Solutions

UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Materials Science & Engineering

MSE 121

Spring Semester 2008
Professor R. Gronsky

Midterm Exam

Instructions

Please PRINT your name in the box above and INITIAL all pages.
Solutions MUST be written neatly and concisely in the spaces provided.
This is an OPEN BOOK exam. NO digital communicators (Laptop, PDA, Cellphone...).

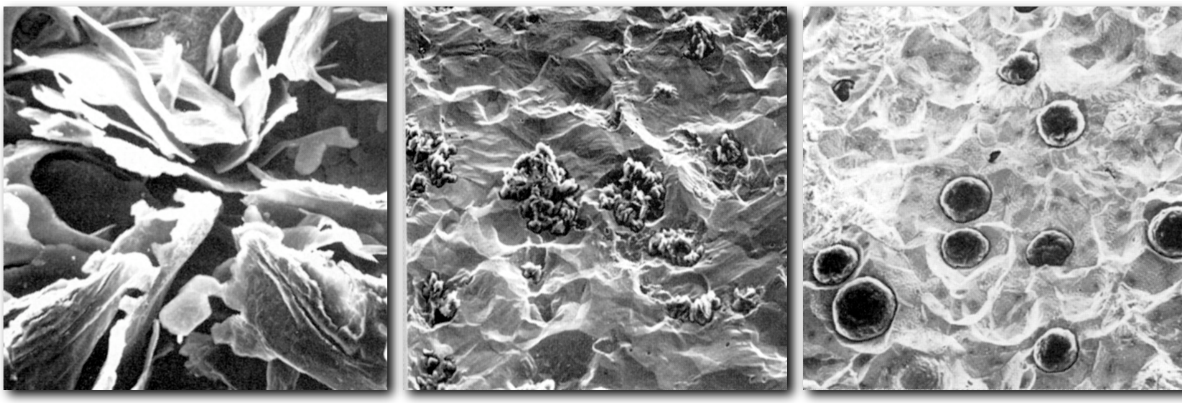
Guidelines

Please read each question FULLY before commencing your answer.
Show ALL of your work for partial credit, as appropriate.
There are 4 questions worth 50 points each.

Solutions

Problem 1(a) [30 points]

Images (*i*) through (*iii*) are "fractographs" (scanning electron micrographs of fracture surfaces) from three (3) different forms of the four (4) varieties of cast iron discussed in lecture, all recorded at the same magnification. Identify each one, and explain how you arrived at your conclusion(s).



(*i*) (*ii*) (*iii*)

Solution

(i) **Gray cast iron**. The graphite flake morphology is the most salient feature of the microstructure. Compare with the light optical micrograph shown in Figure 2.33 of the text. Note that because this is an SEM image, "color" does not have the usual meaning.

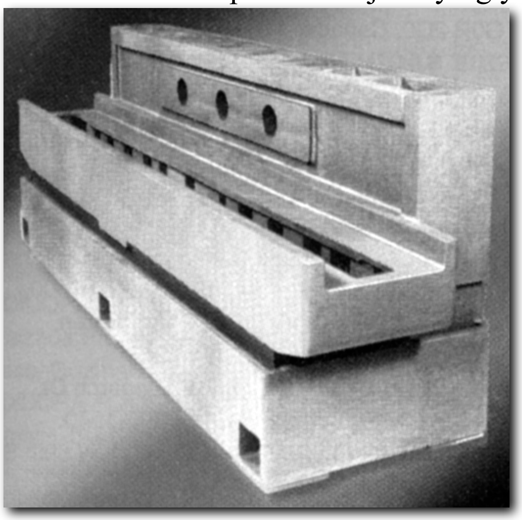
(ii) **Malleable cast iron**. When white cast iron is heat-treated for several days in the range of 900°C, the carbon that was originally incorporated in the cementite phase (Fe_3C) emerges as graphite in a rough nodular (equiaxed) morphology, leaving behind a matrix phase that is nearly pure Fe. It is the very soft matrix that enhances its malleability relative to white cast iron, and shows the ductile tearing shown here. Compare with the light optical micrograph shown in Figure 2.34 of the text.

(iii) **Ductile (or Nodular) cast iron**. The most salient feature of the microstructure is the spheroidal graphite morphology, generated by Mg additions to gray cast iron. Compare with the light optical micrograph shown in Figure 2.35 of the text.

