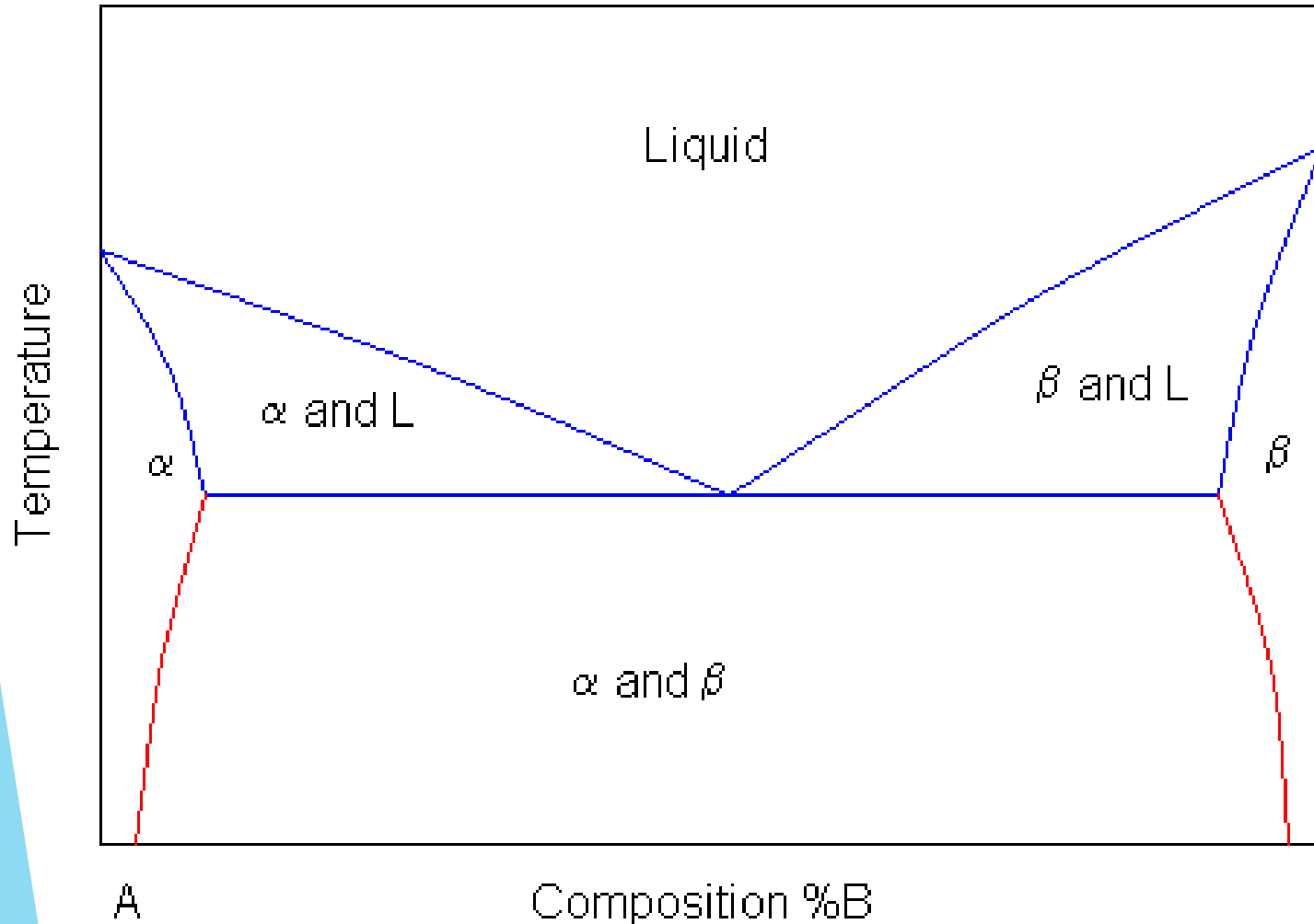


Solidification

Phase Diagram



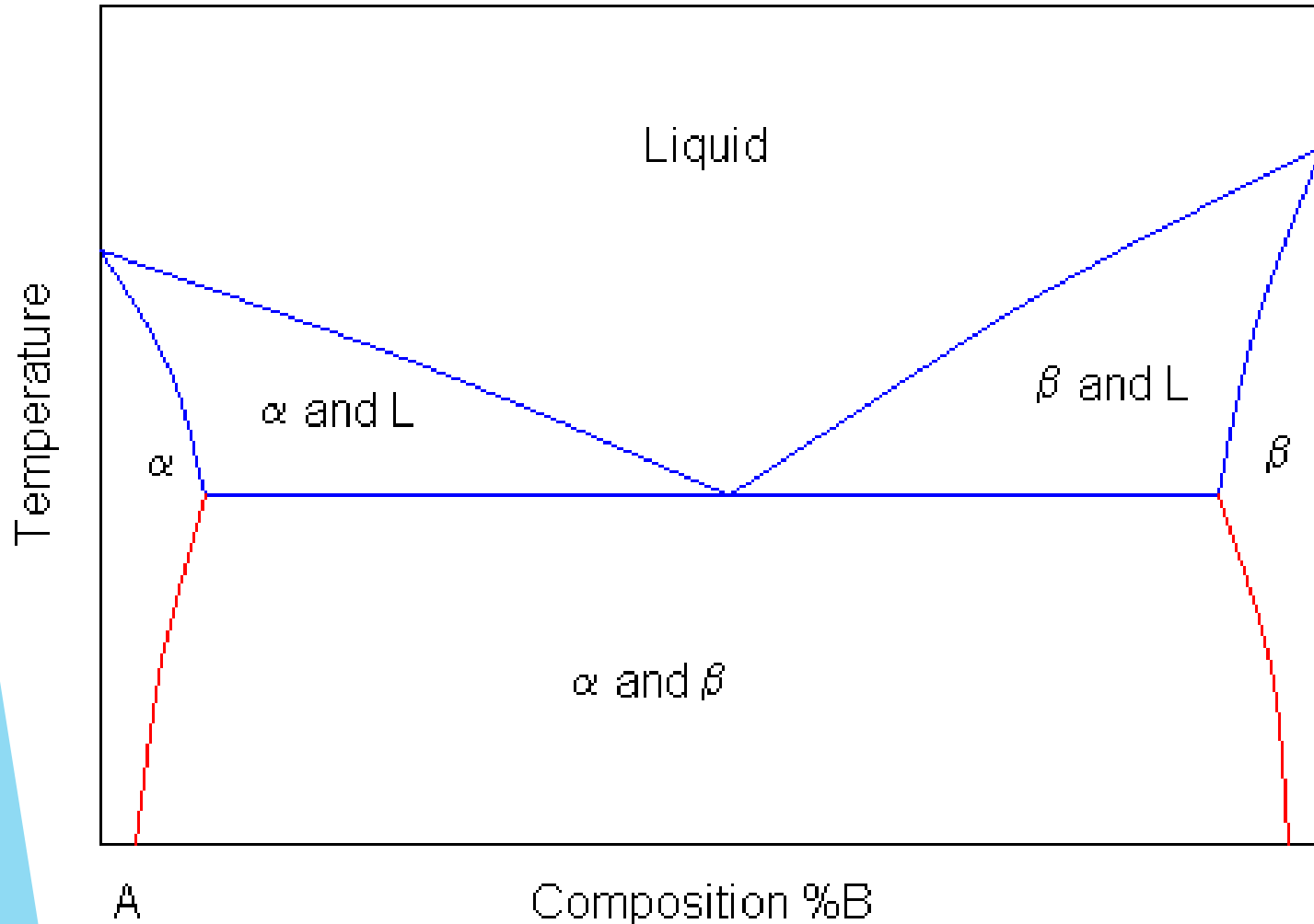
A phase diagram shows the equilibrium states of a mixture, so that given a temperature and composition, it is possible to calculate which phases will be formed, and in what quantities.

As such it is very valuable to be able to construct a phase diagram and know how to use it to predict behaviour of materials.

The main theory behind phase diagrams is based around the latent heat that is evolved when a mixture is cooled, and changes phase.

This means that by plotting graphs of temperature against time for a variety of different compositions, it should be possible to see at what temperatures the different phases form.

Phase Diagram

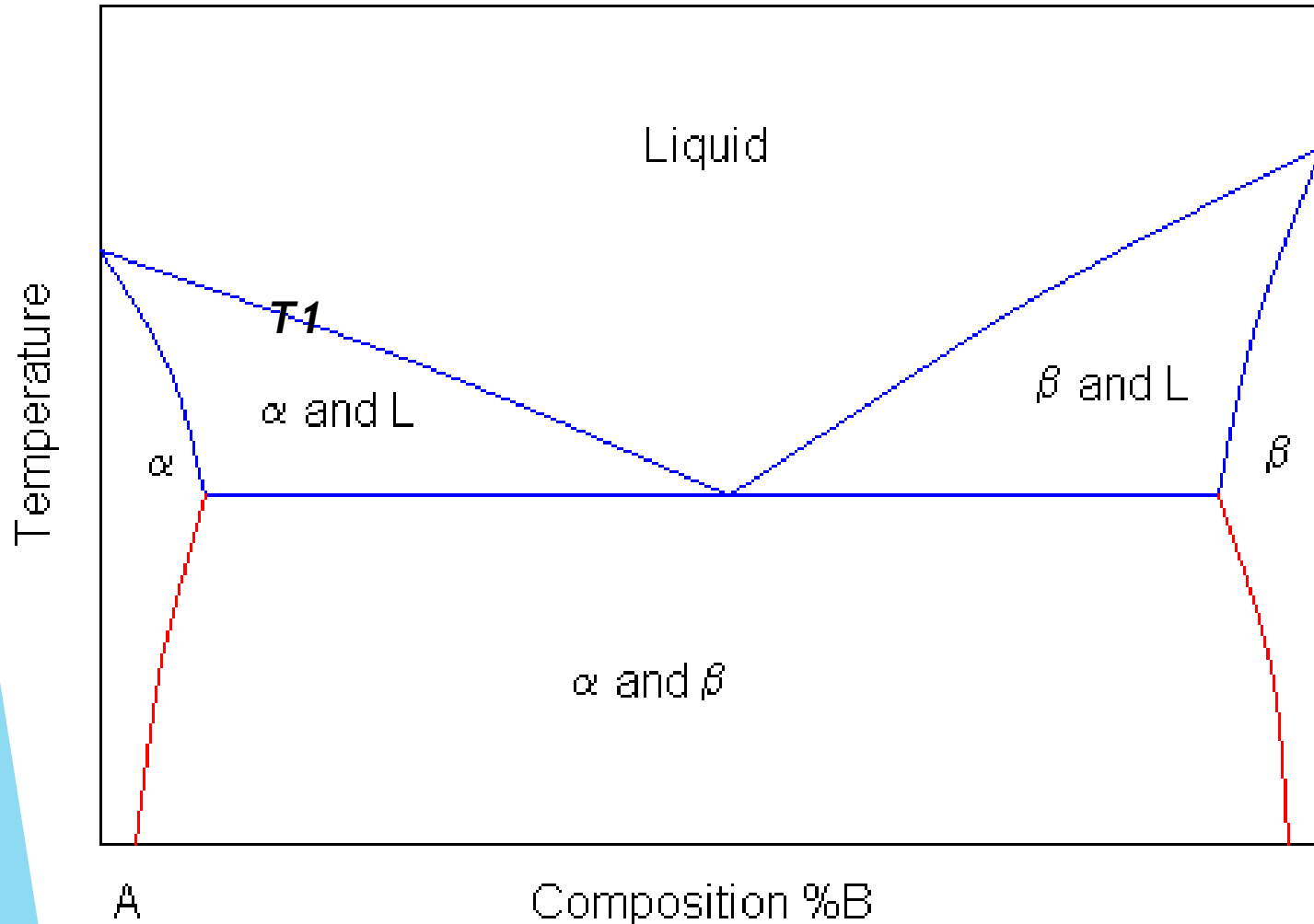


Where L stands for liquid, and A and B are the two components and α and β are two solid phases rich in A and B respectively. The blue lines represent the liquidus and solidus lines, which are relatively simple to measure. The red lines involve a solid-to-solid transition, and so require much more sensitive equipment.

However, there is a lot of thermodynamic theory behind phase diagrams, which allows more problematic or more complex systems to be predicted,

A crucial point to remember is that a phase diagram should always display the equilibrium phases, and so with cooler temperatures, these are hard to attain due to kinetic problems. Even at higher temperatures, there may be problems of having enough time for the solid to fully equilibrate as the system is cooling.

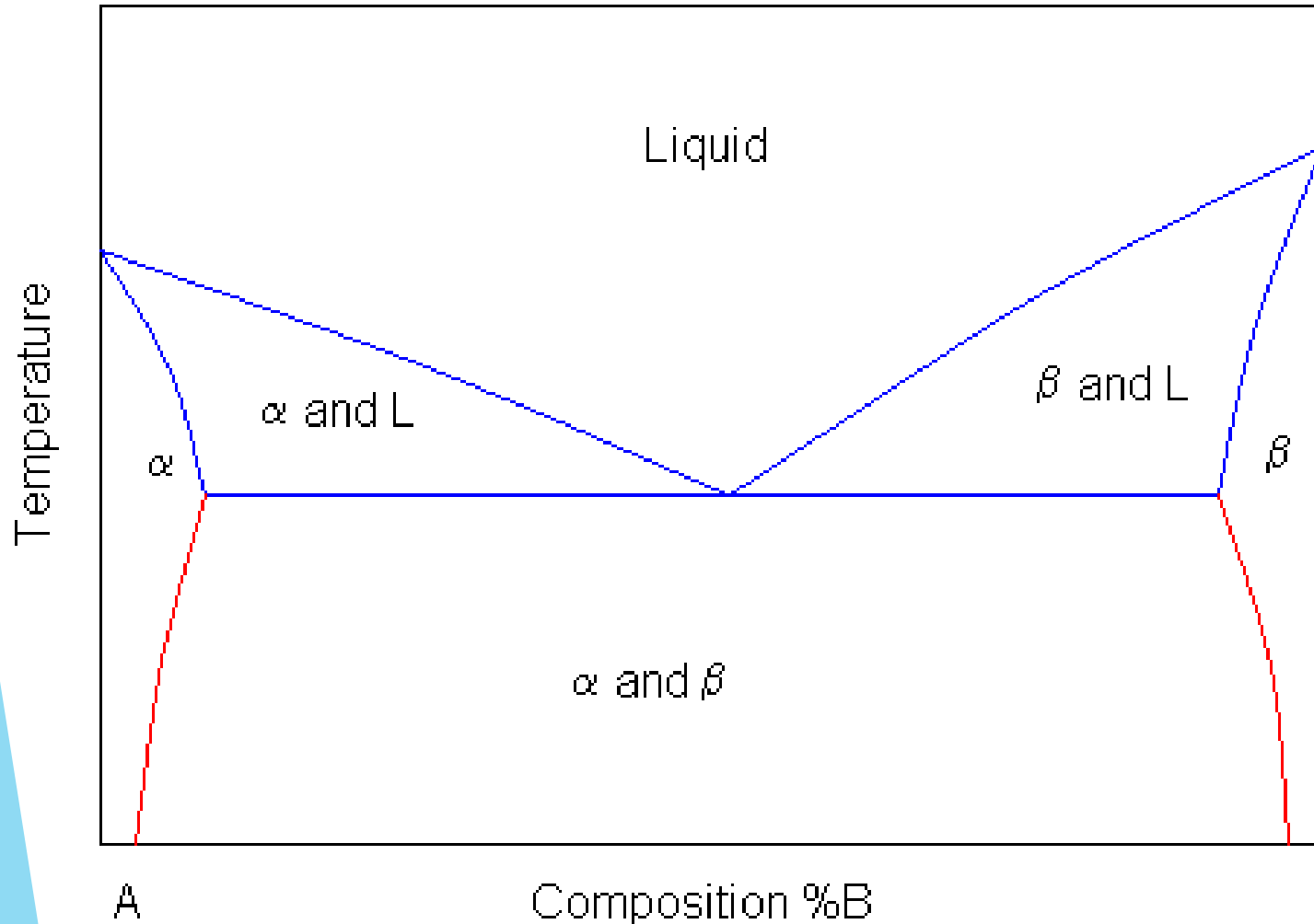
Phase Diagram



The mixture is slow cooled, undergoing no change in state until it reaches temperature T_1 , when it reaches the liquidus line. Here, as the labelling suggests, alpha starts to solidify at any favourable nucleation sites.

