - Solid solubility limit line separating the α and β phase regions
- **Solidus line**
  - Represents the lowest temperature at which a liquid phase may exist
- **Liquidus line**
  - Temperature at which all components are liquid
- **Invariant point**
  - Point where liquidus lines meet (point E)

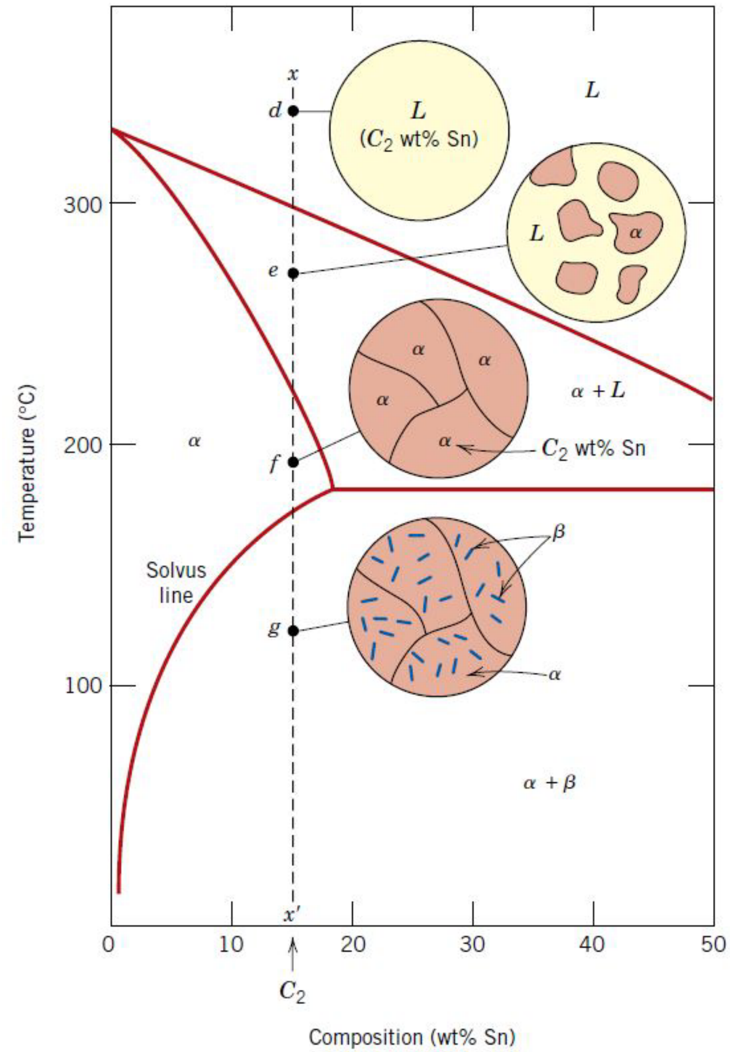


Equilibrium microstructure

Lead-tin alloys also show limited solubility

- Depending on the temperature and composition the microstructure of the material can be very different (all this assumes equilibrium conditions)

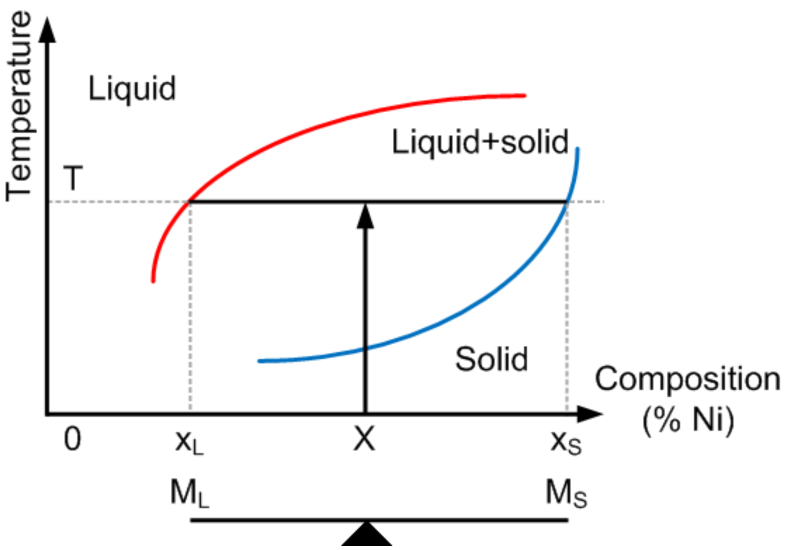




Lever rule

To determine the amounts of each phase in a 2 phase region we must use the **lever rule**