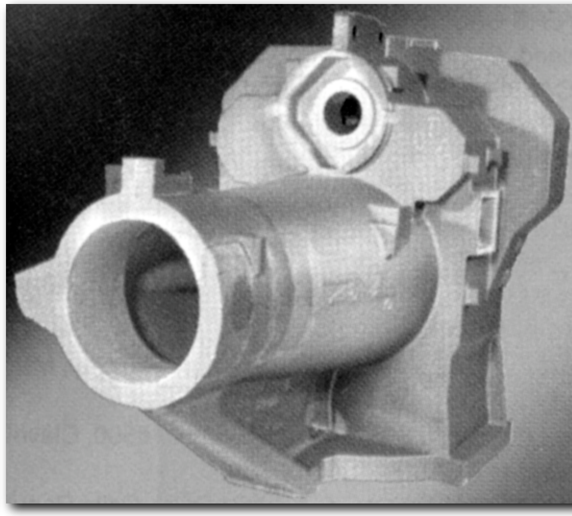
Solutions

Problem 1(b) [20 points]

The images shown here depict (*iv*) a 20-ton machine tool base and (*v*) a 4-ton wind turbine power-generation gearbox housing. For each one, specify a casting *technique* and *type of cast iron* (from 1(**a**) above) that you consider appropriate for the product. Rationalize your answers with brief explanations justifying your choices.



(*iv*)



(*v*)

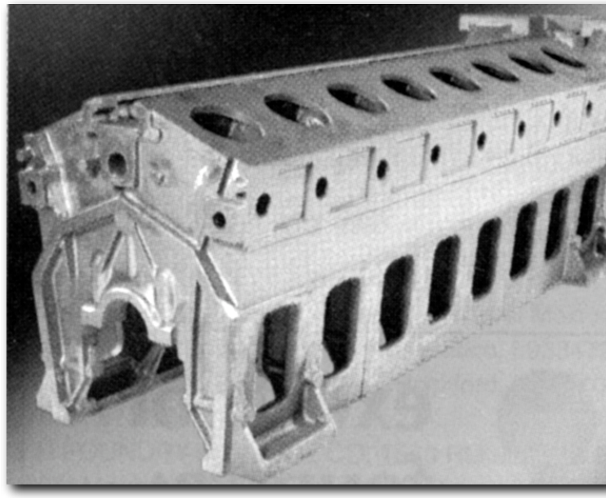
Solution

(i) **Sand casting / gray cast iron**. The very large structure with relatively simple shape makes sand casting the obvious choice of technique. Because of its application as a base for a machine tooling rig, gray cast iron would be preferred due to its capacity for vibration damping and good surface finish. A derivative benefit is that gray cast iron suffers very little shrinkage during solidification, an especially attractive feature for such a large casting that would otherwise require complex riser design.

(ii) **Sand casting / gray cast iron**. All of above same arguments again apply here. A four ton casting is by no means small. Even though the housing seems to contain many intricate surface reorientations, these can be obtained by careful pattern design. All ports to the interior of the housing are easily produced by simple core designs, and can be easily cleaned of flash or burrs by subsequent machining, due to its large size.

Solutions

Problem 2 [50 points]



Consider the shape casting of a gray cast iron biodiesel engine block for marine shipping vessels with actual composition 3.0 wt.% C, 1.9 wt.% Si, 0.35 wt.% Mn, 0.02 wt. % S and 0.04 wt. % P poured from an initial liquid temperature of 1400°C into a sand mold.

Perform a detailed assessment of the solidification front at 1200°C, plotting the variation in **C concentration**, in corresponding **liquidus temperature** and in "actual" **liquid temperature** as a function of **distance** across the solid-liquid interface. Clearly state all assumptions. What do you conclude about the likelihood of constitutional supercooling during solidification of this engine block?