The alpha solidifies as dendrites which grow to become grains of alpha. The first solid to form is called the primary solid and so, in this case, primary alpha is formed.

Phase Diagram

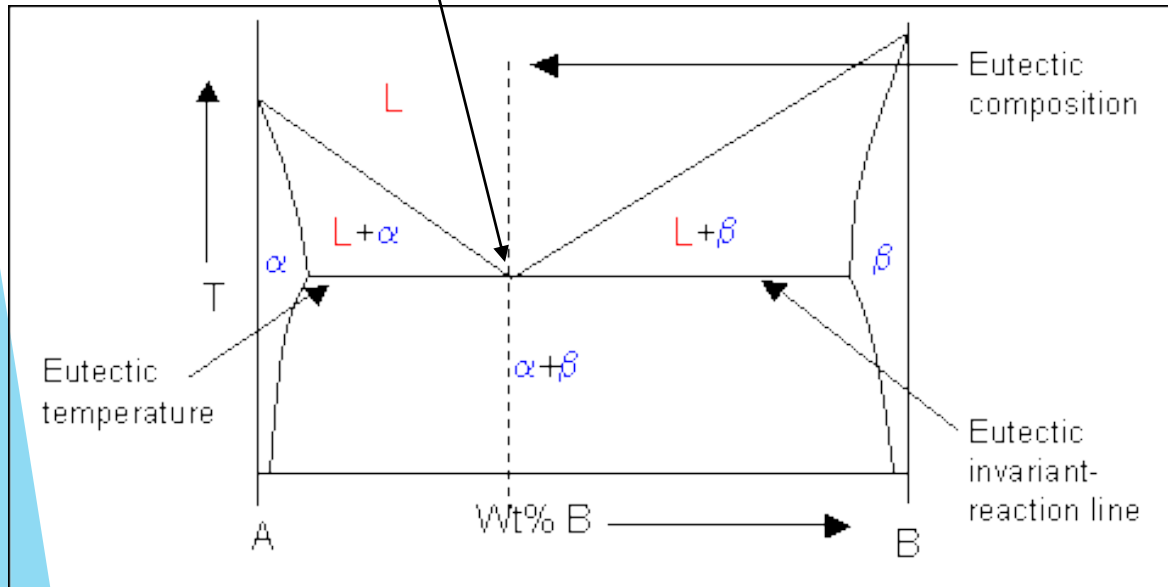


As the alloy continues to cool the existing nucleation sites will grow and further nucleation sites will continue to form within the liquid parts of the mixture. These nucleating and growing regions of solid alloy form **grains** and when these meet grain boundaries are formed. The primary alpha dendrites grow, which accounts for the shapes the alpha forms in cross sectional samples.

As the remaining liquid cools its composition becomes richer in B (effectively sliding down the liquidus line). The composition of the solid alpha also becomes richer in B, as shown by the phase diagram. If cooling is not sufficiently slow (i.e. non-equilibrium) then B atoms will not be able to diffuse into the centres of the grains of alpha. If this is the case then *coring (compositional difference between dendrites and inter-dendritic sites)* will occur.

Eutectic System

Eutectic or invariant point - Liquid and two solid phases co-exist in equilibrium at the eutectic composition CE and the eutectic temperature TE.



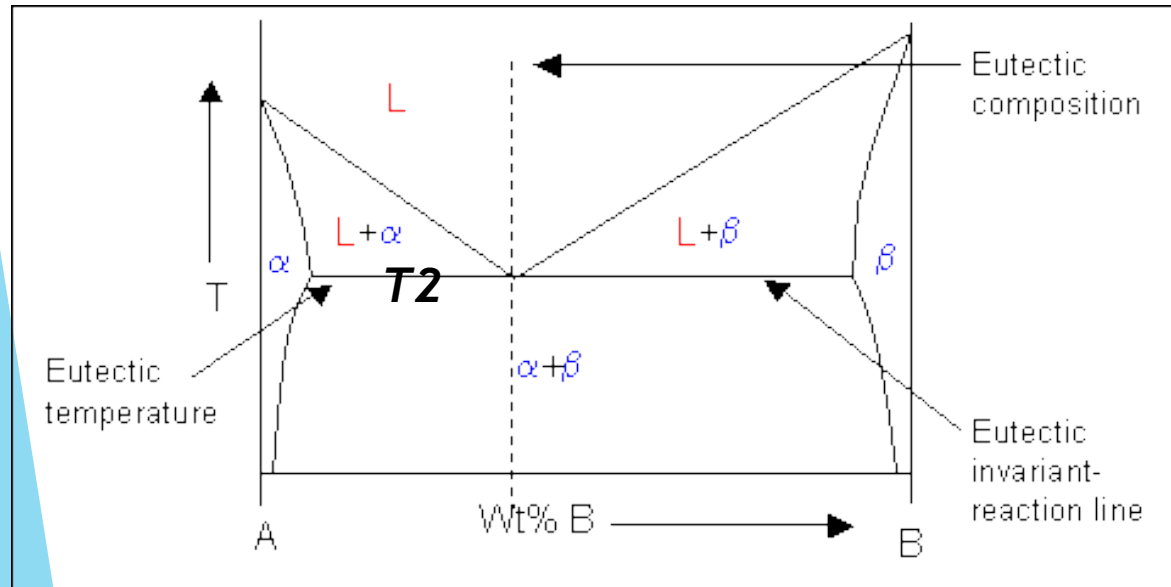
Eutectic systems have a liquidus which contains a V to the eutectic point where it meets the eutectic invariant-reaction line.

Here is an example of a eutectic phase diagram. α and β are both solid phases.

The two-phase solid region on the phase diagram will consist of a mixture of eutectic and either α or β phase depending on whether the alloy composition is hypoeutectic or hypereutectic. The constitution of an alloy under equilibrium conditions can be found from its phase diagram.

- ▶ When the composition of an alloy places it to the left of the eutectic point it is called hypo-eutectic. Note, though, that this is merely convention. If the phase diagram had been drawn the other way around, with 100%A on the right and 100%B on the left, then the same alloy would be called hyper-eutectic, as it would be to the right of the eutectic point.

Eutectic System

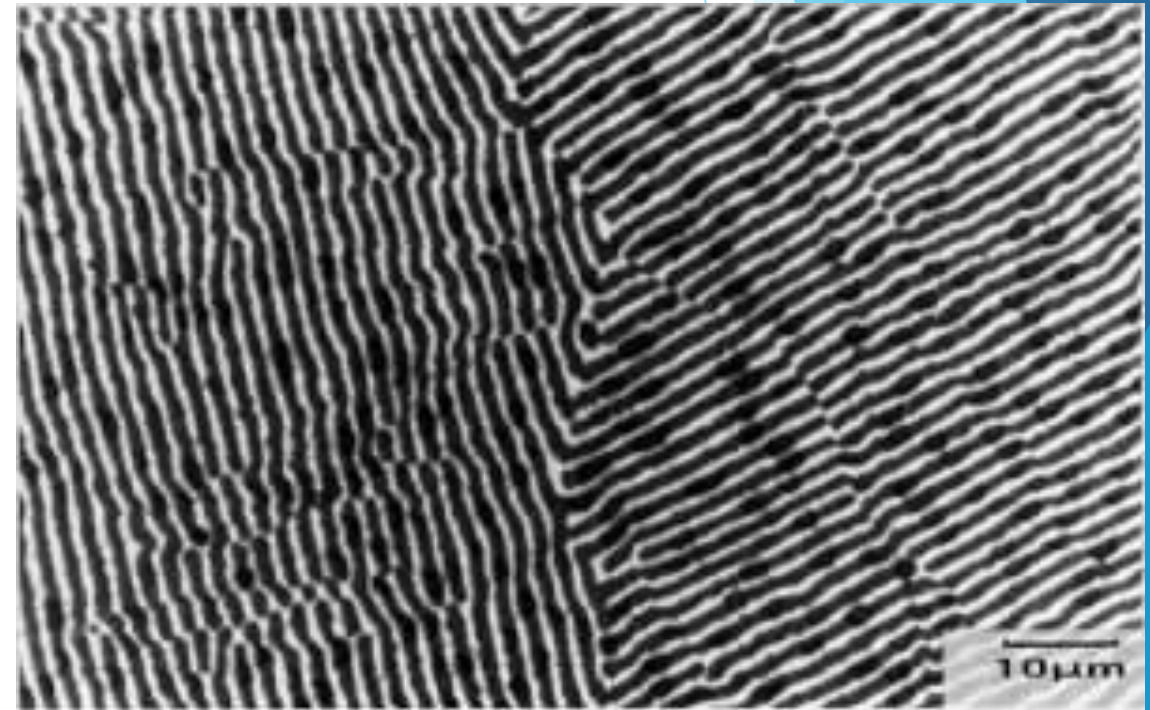


As alpha solidifies it removes A and B atoms from the remaining liquid. Alpha is mostly A (with a small amount of B) and so the remaining liquid becomes relatively *richer in B*. This continues until enough A has been removed so that the remaining liquid - sliding down the liquidus line - is of **eutectic composition**.

This composition will be achieved at temperature T_2 , at the point where the temperature crosses the eutectic line.

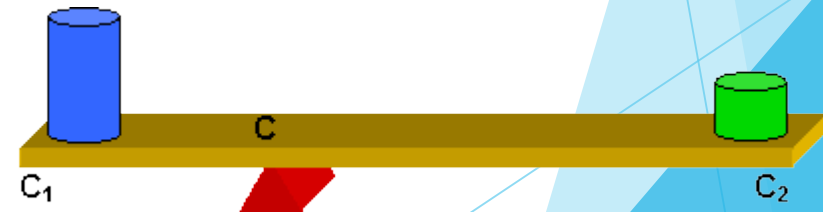
At this point alpha stops forming as a discrete solid and the remaining liquid starts to solidify into the stripy (lamellar) **eutectic composition** of alpha and beta. Therefore, solid eutectic forms.

- ▶ The existing eutectic nucleation sites will grow, adding alpha to the stripes of alpha and beta to the stripes of beta in the eutectic regions. New sites will continue to form.
- ▶ Note that, unlike the alpha solidification, it is not necessary to continue decreasing the temperature to achieve full solidification. The eutectic liquid solidifies in the same way as a pure solid, at a *specific temperature*.
- ▶ The entire alloy has now solidified into a mixture comprising *grains of alpha* and *grains of eutectic mixture* (alpha and beta). The diffusion processes through the solid, which occur as the alloy cools, are more complex than those of the eutectic case.
- ▶ As with a eutectic alloy, the amount of B in the alpha phase changes with temperature, and so B will have to diffuse through the alpha. This diffusion must also occur in the grains of pure alpha, as the composition of alpha also changes. This can be seen by examining the diagram.
- ▶ Therefore, as with eutectic alloys, it is important that the mixture is allowed to cool at equilibrium (i.e. slowly) to ensure full diffusion if the alloy is to be of exactly the composition dictated by its phase diagram.



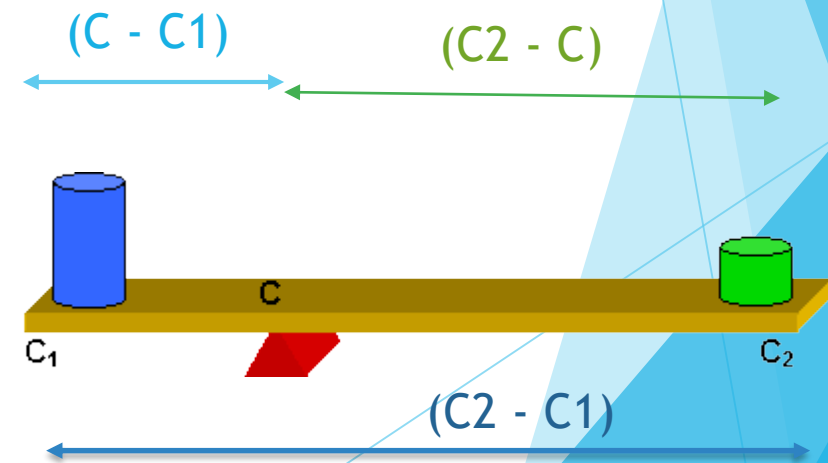
Lever rule

- ▶ If an alloy consists of more than one phase, the amount of each phase present can be found by applying the lever rule to the phase diagram.
- ▶ The lever rule can be explained by considering a simple balance. The composition of the alloy is represented by the fulcrum, and the compositions of the two phases by the ends of a bar. The proportions of the phases present are determined by the weights needed to balance the system.