1. A tie line is constructed across the two-phase region at the temperature of the alloy
2. The overall alloy composition is located on the tie line
3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the other phase, and dividing by the total tie line length
4. The fraction of the other phase is determined in the same manner
5. If phase percentages are desired, each phase fraction is multiplied by 100. When the composition axis is scaled in weight percent the phase fractions computed using the lever rule are mass fractions-the mass (or weight) of a specific phase divided by the total alloy mass (or weight). The mass of each phase is computed from the product of each phase fraction and the total alloy mass



Lever rule - Example

Find the relative mass proportions of solid and liquid phases present in a 2 phase region of a Cu-Ni alloy

M = Total mass of the substance, M_L = Mass of the liquid phase, M_S = Mass of solid phase, M_N = Mass of the nickel,

Mass balance

$$M = M_L + M_S$$

Assume an arbitrary alloy composition X% of Ni

$$\frac{M_N}{M} = \frac{X}{100}$$

$$M_N = \frac{X}{100}(M_L + M_S)$$

In independent mass balance of Ni gives:

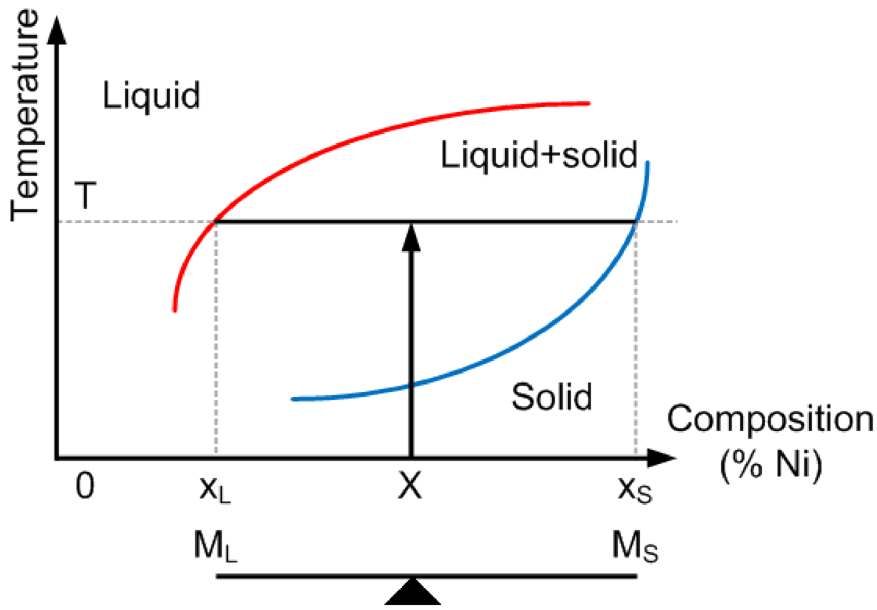
$$M_N = \left(\frac{x_L}{100}\right) M_L + \left(\frac{x_S}{100}\right) M_S$$