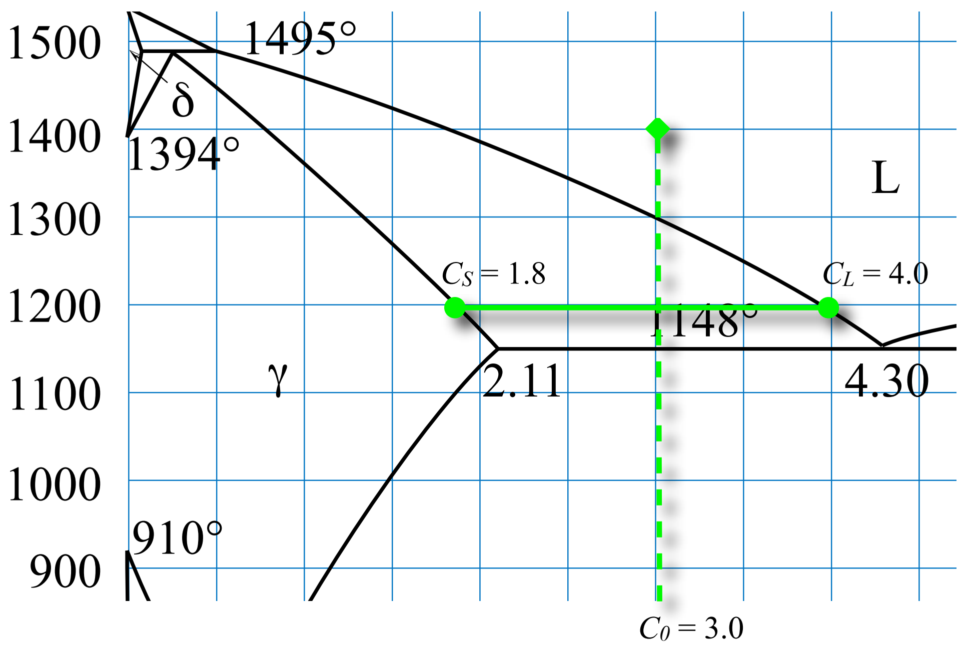
Solution

The most important **assumption** here is that the phase relationships in this multi-component alloy system can *approximated* by the Fe-C binary system, so the phase diagram given in the problem statement can be used for this analysis. Coupled to this assumption is another that the sand mold acts as an insulating mold for this large casting, allowing for very slow cooling, which is a reasonable approximation of *equilibrium* cooling.

Solutions

Begin by locating the alloy composition and its temperature on the Fe-Fe_3C phase diagram and use the tie-line construction to establish the boundary conditions on the composition of both the solid and liquid phases as a function of distance across the solid liquid interface.

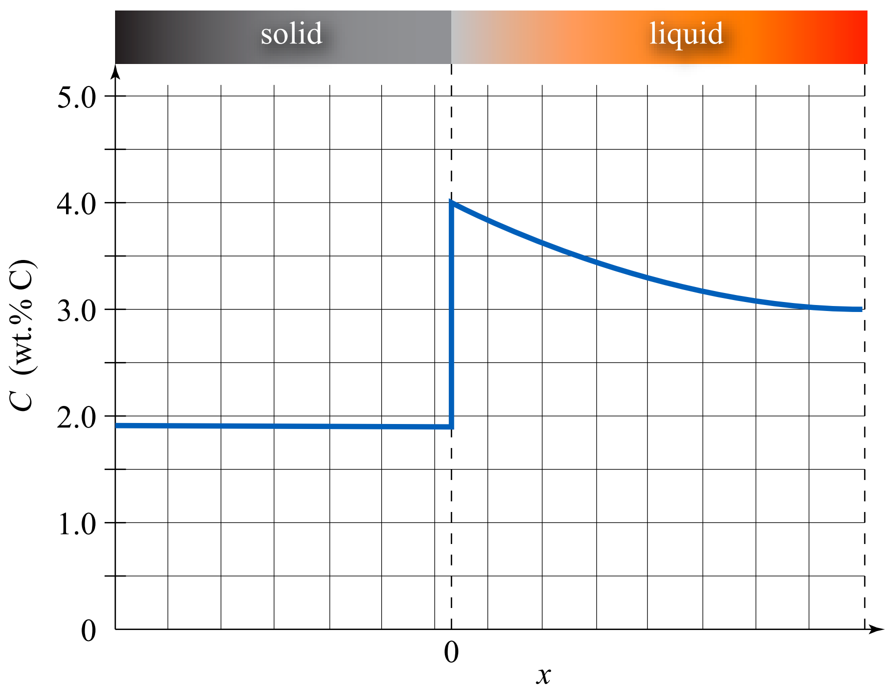
Draw both the vertical line at the nominal composition of the alloy and the horizontal line (isotherm) representing the tie line at the requested temperature of 1200°C.