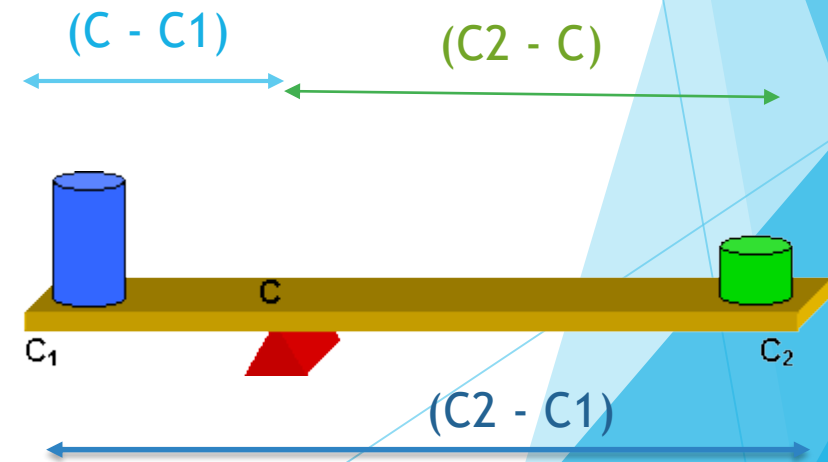
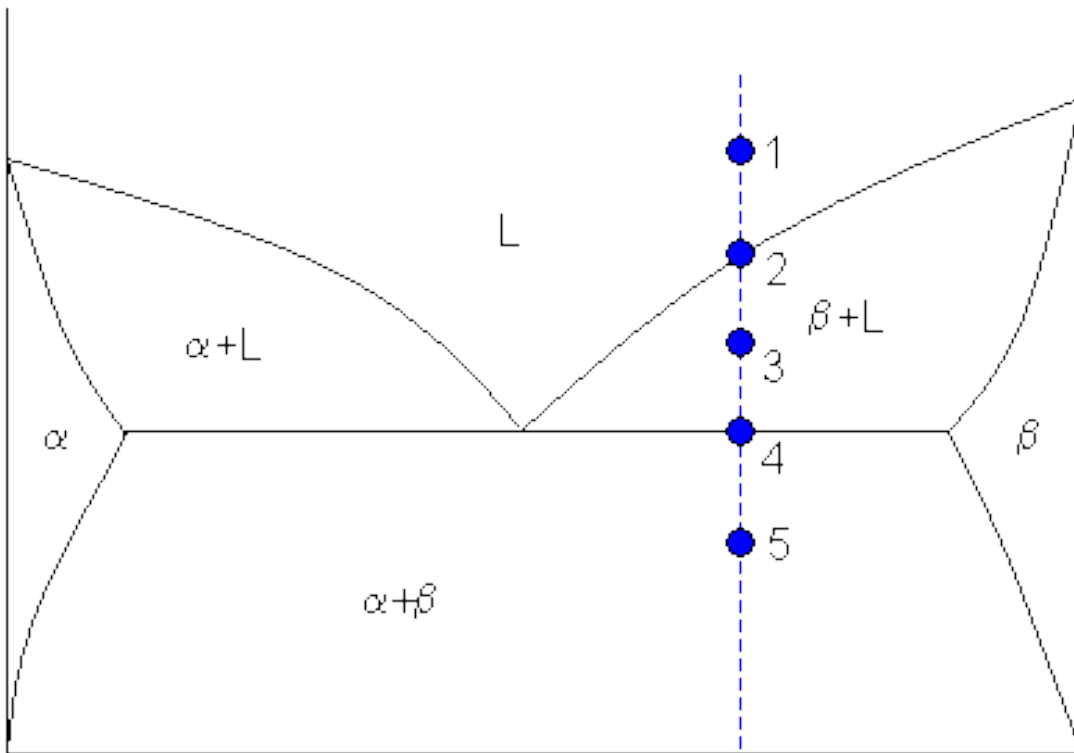
Lever rule

- ▶ So,
- ▶ fraction of phase 1 = $(C_2 - C) / (C_2 - C_1)$
- ▶ and,
- ▶ fraction of phase 2 = $(C - C_1) / (C_2 - C_1)$



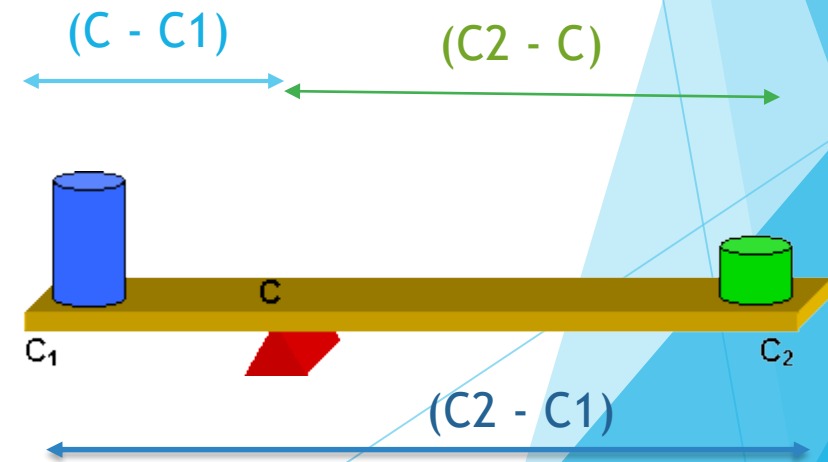
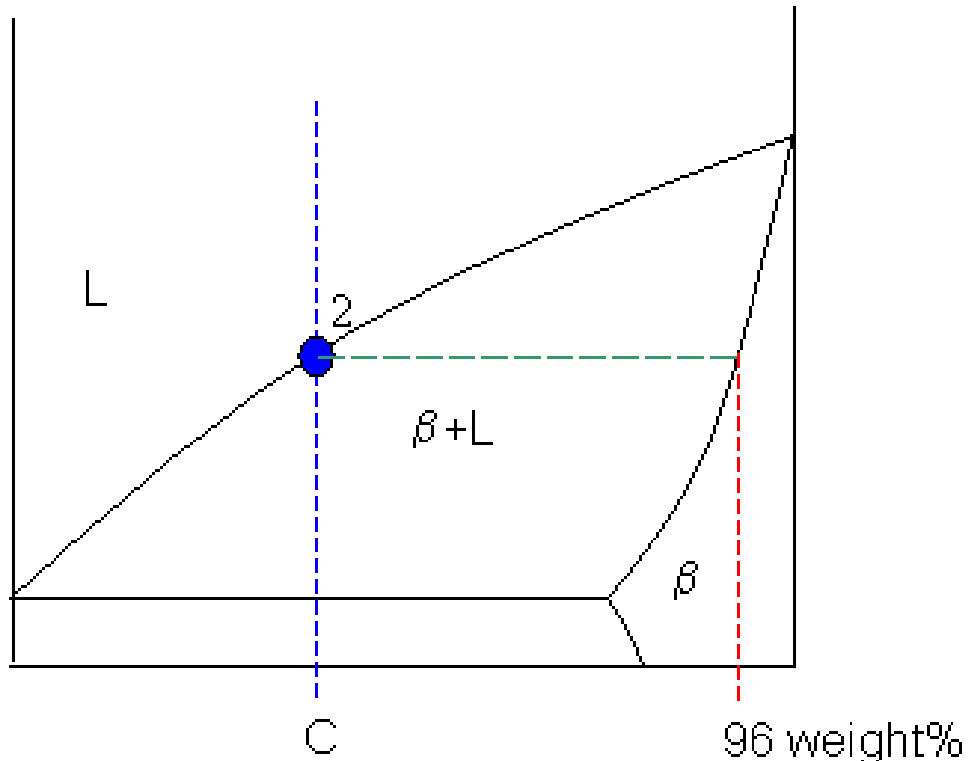
Lever rule applied to a binary system

- ▶ **Point 1**
- ▶ At point 1 the alloy is completely liquid, with a composition C . Let
- ▶ $C = 65$ weight% B.
- ▶ **Point 2**
- ▶ At point 2 the alloy has cooled as far as the liquidus, and solid phase β starts to form.

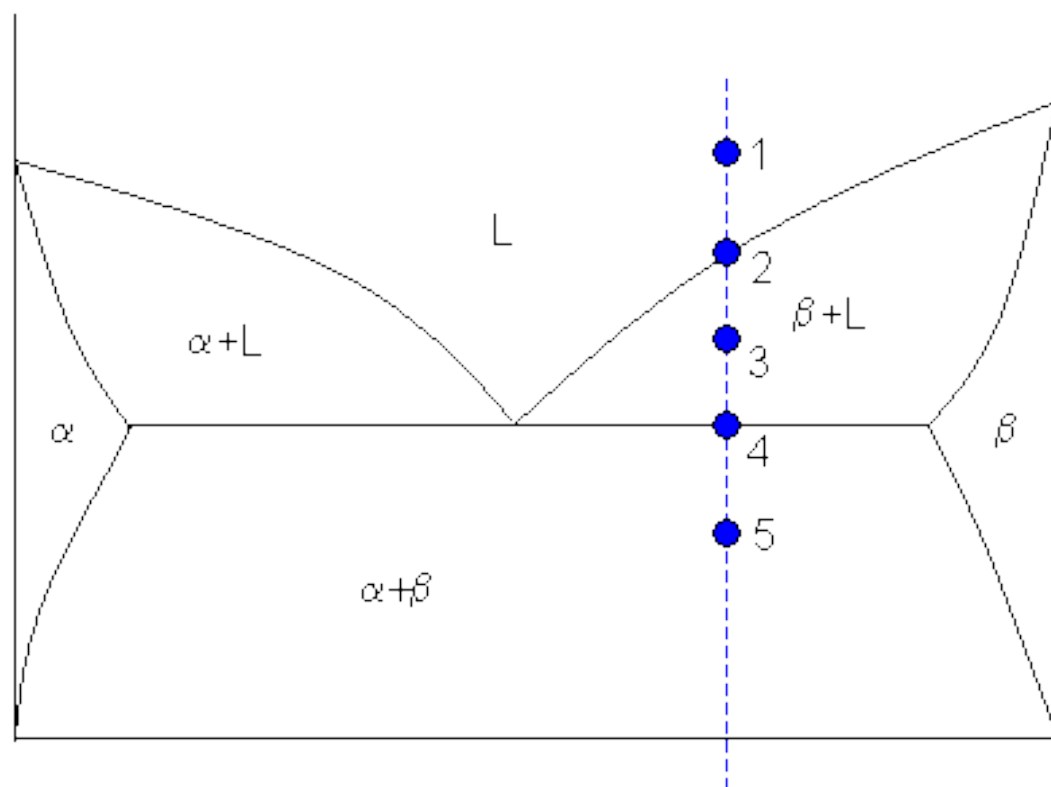


Lever rule applied to a binary system

- ▶ **Point 1**
- ▶ At point 1 the alloy is completely liquid, with a composition C . Let
- ▶ $C = 65$ weight% B.
- ▶ **Point 2**
- ▶ At point 2 the alloy has cooled as far as the liquidus, and solid phase β starts to form. Phase β first forms with a composition of 96 weight% B. The green dashed line below is an example of a *tie-line*. A tie-line is a horizontal (i.e., constant-temperature) line through the chosen point, which intersects the phase boundary lines on either side.



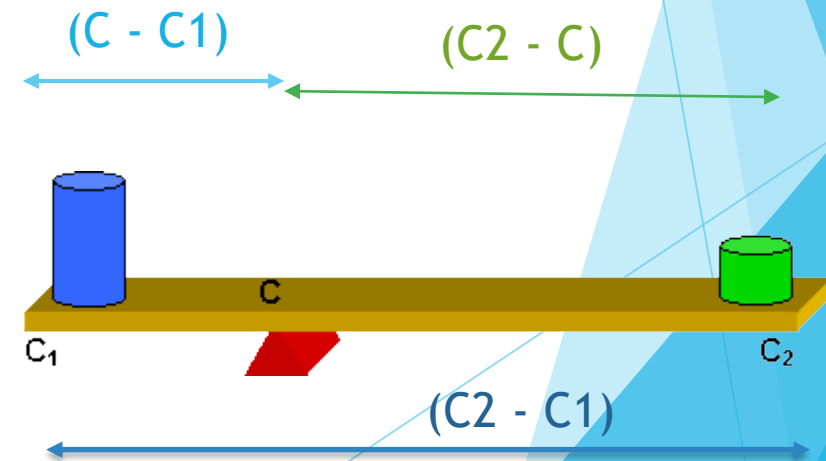
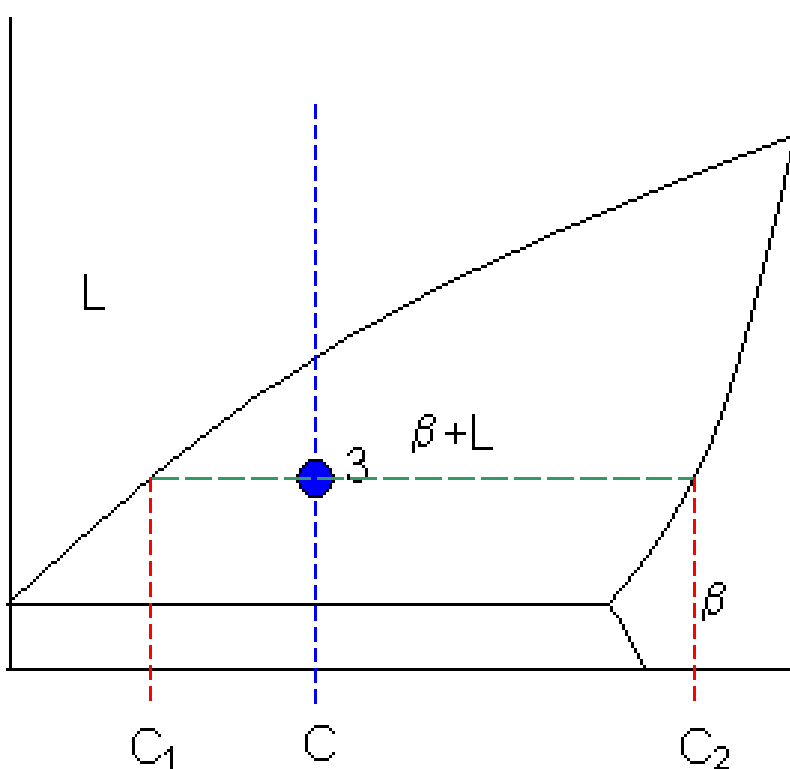
Point 3



Lever rule applied to a binary system

- ▶ **Point 3**
- ▶ A tie-line is drawn through the point, and the lever rule is applied to identify the proportions of phases present. Intersection of the lines gives compositions C_1 and C_2 as shown.
- ▶ Let $C_1 = 58$ weight% B
- ▶ And $C_2 = 92$ weight% B
- ▶ So, fraction of liquid = $(92 - 65) / (92 - 58) = 80$ weight%

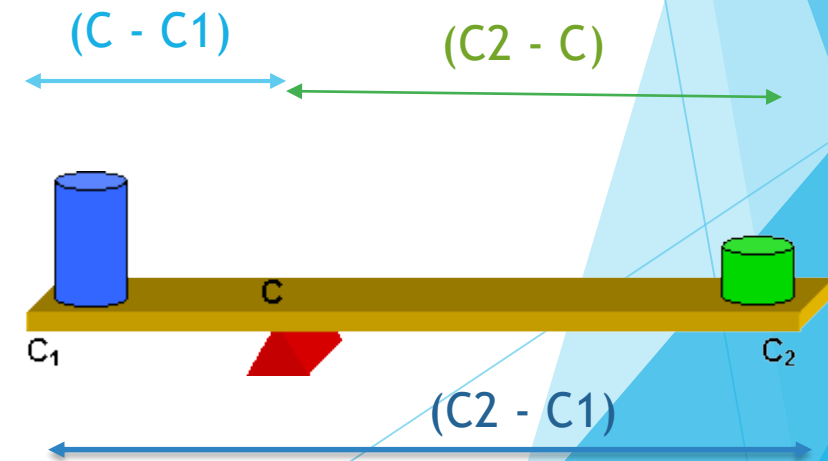
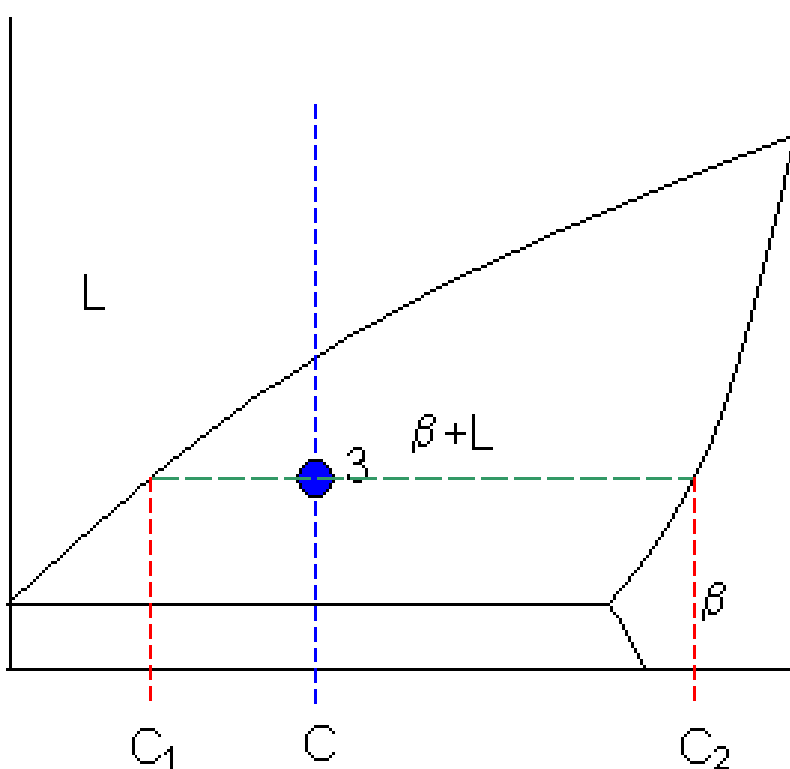
$$\text{fraction of phase 1} = (C_2 - C) / (C_2 - C_1)$$