Eliminating between the 2 previous equations

$$(X - x_L)M_L = (x_S - X)M_S$$

In the 2 phase region $M_L + M_S = 1$ therefore

$$M_L = \frac{x_s - X}{x_s - x_L} \qquad M_S = \frac{X - x_L}{x_s - x_L}$$

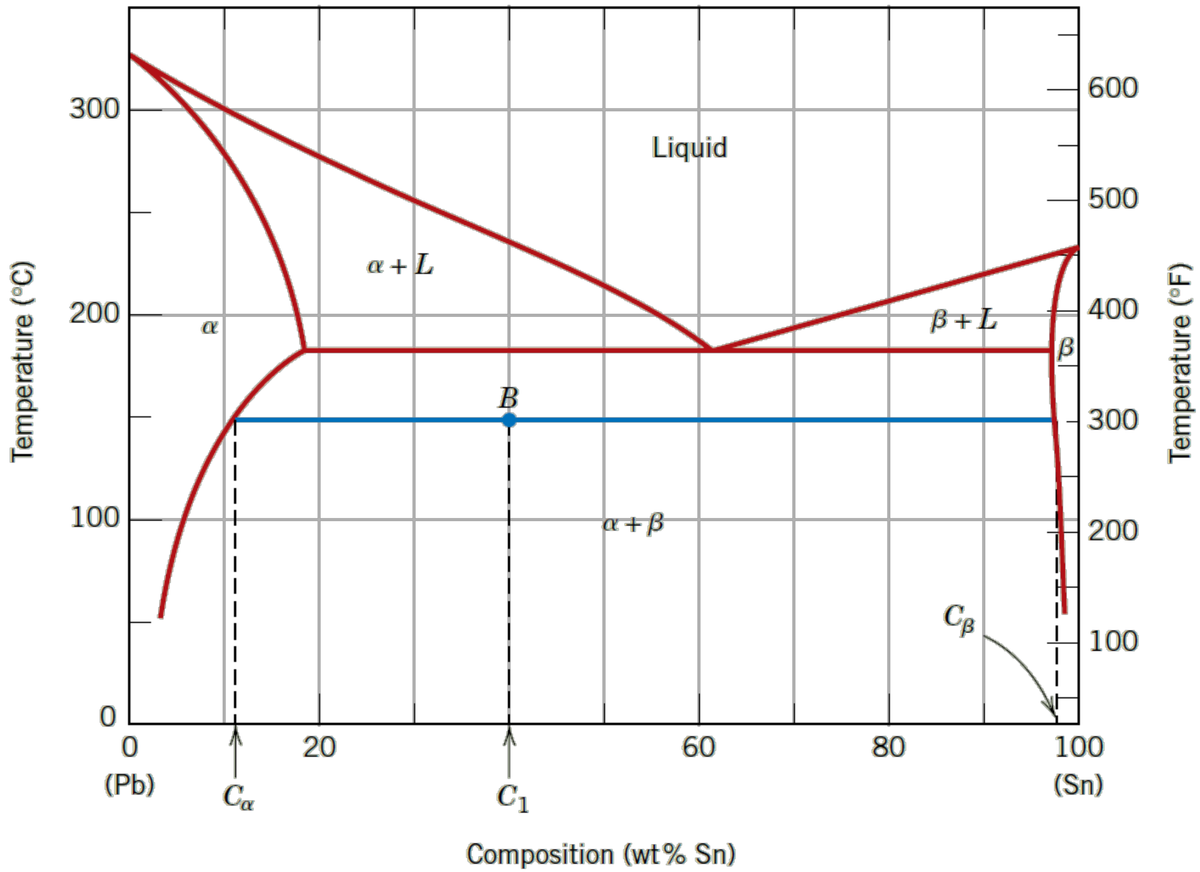


Lever rule – Example

For a 40 wt% Sn–60 wt% Pb alloy at 150 °C

What phase(s) is (are) present?