Solutions

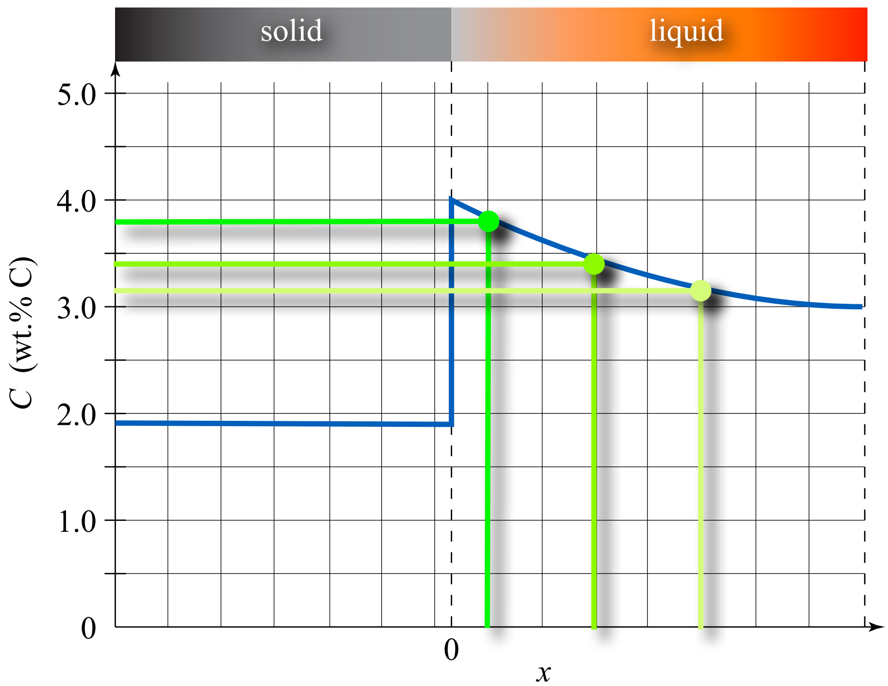
Next, plot these boundary conditions on a *C vs x* diagram as follows.
(1) the equilibrium composition of the **solid** phase at the interface (C_S = 1.8 wt% C);
(2) the equilibrium composition of the **liquid** phase at the interface (C_L = 4.0 wt% C); and
(3) the equilibrium composition of the liquid **far from** the interface (C_0 = 3.0 wt% C, the original composition of liquid, in its "as poured" condition).

Note also the relative amounts of the solid phase (≈45%) and liquid phase (≈55%) from the lever rule.



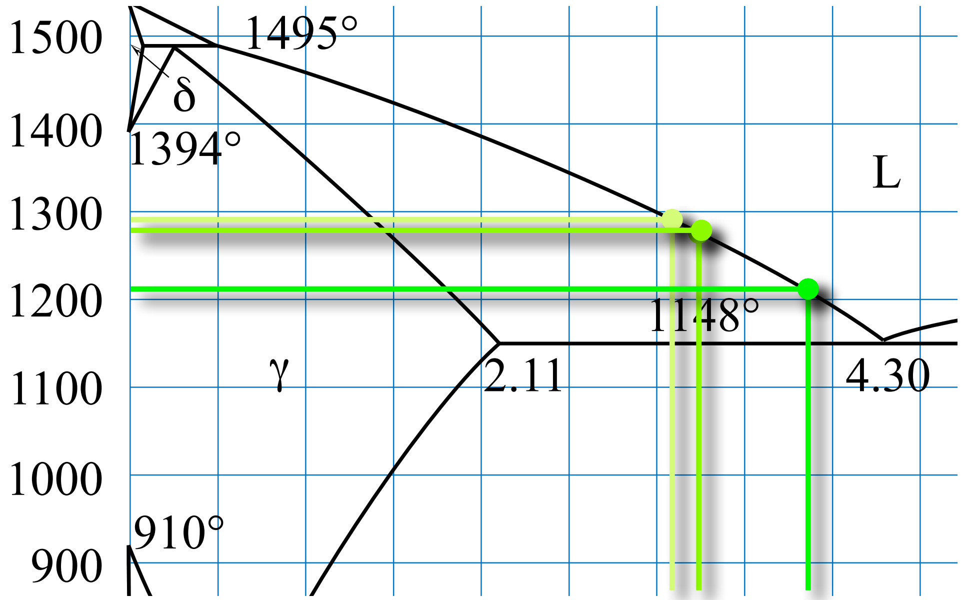
Solutions

Now choose an appropriate number of locations ahead of the interface to adequately profile a gradient (in this case, three are shown) and mark the **compositions** corresponding to these locations.