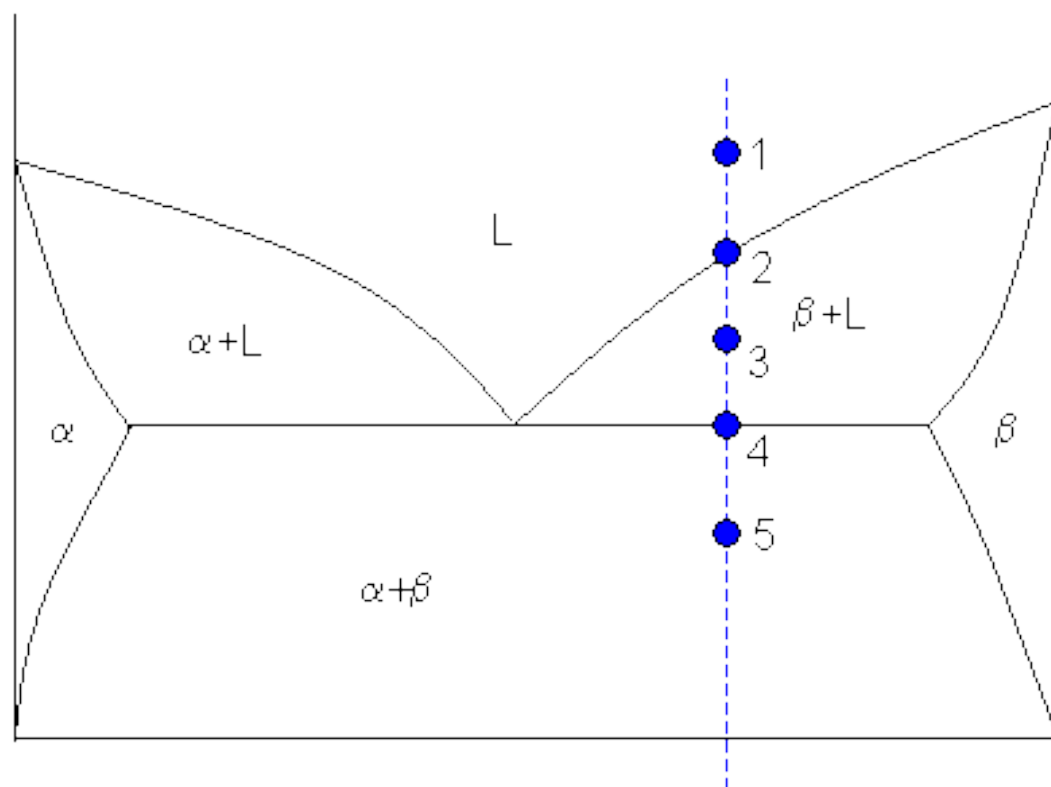
Lever rule applied to a binary system

- ▶ **Point 3**
- ▶ A tie-line is drawn through the point, and the lever rule is applied to identify the proportions of phases present. Intersection of the lines gives compositions C_1 and C_2 as shown.
- ▶ Let $C_1 = 58$ weight% B
- ▶ And $C_2 = 92$ weight% B
- ▶ So, fraction of solid B = $(65 - 58) / (92 - 58) = 20$ weight%

$$\text{fraction of phase 2} = (C - C_1) / (C_2 - C_1)$$

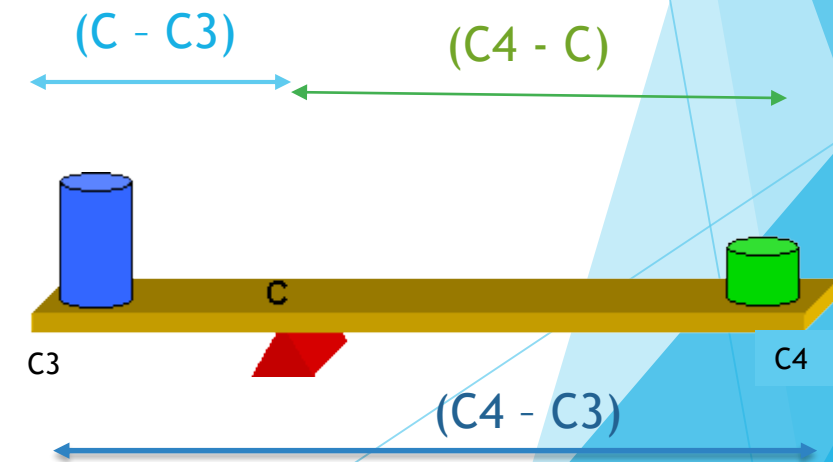
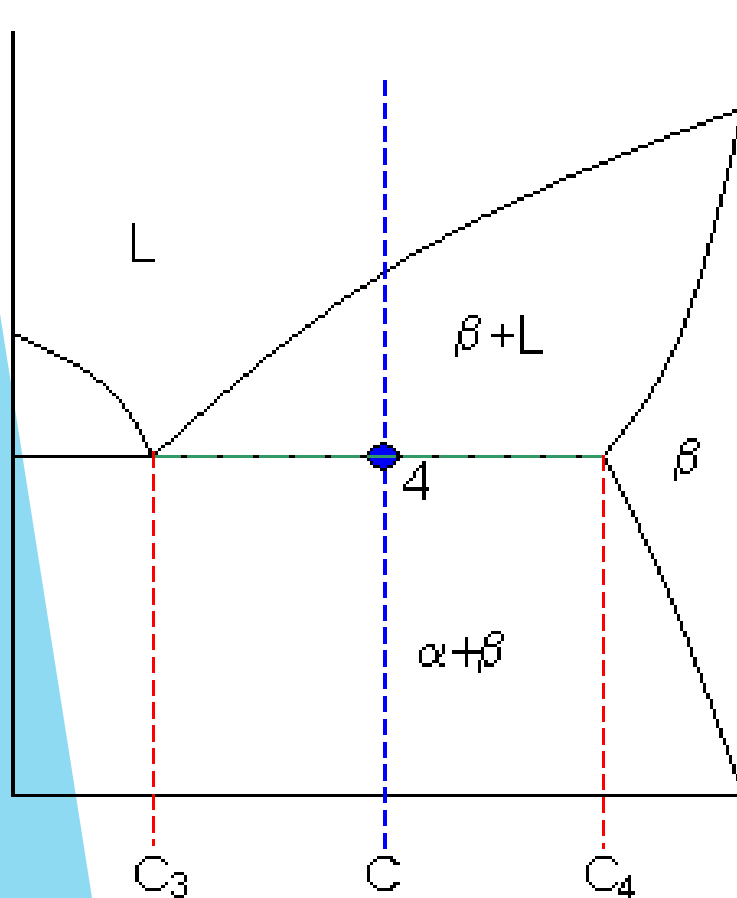


Point 4

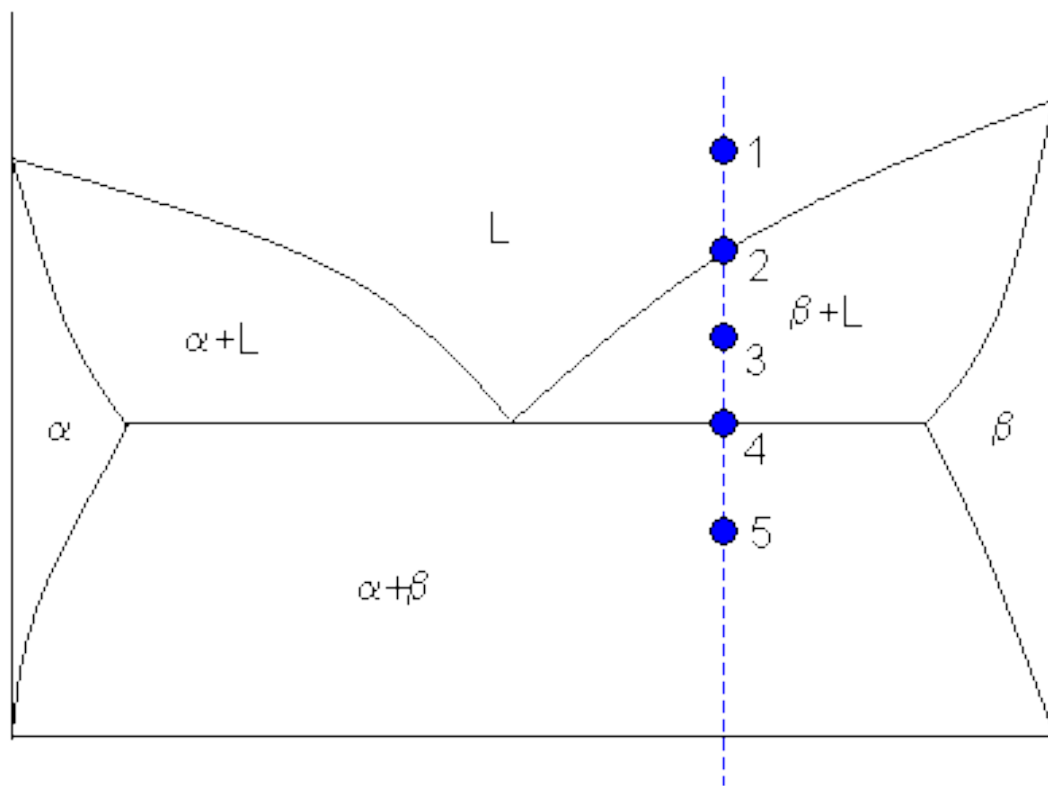


Lever rule

- ▶ **Point 4**
- ▶ Let $C_3 = 48$ weight% B
- ▶ And $C_4 = 87$ weight% B
- ▶ So fraction of solid B = $(65 - 48) / (87 - 48) = 44$ weight%.
- ▶ As the alloy is cooled, more solid B phase forms.
- ▶ At point 4, the remainder of the liquid becomes a eutectic phase of $\alpha + \beta$ and fraction of eutectic = 56 weight%

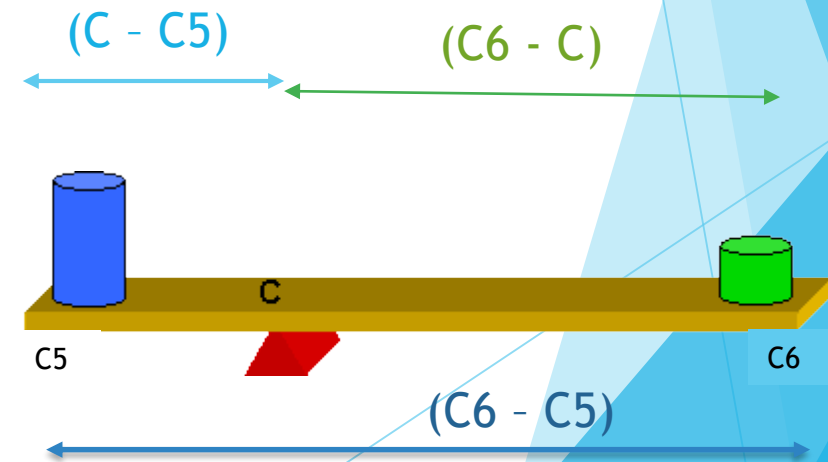
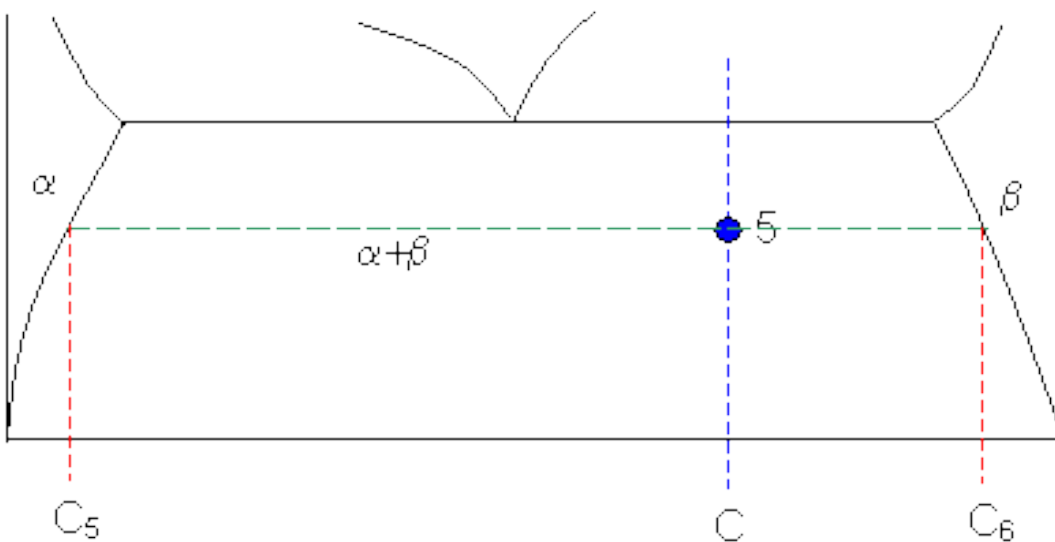