@ point B which is in the α+β region both α and β phases will co-exist

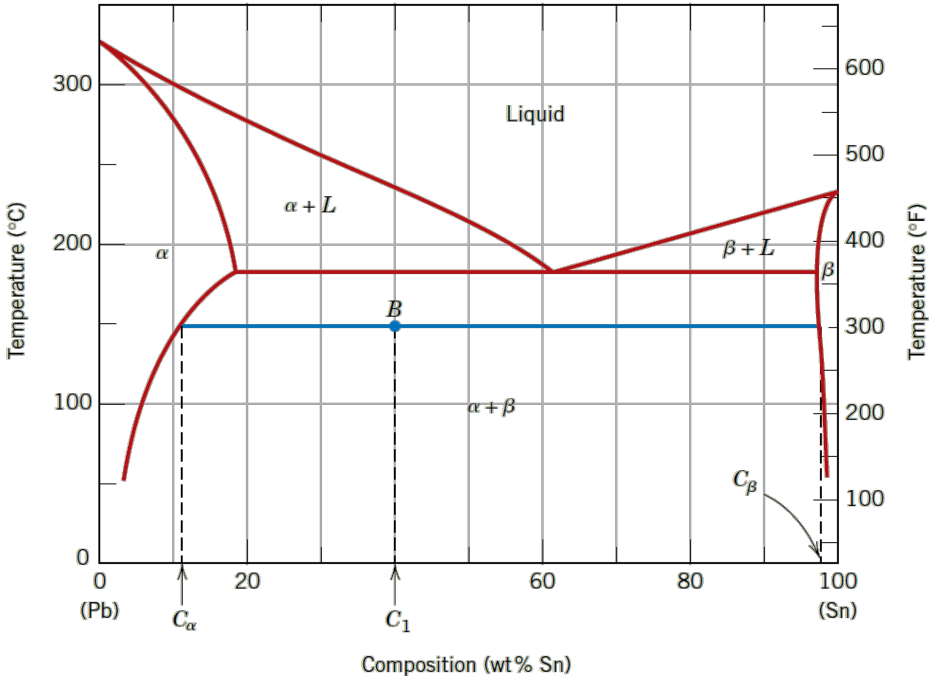


Lever rule – Example

For a 40 wt% Sn–60 wt% Pb alloy at 150 °C

What are the compositions of the phases?

1. Construct tie line at 150°C across the α+β region
2. The composition of α corresponds to the α/α+β solvus phase boundary with the tie line ~10 wt% Sn – 90 wt%Pb (C_α)
3. The composition of β corresponds to the β/α+β solvus phase boundary with the tie line ~98 wt% Sn-2 wt% Pb (C_β)



Lever rule - Example

For a 40 wt% Sn–60 wt% Pb alloy at 150 °C

What are the relative mass and volume fractions?

Assume densities of 11.23 and 7.24 g/cm^3 for Pb and Sn respectively

C_1 = Overall alloy composition, W_α= wt% α, W_β = wt% β

$$W_\alpha = \frac{C_\beta - C_1}{C_\beta - C_\alpha} = \frac{98-40}{98-10} = 0.66$$

$$W_\beta = \frac{C_1 - C_\alpha}{C_\beta - C_\alpha} = \frac{40-10}{98-10} = 0.34$$

$C_{Sn(\alpha)}$ = Concentration in wt% of tin in α

$C_{Pb(\alpha)}$ = Concentration in wt% of lead in α

$$\rho_\alpha = \frac{100}{\frac{C_{Sn(\alpha)}}{\rho_{Sn}} + \frac{C_{Pb(\alpha)}}{\rho_{Pb}}}$$

$$V_\alpha = \frac{\frac{W_\alpha}{\rho_\alpha}}{\frac{W_\alpha}{\rho_\alpha} + \frac{W_\beta}{\rho_\beta}}$$

$$\rho_\alpha = \frac{100}{\frac{10}{7.24 g/cm^3} + \frac{90}{11.23 g/cm^3}} = 10.64 g/cm^3$$

$$\rho_\beta = \frac{100}{\frac{98}{7.24 g/cm^3} + \frac{2}{11.23 g/cm^3}} = 7.29 g/cm^3$$

$$V_\alpha = 0.57$$

$$V_\beta = 0.43$$

Summary

- Describe why alloys are used and be able to define the terms used for their description
- Evaluate an equilibrium phase diagram and be able to label the various lines and regions present
- Apply the lever rule to determine key characteristics of a phase diagram
- Analyse and describe the microstructural changes which occur when cooling an alloy of given composition from the liquid phase

Keep flipping

Please watch this video on

"Why is the carbon content in steel so important"

https://youtu.be/-YIGjX-jcMo

Next time on M&M…