Solutions

Using the phase diagram, determine the equilibrium **liquidus** temperatures corresponding to these compositions at the three chosen locations ahead of the interface.



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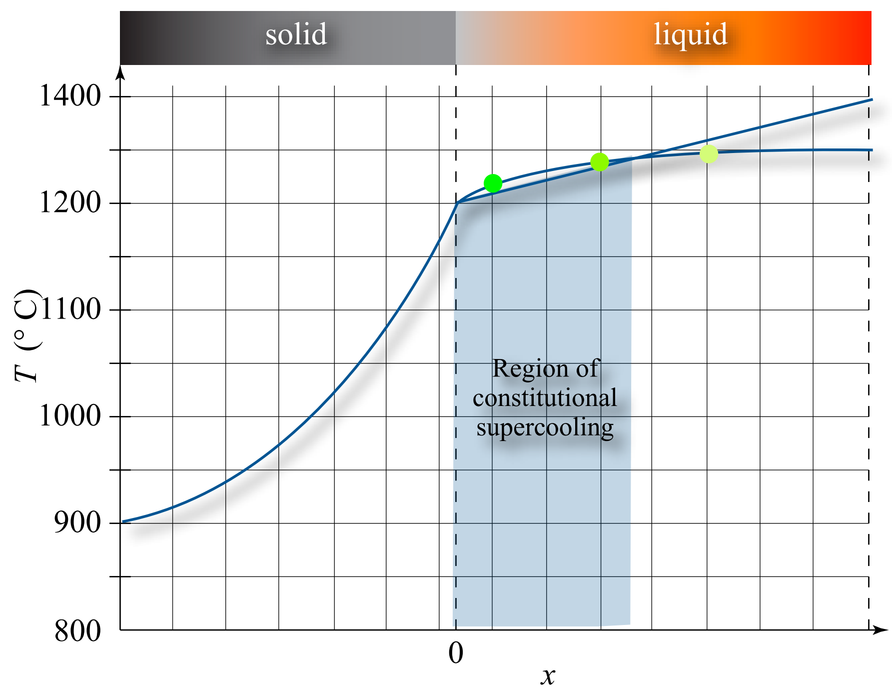
Finally, on a plot of the temperature profile across the solid liquid interface with the same scale as the composition profile above, show both the **actual temperature** (assume any reasonable shape for $\Delta T/\Delta x$, which could range from an error function shape similar to those calculated in homework solutions to a simple linear approximation), and the **liquidus temperature** as determined above. Note that the liquidus temperature must approach 1300°C as an asymptote, because this is the liquidus temperature of the 3% alloy.



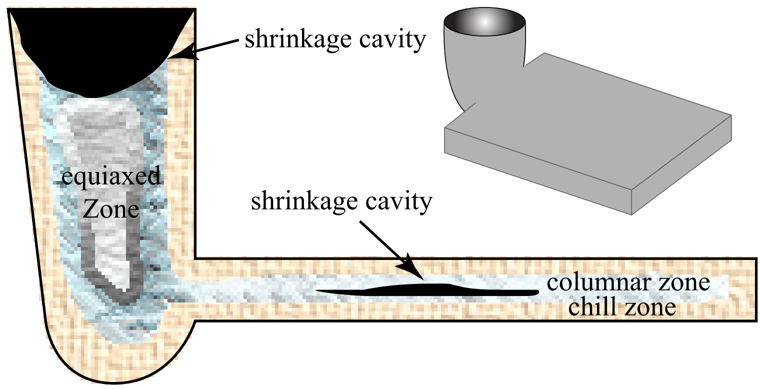
The crossover of these two curves determines the threshold of **constitutional supercooling**, as shown on the sketch below.