Point 5



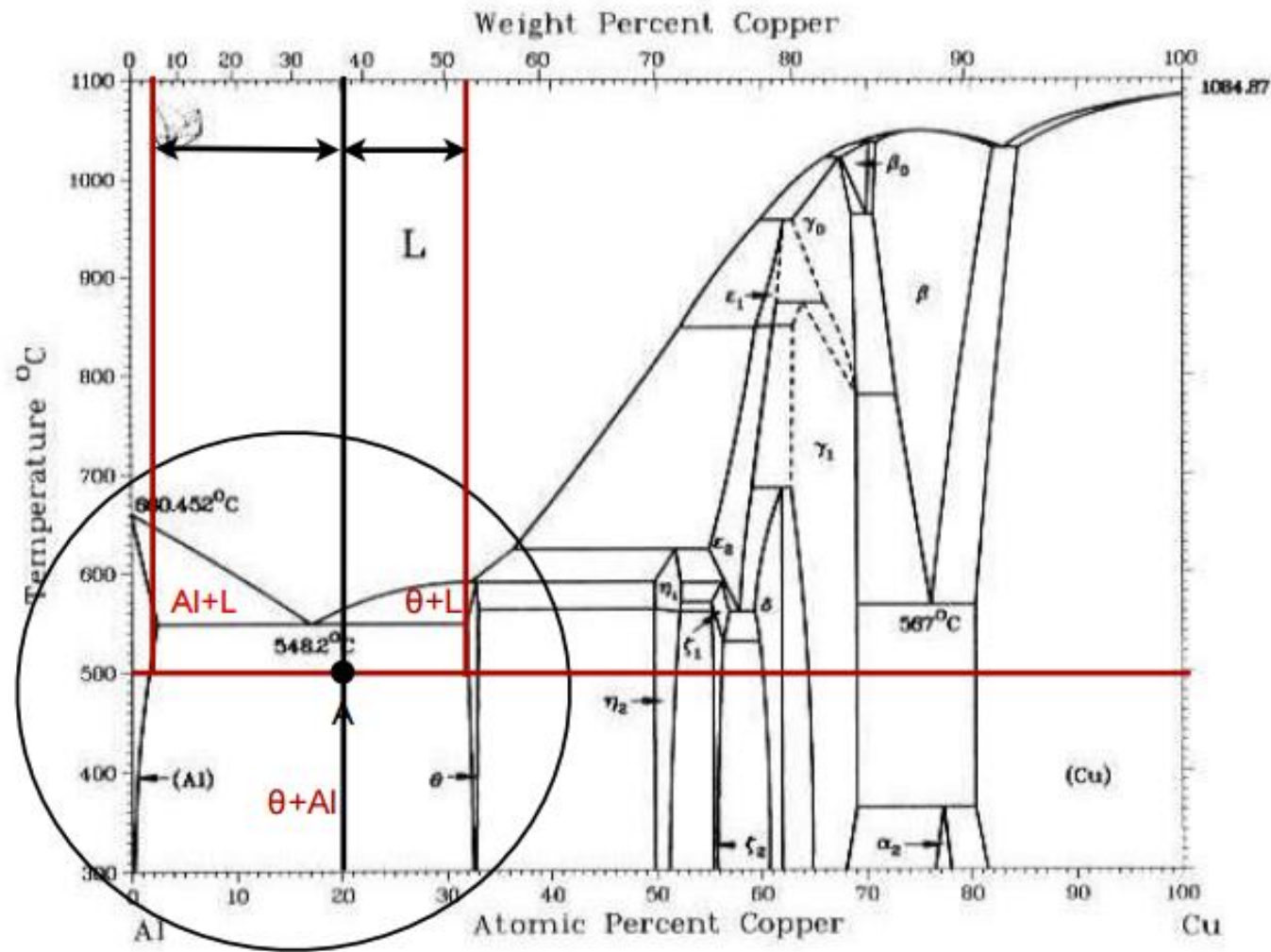
Lever rule

- ▶ **Point 5**
- ▶ Let $C_5 = 9$ weight% B
- ▶ And $C_6 = 91$ weight% B
- ▶ So fraction of solid $\beta = (65 - 9) / (91 - 9) = 68$ weight%
- ▶ And fraction of solid $\alpha = (91 - 65) / (91 - 9) = 32$ weight%.



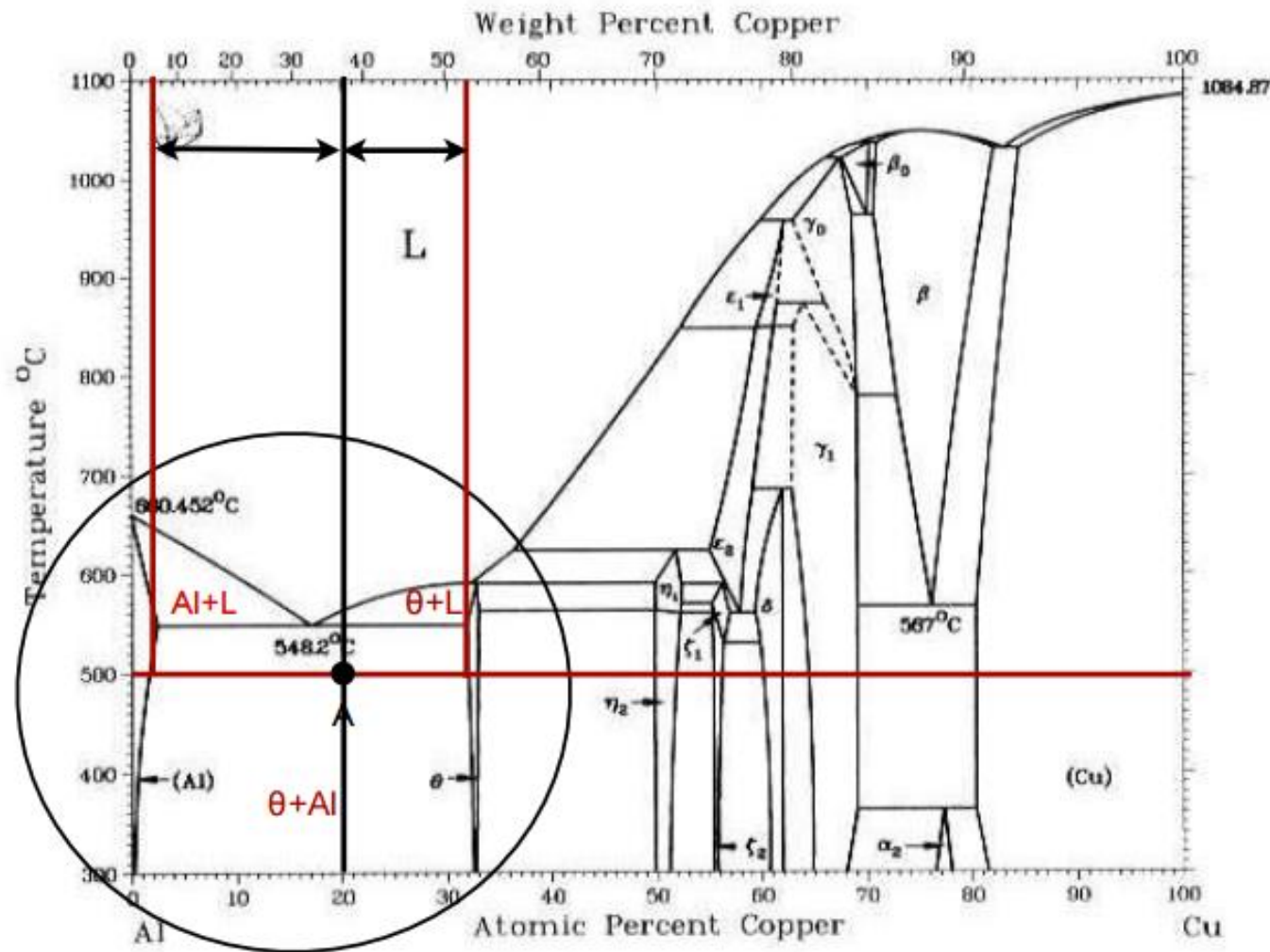
- ▶ Phase diagrams are not just an abstract construction - they have applications in the real world, in deciding which compositions to use.
- ▶ A major use of eutectics, or near eutectics is in solder. In plumbing, solder is used to join copper pipes together, producing a waterproof seal. For many years a lead-tin alloy has been used, as this has a low melting point, especially at eutectic. However, although a low melting point is sought, it is useful to be able to move the pipes around slightly when they are in place and the solder is solidifying. This means that a eutectic should not be used, as although it has the lowest melting point for the alloy system, it will all solidify at once, leaving little room for error. Instead it is useful to use an alloy whose composition deviates slightly from that of the eutectic, so that the solidification will take longer, making the solder easier to use, despite the higher temperatures, and so resulting in a better join.
- ▶ Electrical solder uses a similar alloy to join parts of an electronic circuit together. In the case of a standard electrical solder, the eutectic is used, as high temperatures are to be avoided, and it is useful for the solder to solidify all at once.

- ▶ In more modern soldering applications, such as a ball grid array which joins the chip to some circuit boards, the eutectic is still used. However, there are also situations where a slightly off-eutectic can be used. If there are several processing steps, it is useful to start off with a higher melting point alloy, and only use the eutectic in the final soldering stage. This allows the previous solders to stay in place when the heating takes place on the later stages.
- ▶ Modern solders have moved away from lead-based alloys, because of environmental considerations, and been replaced with new alloys. In the case of plumbing, there is a tendency to use plastic piping instead of copper piping, so there is less need for solder in this industry. In the electronics industry, lead-tin is being replaced by copper-, tin-, and silver-based systems, which have less environmental problems, but can still be used to create low melting points and flexibility which the lead-tin systems provide. Lots of the modern research on solders relates to alternative systems, and characterising them for use. Part of this characterisation involves the production of phase diagrams to allow good choice of composition for the right properties.
- ▶ In recent times, it has become necessary to mix several elements in order to improve properties of the materials. It is therefore useful to create phase diagrams which involve three elements, called "ternary" diagrams. These are more complicated than two element "binary" phase diagrams, but allow improved optimisation, and hence can produce better results.



c) Determine the weight percent of each phase at 500 °C for an overall composition of $C_0=20\text{at\%Cu}$. (5 pts)

d) Calculate the overall weight percent of Aluminum for $C_0=20\text{ at\%Cu}$ at 500 oC using parts b and c, and check to make sure this agrees with the phase diagram. (5 pts)



c) Using weight percent Cu
 $W_{\theta} = (C_0 - C_{Al}) / (C_{\theta} - C_{Al}) = (38\% - 4\%) / (52\% - 4\%) = 71\%$
 $W_{Al} = 100 - W_{\theta} = 29\%$

d) Overall %Al = $W_{\theta}(\%Al \text{ in phase composition of } \theta) + W_{Al}(\%Al \text{ in phase composition of Al})$
 Overall %Al =
 $(.71)(.48) + (.29)(.96) = .34 + .28 = .62 \text{ or } 62\% \text{ Al.}$
 The phase diagram shows 38% Cu.

c) Determine the weight percent of each phase at 500 °C for an overall composition of $C_0 = 20 \text{ at\% Cu}$. (5 pts)

d) Calculate the overall weight percent of Aluminum for $C_0 = 20 \text{ at\% Cu}$ at 500 °C using parts b and c, and check to make sure this agrees with the phase diagram. (5 pts)

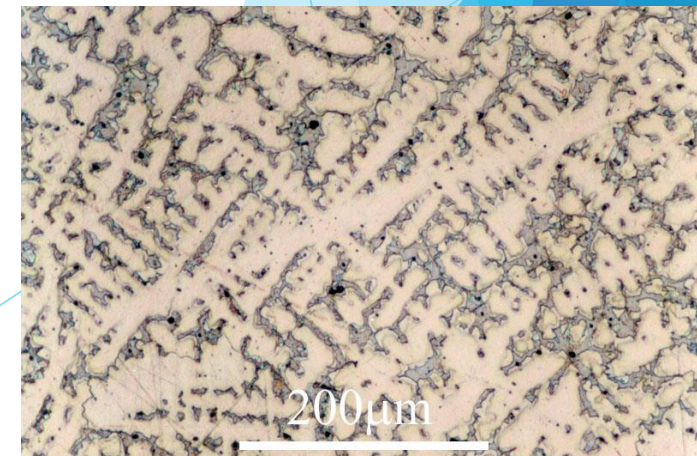
Solidification of metals and alloys

- ▶ https://www.youtube.com/watch?v=G5z9KknF_s8

- ▶ Solidification of a solid phase from a liquid requires the creation of a new surface separating the liquid and solid phases.
- ▶ Energy is required to produce these new surfaces.
- ▶ Surface energy is associated with the liquid solid interface (cf grain boundary in a solid)
- ▶ The energy to create new surfaces requires that liquids cool below their equilibrium freezing temperature or that they are *undercooled*, before solidification begins,
- ▶ Solidification will occur more spontaneously if there is a high degree of undercooling.
- ▶ The degree of undercooling necessary for solidification is minimized if existing surfaces are present, which act as nuclei for solid crystals.
- ▶ As such, when a metal is poured into a cooler mould, the mould walls act as the initial nuclei for solidification. In this manner, many small *chill crystals* with random crystallographic orientations nucleate along the mould walls

- ▶ The conduction of heat from the liquid through the chill crystals to the cooler mould creates a temperature gradient within the newly formed solid phase.
- ▶ The *latent heat of solidification* is released at the solid-liquid interface, creating the temperature profile shown, with an interface temperature above that of both the liquid and solid phases.
- ▶ Consequently, heat is conducted away from the interface to the solid, as well as to the undercooled liquid.
- ▶ The steep temperature gradient, ahead of the advancing solid phase causes the solid-liquid interface to become unstable and protrusions to grow into the liquid at a faster rate than would otherwise evolve from a stable interface.

Department of Materials, University of Leeds: A good example of dendritic solidification, which occurs when the solidification front becomes unstable with respect to small perturbations. This results in the growth of the perturbations, producing dendrites (from the Greek for tree) of the primary phase. Subsequently the secondary phase forms between in the enriched melt between the dendrites. Copper/Tin alloy (bronze)



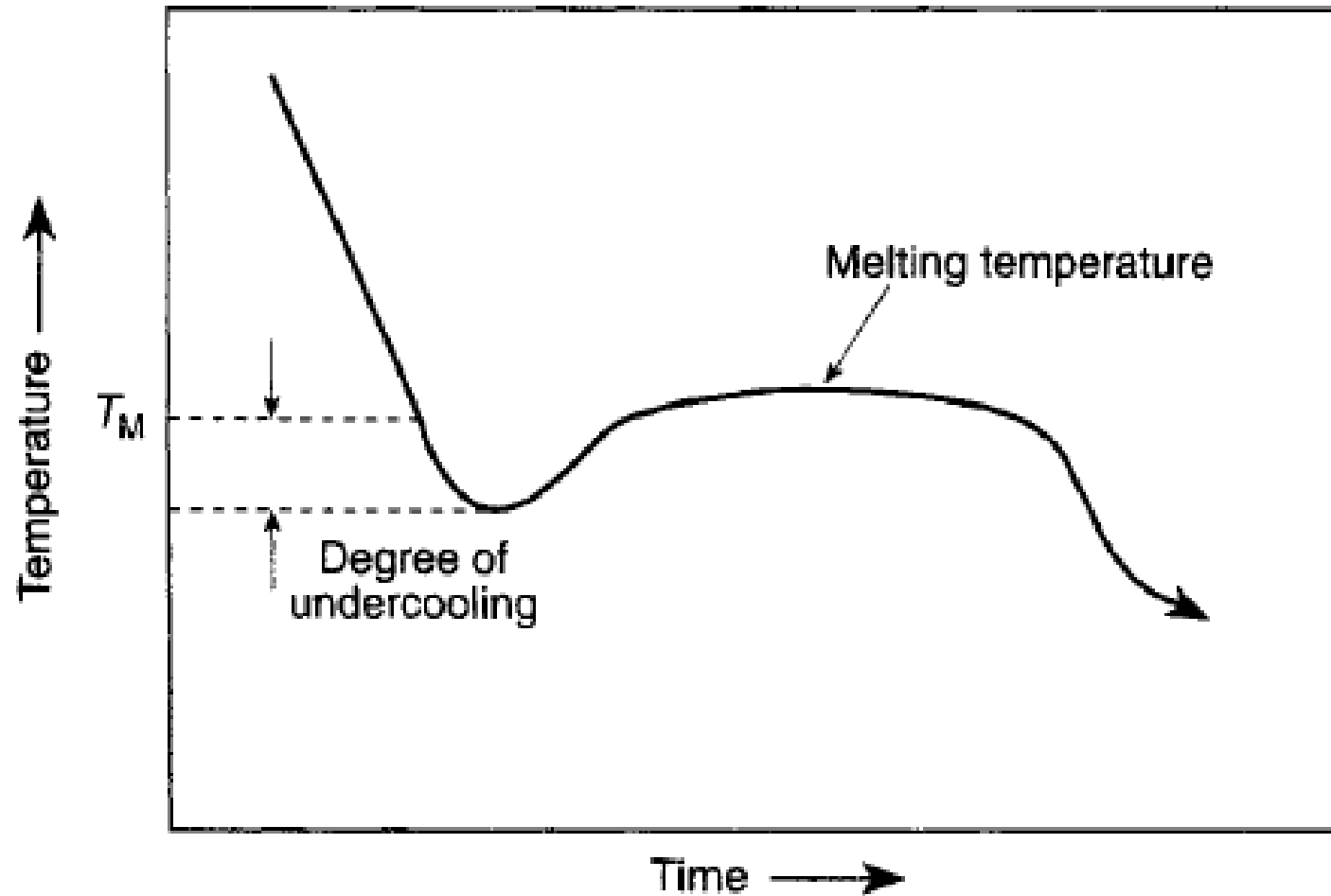


Fig. 2.11 Cooling curve for a pure metal illustrating the degree of undercooling required to initiate solidification.

Solidification and casting processes

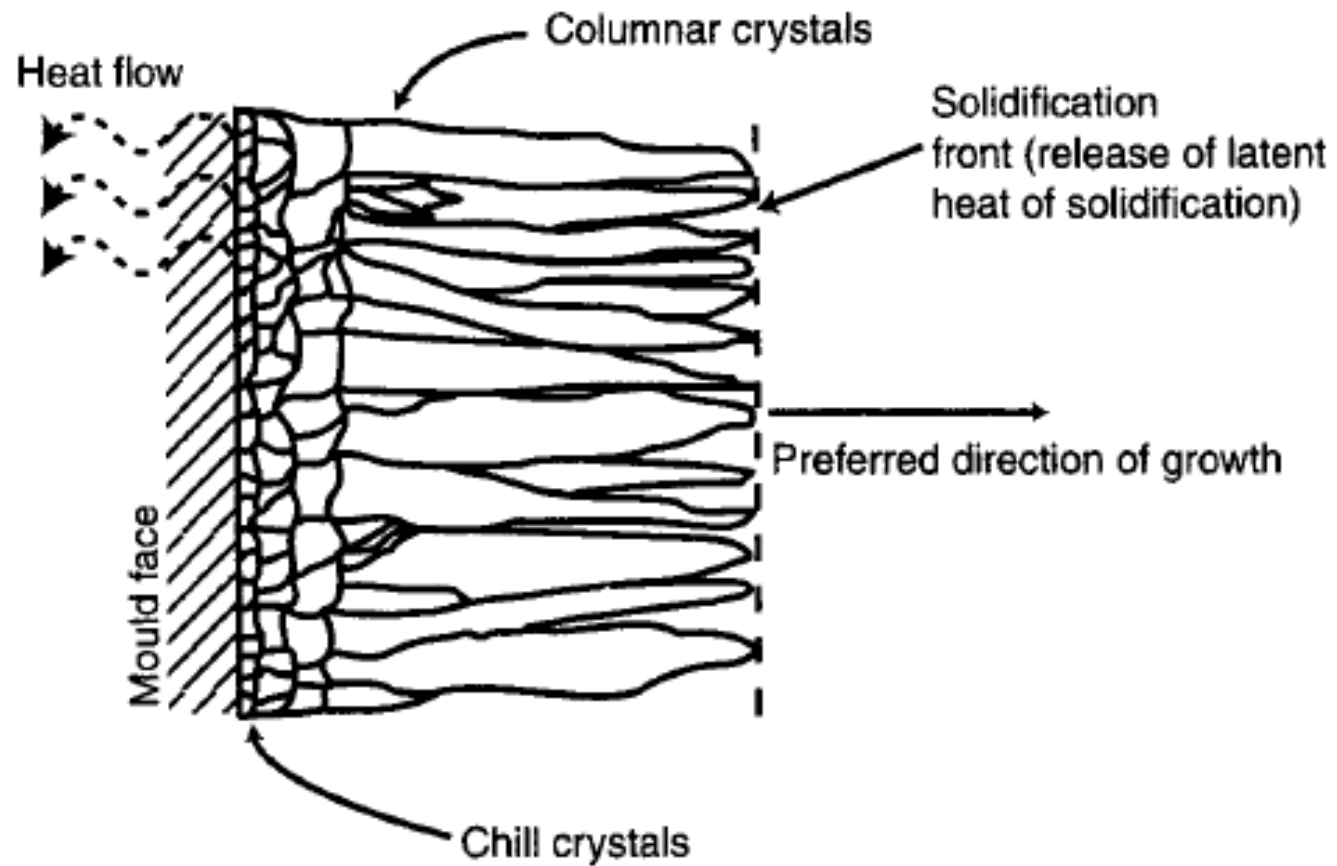
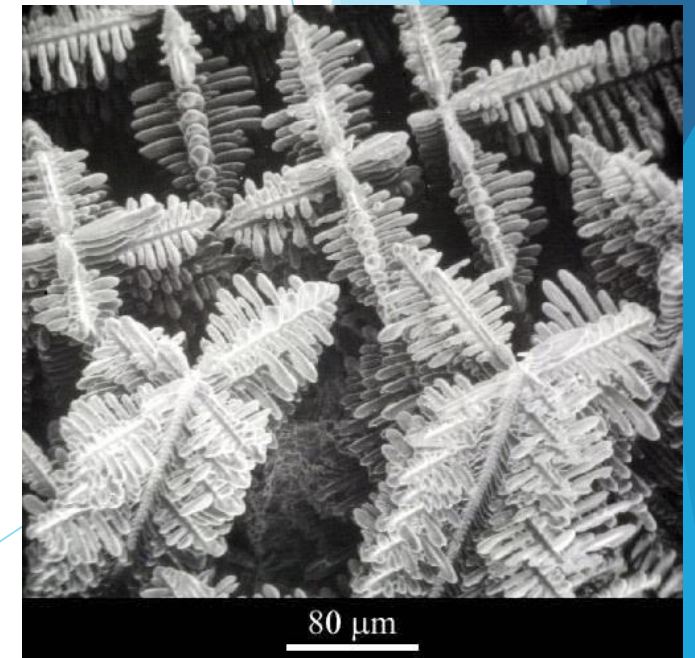


Fig. 2.12 Initial solidification of chill crystals and columnar crystals in a casting.

- ▶ The faster growth rate of the protrusions occurs because they are surrounded by more highly undercooled liquid metal as they grow further from the stable liquid-solid interface. The rapid growth of protrusions from the liquid-solid interface leads to a transition from a flat interface to a *dendritic* structure. The dendrites grow in preferred crystallographic directions, (100) for cubic and (101) for hexagonal metals, and consequently secondary or tertiary dendrite arms often form.
- ▶ In the casting dendrites grow perpendicularly away from the mould wall, developing into columnar grains.
- ▶ A consequence of the formation of columnar grains is that pure metals often have a cast structure similar to that shown

SEM of deeply etched Co-dendrites Cobalt-Samarium-Copper Cambridge University
Using this alloy composition, a relatively low volume fraction of dendrites is formed. Due to their different chemistry the interdendritic Sm and Cu enriched phases can be etched away to reveal the three-dimensional structure of dendrites. The dendrite tips have the form of a paraboloid, and anisotropy develops behind them with the secondary dendrite arms.



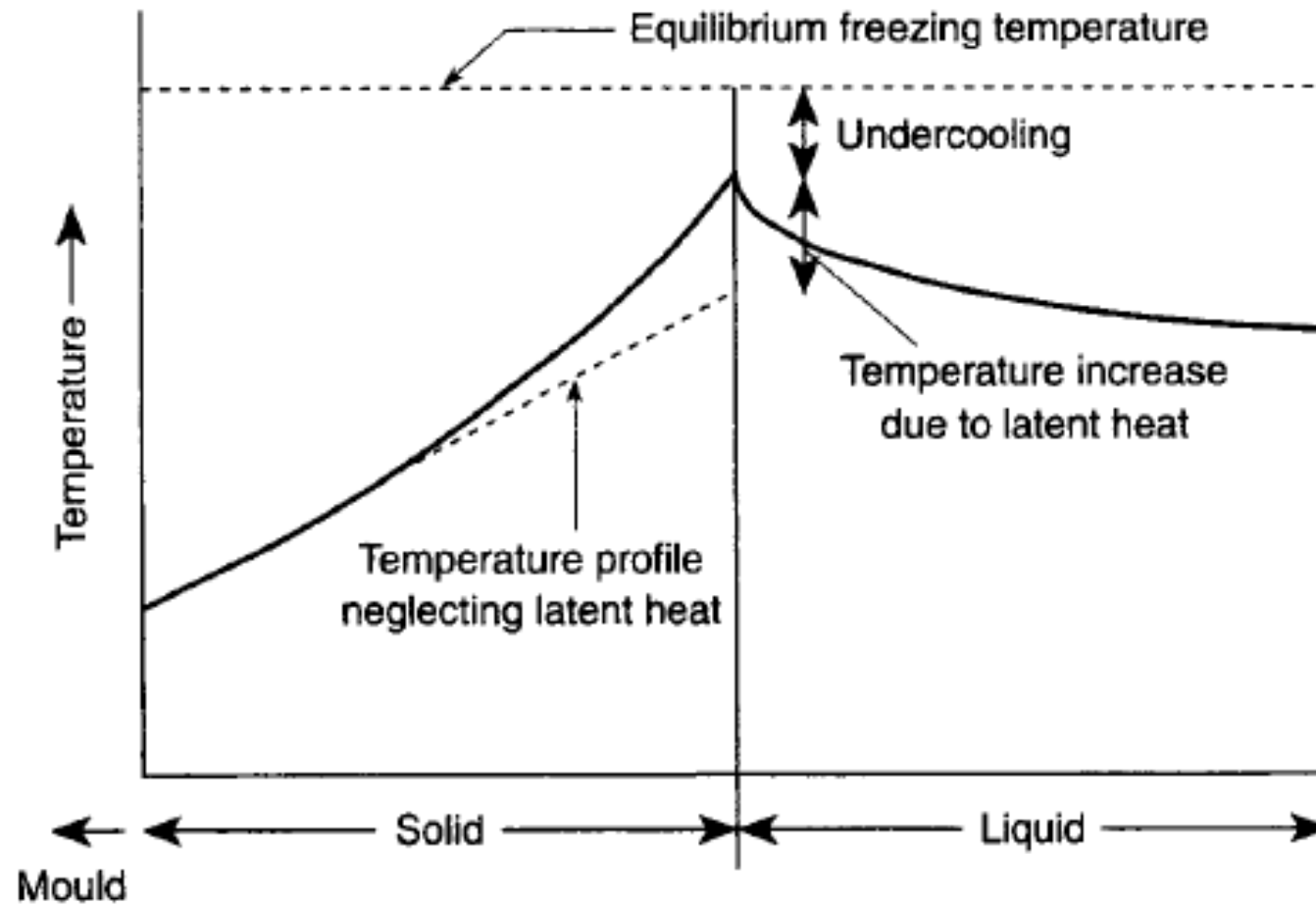


Fig. 2.13 Temperature profile from the mould, through solid chill crystals to the liquid.

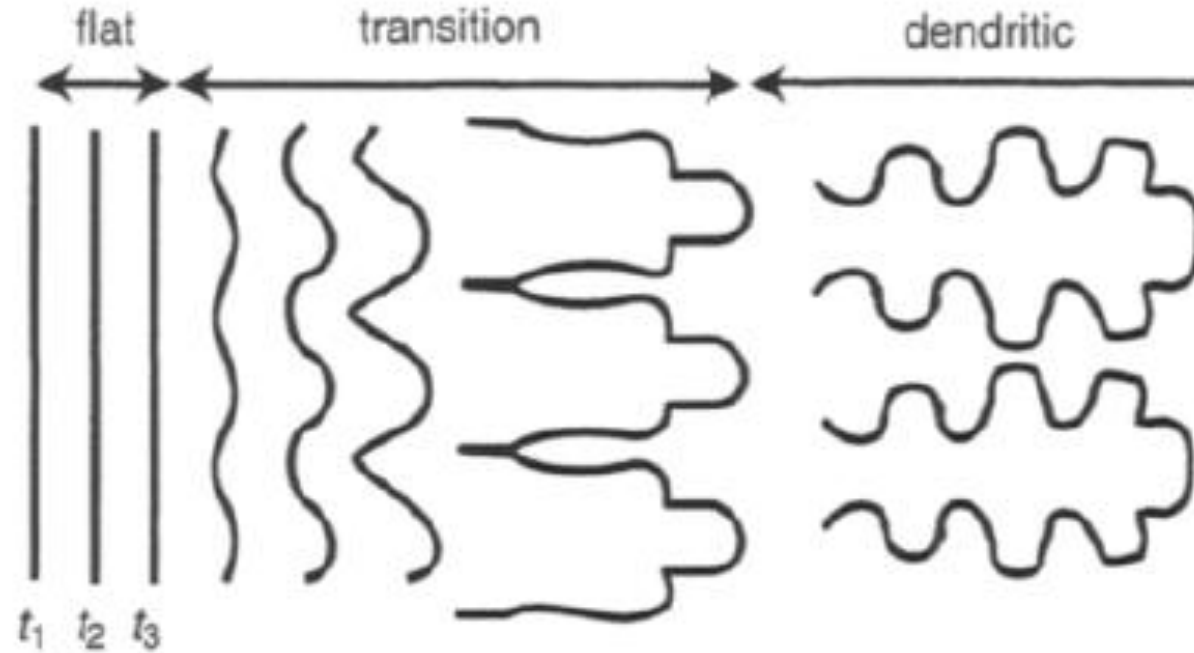


Fig. 2.14 Illustration of transition from flat to a dendritic liquid–solid interface. The mould surface is to the left.