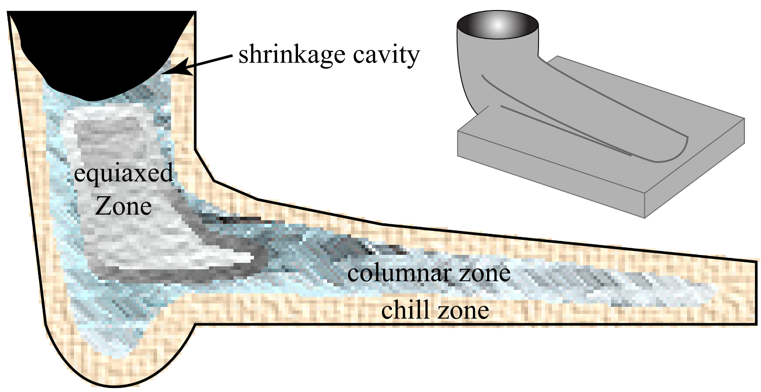
This analysis reveals that constitutional supercooling is **expected to occur** in this shape casting due to the concentration profile ahead of the advancing solidification front where carbon and perhaps many of the other alloying constituents are rejected into the liquid phase, forming a boundary layer of liquid that is always "constitutionally" supercooled.

Solutions

Problem 3(a) [30 points]

Rationalize the addition of the flange (elevated wedge) in the lower casting as a precaution against the development of macroporosity in a plate product made from an Al-12 wt.% Cu alloy.





(i) Show directly on the cross-sectional cuts though the centerline of the riser the development of the solidification product, indicating by labels the **chill**, **columnar**, and **equiaxed** zones in both cases.

(ii) Clearly label the locations of all **shrinkage** cavities in both casting configurations.

(iii) What are the implications of the flange during solidification with respect to the development of macroporosity? Is such a flange always a desirable attribute in such a casting? Explain.

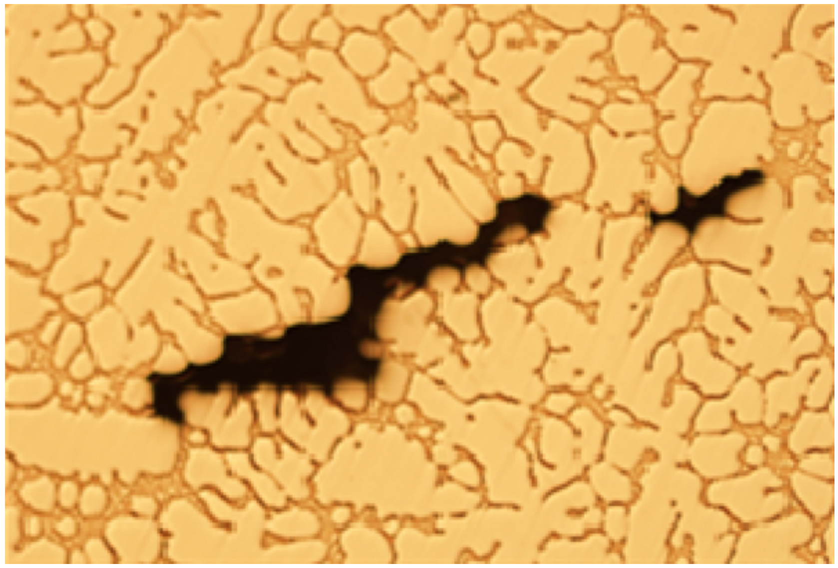
Solution

(i) and (ii) See labeled drawings above.

(iii) The flange inhibits the development of macroporosity by shaping the solidification front profile. It offers enhanced feeding of liquid into the solidifying product through a wider opening. In the thin cross section without a flange, a shrinkage cavity is expected to form as a consequence of the trapped liquid phase during the development of the columnar zone and isolation from the liquid phase remaining in the sprue. Obviously this role of the flange is desirable, but only if it can be retained in the final casting. Removal would require costly machining.

Solutions

Problem 3(b) [20 points]



The light optical micrograph shown at right is taken from a cut-and-polished section through the shape casting of the Al-12 wt.% Cu alloy made above.

(iv) Explain the microstructure seen here, commenting on both the light and dark regions.