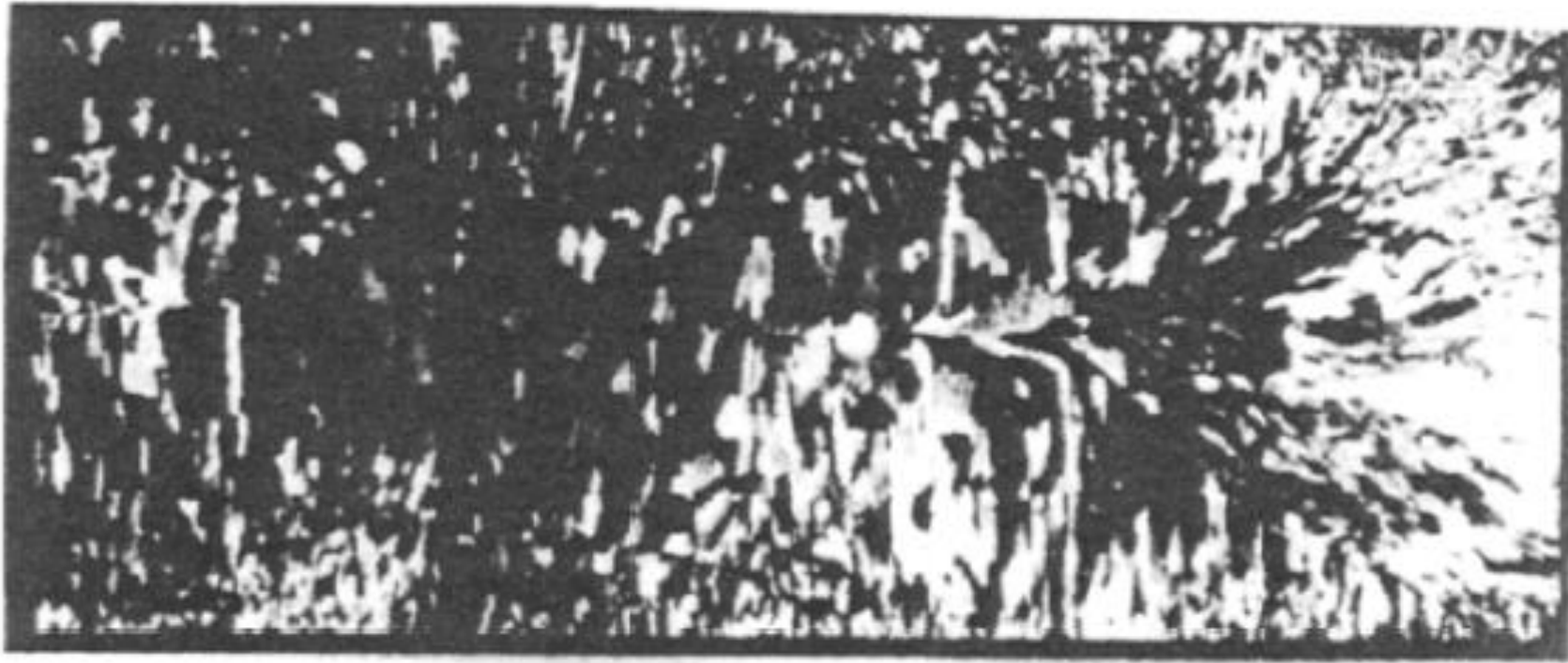


Fig. 2.15 Cast grain structure of a bar displaying chill crystals adjacent to the mould walls, some of which grow into columnar grains. (Reprinted with permission from *Continuous Casting of Non-Ferrous Metals and Alloys*, H.D. Merchant, D.E. Tyler, and E.H. Chia, Fig. 3, page 287, © The Minerals, Metals & Materials Society (TMS), Warrendale, PA, 1988.)

- ▶ The liquidus temperature, T_L or T_{liq} specifies the temperature above which a material is completely liquid and the maximum temperature at which crystals can co-exist with the melt in thermodynamic equilibrium. It is mostly used for impure substances (mixtures) such as glasses, alloys and rocks.
- ▶ In chemistry, materials science, and physics, the solidus is the locus of temperatures (a curve on a phase diagram) below which a given substance is completely solid (crystallized) (beginning of melting)

► Solidification of alloys

- Pure metals solidify at a unique temperature.
- Alloys, however, solidify over a range of temperatures. For example, the 50wt% Cu-50 wt% Ni alloy to solidify at 1310~ the *liquidus* temperature, but does not become fully solid until 1260~ the *solidus* temperature.
- During solidification, the temperature range between the liquidus and solidus is referred to as the *mushy zone*, as the metal is in a liquid-solid state.
- Proper control of the heat transfer from the liquid-solid mushy zone to the casting mould can be difficult, and this can give rise to a number of defects as well as difficulty in controlling the entire solidification process.
- Difficulties associated with solidification control in the mushy zone regions is the problem that makes continuous casting of alloys with a large mushy zone difficult or impossible with current technology.
- The undercooling that occurs during the solidification of pure metals technically called *thermal* undercooling, also occurs during the solidification of alloys.
- A second type of undercooling - *constitutional* undercooling - occurs in many alloys, compounding the effects of thermal undercooling.

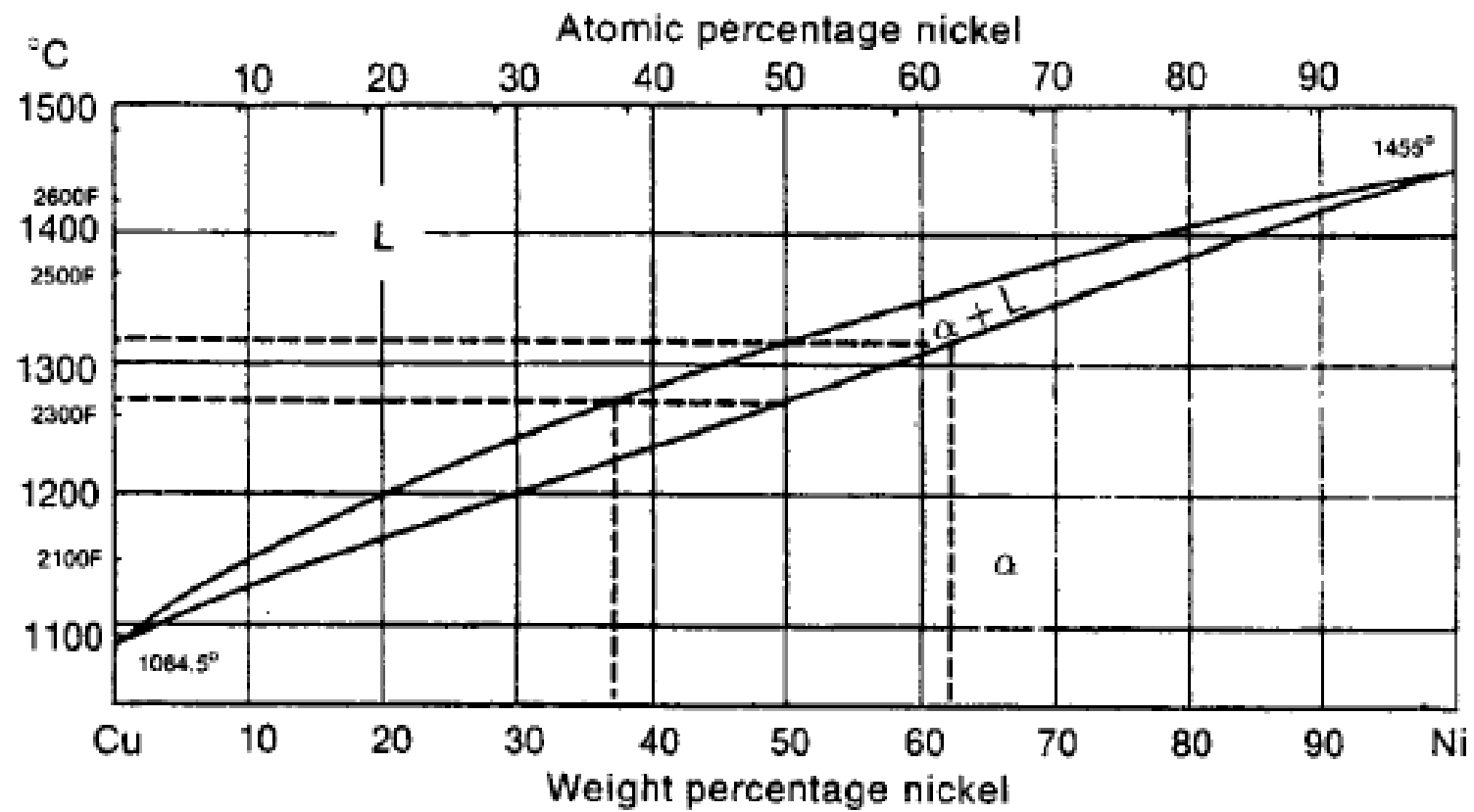


Fig. 2.16 Cu-Ni phase diagram.

- ▶ These two types of undercooling give rise to a well developed dendrite structure in many alloys.
- ▶ Constitutional undercooling results when the freezing metal has a composition different from that of the liquid from which it is solidifying.
- ▶ Consider the solidification of a 50: 50wt% Cu-Ni alloy. When the temperature of the casting falls to the liquidus line 1310~ the first solid to appear has a composition of 62 wt% Ni, but the liquid has a composition of 50 wt%Cu.
- ▶ At a temperature just above the solidus 1260~ the solidifying product has a composition of about 50wt% Cu, while the liquid remaining has a composition around 37 wt% Ni. In other words, the first solid is Ni rich, whereas the liquid is enriched in the low-melting-point component, in this case Cu.
- ▶ As a consequence of compositional differences between the solidified and liquid phases during solidification, the dendrite arms can have substantially different compositions from the
- ▶ metal that solidifies in the *interdendritic regions*. Local compositional differences resulting from cooling through two phase regions is termed micro-segregation or coring.

- ▶ The Cu-Ni alloys are part of a family of corrosion-resistant alloys known as *monels*. When they are cast, coring causes a considerable decrease in the corrosion resistance. In many alloys the mechanical properties can also be seriously degraded by coring.
- ▶ Like the solidified structure of pure metals, chill crystals and columnar grains also develop during alloy casting. As a consequence of the combined effects of thermal and constitutional undercooling, solidification nuclei can form in the central regions of an alloy casting.
- ▶ Solidification in this central region can occur by the formation and growth of new grains, rather than continued growth of columnar grains from the mould wall.
- ▶ This mechanism leads to randomly oriented, equiaxed grains in the central region. The grain structure here is generally coarser than the chill crystals that form at the mould wall.
- ▶ Columnar grain boundaries are favourable sites for embrittling impurities and porosity, which gives rise to poor mechanical properties and formability.
- ▶ Often casting is only the beginning of the fabrication process and the subsequent plastic forming operations, such as forging, may eliminate the columnar structure through deformation and recrystallization. Nevertheless, in most castings a *grain refiner* is added during solidification to provide uniform nucleation of grains throughout the casting.

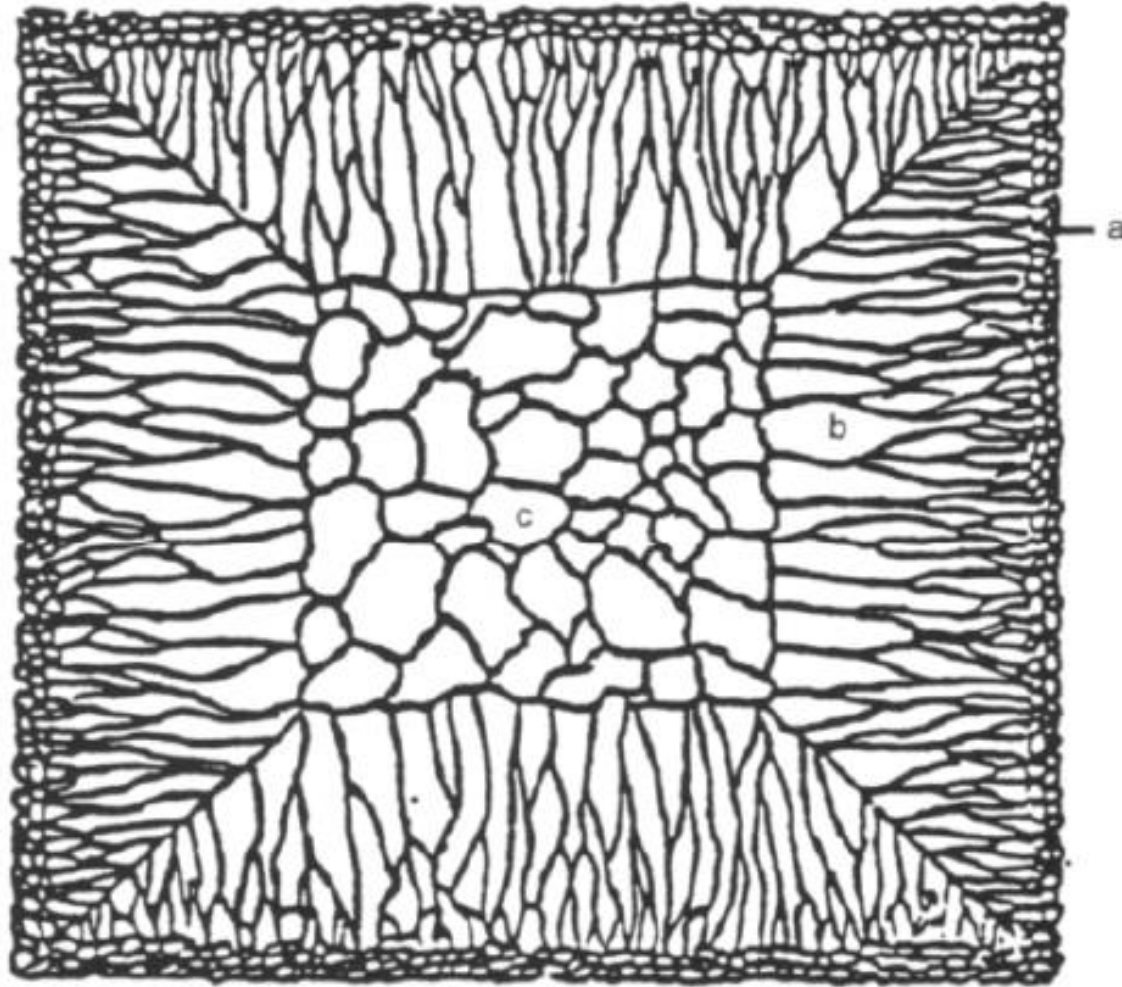


Fig. 2.17 Sketch of solidified grain structure of an alloy: (a) chill crystals; (b) columnar grains; and (c) region of coarse equiaxed grains in centre.

- ▶ Vanadium is an effective grain refiner for steel, whereas titanium and niobium can be used for light metals such as aluminium and magnesium as well as steel.
- ▶ Most direct chill or continuously cast aluminium is grain refined by the addition of titanium diboride. Appropriate additions of grain refiners during casting can completely eliminate the formation of columnar grains and produce a uniform equiaxed grain structure throughout the cast thickness,

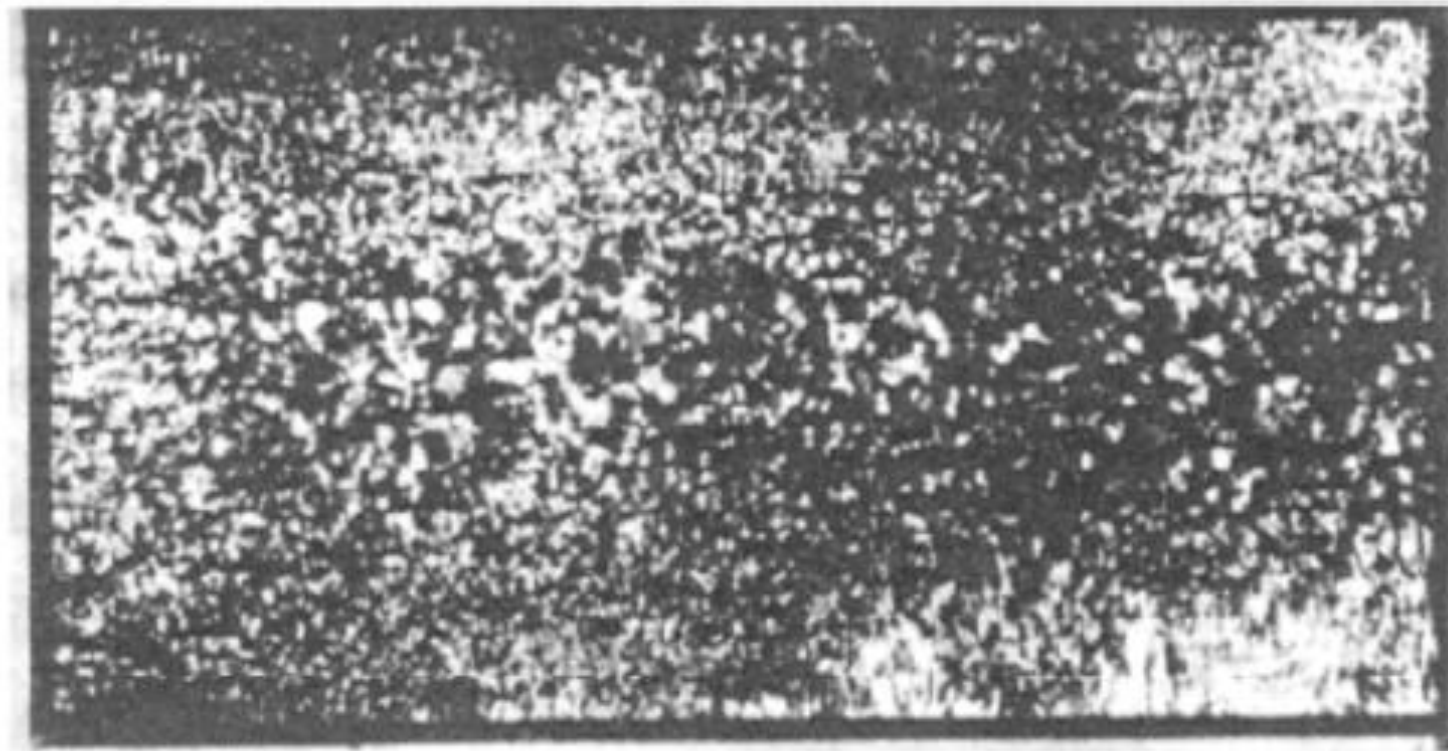


Fig. 2.18 Cast structure of the same alloy as Fig. 2.15, but with a fine grained equiaxed structure throughout. (Reprinted with permission from *Continuous Casting of Non-Ferrous Metals and Alloys*, H.D. Merchant, D.E. Tyler, and E.H. Chia, Fig. 3, page 287, © The Minerals, Metals & Materials Society (TMS), Warrendale, PA, 1988.)

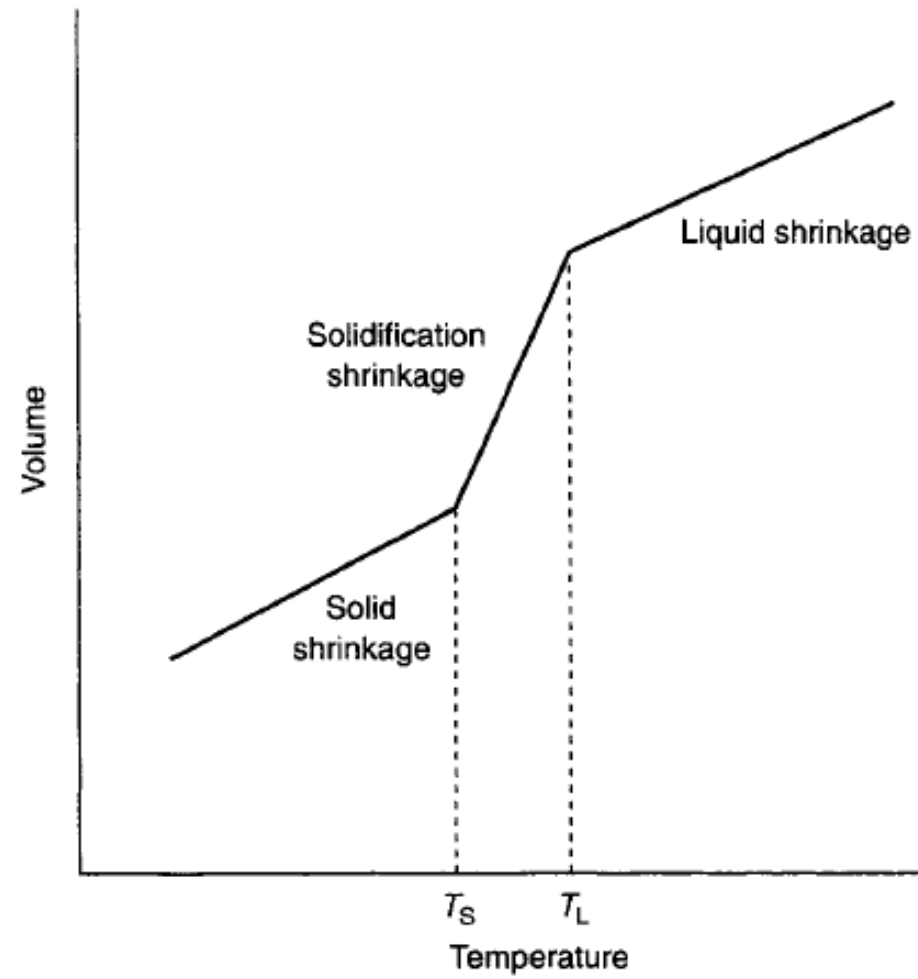


Fig. 2.19 Changes in volume as a metal alloy solidifies.

- ▶ Changes in volume as a metal alloy solidifies.
- ▶ As a metal casting solidifies and cools, the volume decreases, as shown in Fig. 2.19.
- ▶ The reader may wish to consider why the volume of most metals decreases on solidification,
- ▶ whereas the volume of water increases when it changes to ice. There are three
- ▶ major contributions to volume shrinkage: liquid shrinkage, solidification shrinkage
- ▶ and solid shrinkage. The amount of shrinkage occurring for a few common metals
- ▶ is listed in Table 2.1. Liquid shrinkage does not cause casting problems, as long as
- ▶ sufficient metal is available to fill the shrinkage cavity. To account for
- ▶ solidification
- ▶ shrinkage the casting pattern must be oversized appropriately and risers added to
- ▶ prevent the formation of shrinkage cavities during solidification.

- ▶ The effect of solidification and solid shrinkage is illustrated by sand casting a cube,
- ▶ The casting first forms a solid skin at the mould-liquid interface as it begins to solidify
- ▶ This effectively isolates the liquid remaining in the central region of the cube. As this material solidifies, it shrinks and a void forms
- ▶ Void formation in this manner is termed macroporosity. Further solidification and solid shrinkage causes distortion and produces a solidification pipe at the top of the cube
- ▶ To prevent macroporosity and pipe formation, risers are used which act as a source of liquid metal to compensate for the solidification shrinkage that would otherwise form. As the casting solidifies and shrinks, liquid metal from the riser is drawn into the casting. In this manner, the voids and solidification pipe form in the riser rather than in the casting.

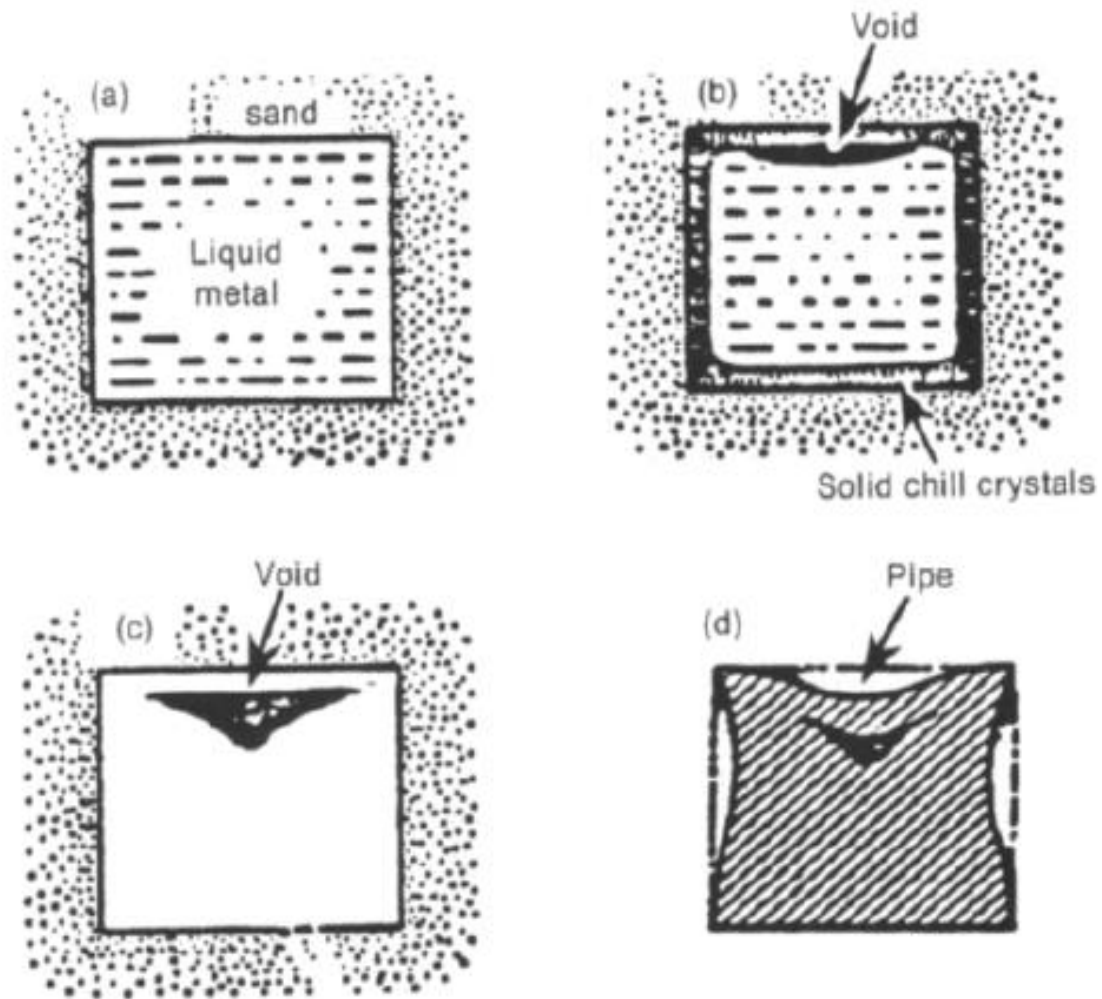


Fig. 2.20 Shrinkage occurring during sand casting of a cube (see text for explanation).

A cube casting incorporating a riser

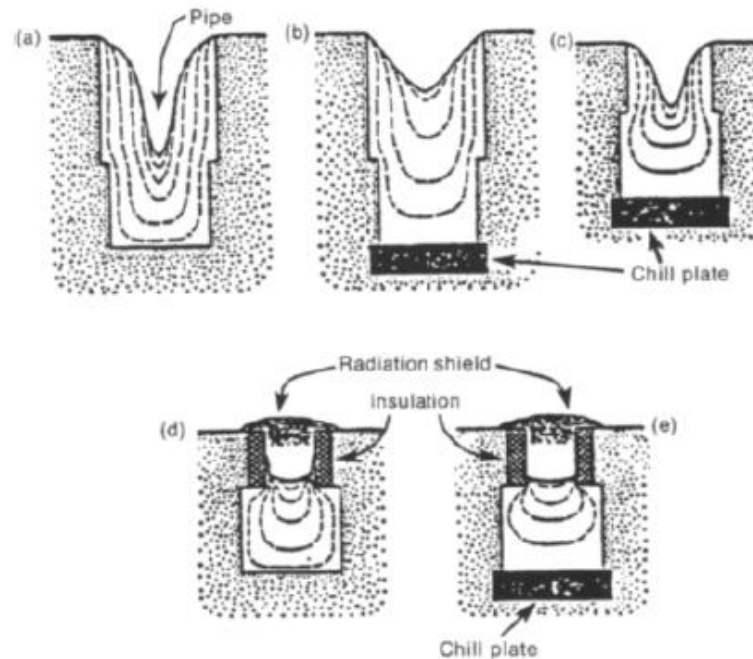


Fig. 2.21 Sand casting the same cube as Fig. 2.20, but with a riser (a), chill plate (b) and (c), insulation and radiation shield (d), and all three (e).

- ▶ This requires that the riser does not solidify prior to the casting. In effect, risers represent excess metal to the casting which must be removed.
- ▶ Therefore, it is necessary to minimize their size and number. Metal chills, insulation and radiation shields can be used to modify the heat transfer, thereby minimizing the riser size required

- ▶ During processing some products may undergo more than one melting and casting operation. Sometimes this is done to improve the metallurgical structure of the product, but more often so that large quantities of metal can move through industrial processes in an efficient manner.
- ▶ For example, it is not practical to produce a large number of finished products at a large primary smelter. Instead, a number of ingot sizes are produced from primary operations that can then be transported to other facilities for re-melting and casting into semi-finished or fully finished forms.
- ▶ One of the common ingot forms produced at aluminium smelters is the s o w . It is produced by pouring aluminium, taken directly from the pots in a ladle, into an open steel mould, such as that shown in Fig. E2.1. Each sow weighs about 700 kg, and is approximately 1 m square and 0.5 m high. Sows of this size are easily moved by forklifts and trucks.
- ▶ The casting of sows is not unlike the casting of the cube, except that instead of a sand mould, a steel mould is used for durability and reusability.

- ▶ Consequently, the sow exhibits many undesirable features.
- ▶ The sow has columnar grains around the periphery of the ingot, which are larger at the top surface due to a lower heat extraction rate from this region (heat is absorbed by the steel mould much faster than by the air above the sow).
- ▶ Columnar grains generally have poor mechanical properties but, as the sow is remelted as part of further processing this is of little consequence.
- ▶ Additionally the top of the sow is depressed due to thermal shrinkage (sows are sold by weight, not volume).
- ▶ The occurrence of quite large shrinkage voids or macroporosity inside the sow is more serious. Often cracks that occur along the boundaries of weak columnar grains connect the shrinkage voids to the top surface.

- ▶ Consequently, if the sow is left unprotected in rain or snow, it is possible for water to enter and possibly fill the shrinkage voids. Water inside the shrinkage voids can lead to disastrous results when the sow is remelted.
- ▶ As the sow is heated for melting, the water vaporizes and expands. The expanding vapour cannot escape, because melting of the outer surface of the sow seals the cracks that allowed water to enter.
- ▶ This causes high internal pressures which can cause the sow to break open, potentially exposing water vapour to molten aluminium. Violent explosions of the molten aluminium can occur in these circumstances:
- ▶ first, the rapidly expanding water vapour can eject molten aluminium from the melting furnace;
- ▶ second, the water vapour can react with the aluminium, releasing large amounts of chemical energy. Although this sequence of events may seem unlikely, it does happen leading to needless injury or loss of life.

- ▶ To avoid such explosions, it is imperative that sows are protected from rain or snow and are stored in dry locations. Additionally, many facilities have drying ovens, in which sows are heated to a temperature below the melting temperature, but high enough to vaporize and drive off any water in the shrinkage voids.
- ▶ This operation requires an extended time, which reduces its economic viability, making it more important that sows are kept dry. In general terms it is important to avoid any moisture in contact with molten metals for the safety reasons demonstrated by this example.