(v) Now comment on the rationale for a further refinement in the casting of the plate product, namely, increasing the Cu content of the alloy to 33.2 wt. %. Be specific in your explanation of the logic behind this proposal.

Solution

(iv) The microstructure shows a dendritic solidification product in the light regions delineated by etched boundaries where solute segregation (also known as coring) causes deeper attack by the etching reagent. The dark regions generate no reflected light, so they are void spaces, the result of microporosity in the interdendritic regions.

(v) As discussed in the text on page 50, the shrinkage of isolated liquid phase generates micropores, and one of the best ways to reduce microporosity is to choose an alloy with a eutectic composition. By cooling through the eutectic isotherm at the eutectic composition, there is *no* mushy zone and no opportunity for liquid phase to become trapped among interpenetrating dendrite arms. Reference to the phase diagram at the beginning of this exam shows that the a Cu composition of 33.2% is equivalent to an Al composition of 66.8%, which *is* the eutectic composition on the Al-rich side of the phase diagram.

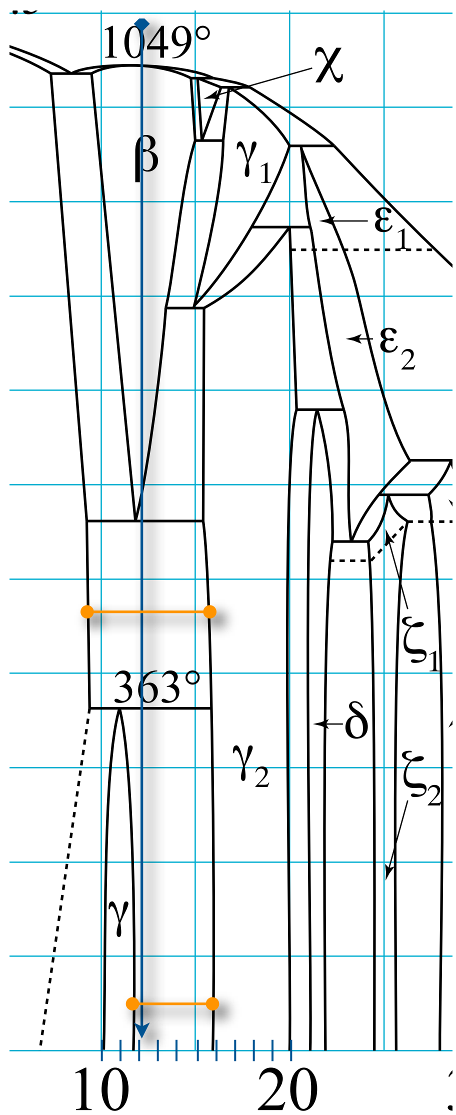
Solutions

Problem 4 [50 points]

Sketch and describe the microstructural evolution of a Cu-12 wt.% Al alloy when cooled from the liquid phase at 1100°C to room temperature. Assume equilibrium cooling within a heated insulating mold, and be specific about the effects on the final microstructure of crossing each of the reaction isotherms.

Solution

The phase diagram shows that a Cu-12%Al alloy at room temperature should exhibit a microstructure consisting of γ and γ_2 phases at equilibrium. The morphologies of these two phases are determined by the path through the phase diagram during cooling, and there are three primary reactions to consider along the way.



The first is the maximum melting point at 1049°C, below which the liquid phase transforms fully to β phase. This results in no mushy zone, and is very similar to the solidification of a pure element.

The second is the eutectoid reaction at approximately 570°C, where the transformation is $\beta \rightarrow Cu + \gamma_2$ and the reaction product has a lamellar morphology. The lever rule indicates that the Cu lamellae will be slightly thicker than the γ_2 lamellae, and this two-phase product completely consumes the β phase. There is no β phase left below 570°C.

Solutions

Finally, at 363°C, a peritectoid reaction isotherm is crossed, accompanied by the reaction $Cu + \gamma_2 \rightarrow \gamma$. The γ phase will therefore nucleate at the interlamellar interfaces and grow outwards, consuming all of the Cu phase, resulting at room temperature in a mixture of approximately 95% γ phase, and 5% γ_2 phase dispersed in lamellar-like strings as a remnant of the higher temperature eutectoid precursor through which it evolved.

The resulting microstructure is sketched below.