1)

Rate

T_E-T

The rate is zero at T_E and at 0K so we get a peak at an intermediate temperature. This corresponds to a minimum in the time needed to effect a transformation, hence the nose in the curves at a temperature a bit below the transformation temperature.

The peak transformation rate for carbide precipitation is well above the temperature at which martensite forms. In low alloy steels considerable precipitation can take place even at fast cooling rates. The alloying elements slow down the diffusion need to form precipitates so that a slower cooling rate can be used to form 100% martensite. This allows larger samples to be transformed to martensite.

These diagrams are derived by a quench, hold, quench, process. Not by cooling at different rates.

En 12 has low hardenability and is cheaper than En24. It will be used for small hard articles where cost is important, or for larger items like car crankshafts, where we want a hard surface but a more ductile interior.

Hardenability is a measure of how far the nose is from the axis of the TT diagram and therefore how large an item can be hardened. When steel is welded regions near the weld cool very rapidly and martensite can be formed. Since this is very brittle this is very damaging to the strength of the weld. To avoid this a low hardenability steel is needed for good weldability.

In the Jominy test a sample of the steel of interest is quenched at one end so that different rates of cooling occur along the length. The hardness is then measured along the bar. This gives a useful measure of the hardenability of the steel. Subsequent tempering lowers the yield strength but increases the fracture toughness. By measuring these along the bar a suitable heat treatment for a particular application of this steel can be devised.

To ensure 100% martensite we need to cool the sample to below 290C in less than 15 secs.

$290-20=(900-20) \ erf(x/\sqrt(9 \ 10^{-6} \ 10))$

$erf(x/\sqrt(9 \ 10^{-6} \ 10))=0.31$

$x/2\sqrt(9 \ 10^{-6} \ 10)=0.28$

$x=5.3$ mm.

40

This is an underestimate as the TTT diagram is constructed by holding the material at a constant temperature for various times. If we start at a high temperature there is much less rapid transformation than at the lower temperature of the nose, so the degree of transformation is less than if the sample were held at the nose temperature.

The result is reasonably consistent with the untempered curve Fig 5.5, which drops rapidly over the first 5mm., although one would expect a flat section up to 5mm while the in practice the curve is dropping fairly rapidly from a shorter distance. However the distances are of the right order and one cannot expect much better agreement than this in what is a very complex process..

Toughness

Tempered

As quenched

Distance
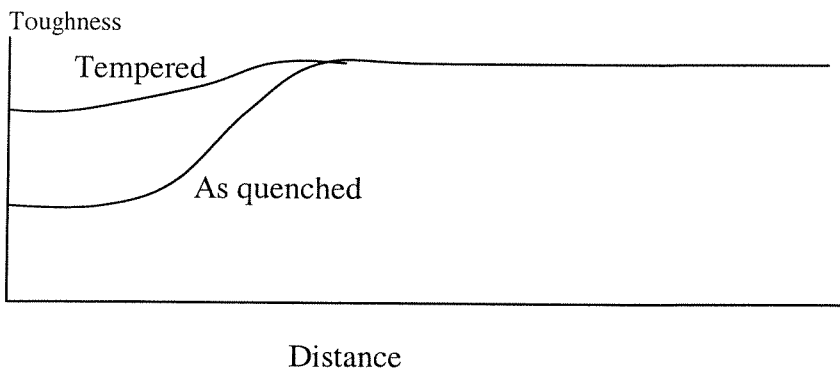
Decreased hardness causes an increase in fracture toughness.

Modulus

Distance
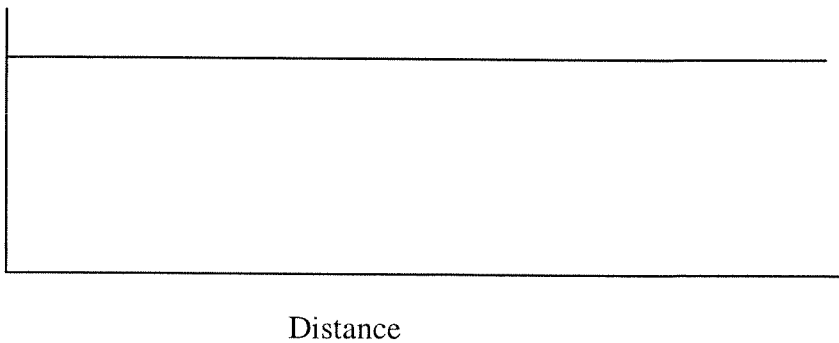
The modulus is not affected significantly by heat treatment.

Comments

About half the candidates thought that heat treatment affected the modulus and a good many thought that a steel with high hardenability was harder than a steel with low hardenability..

2) Surface energy is the energy required to create unit area of surface in a liquid or solid. For a surface at a vacuum or gas it is due to the unattached bonds at the surface which in the solid, or liquid, are attached to neighbouring atoms so an approximate figure is given by the binding energy divided by the atomic area. Between solid phases it is due to the mismatch in structure at the boundary which causes local strain. Since the energy to be gained by a phase transformation is proportional to the volume while the energy needed to make a surface is proportional to the surface area, a certain size of nucleus is needed before it becomes energetically favourable to change phase. This leads to supercooling of liquids and gases. For liquid to solid, or solid to solid, phase changes the surface energies are much smaller then if the surface is to a vacuum or gas.

In an isotropic material surface energy considerations favour spherical precipitates. However the diffusion paths to lamellae are shorter so these form first. Only after long annealing will the surface energy break the lamellae into separate particles.

A typical structure is pearlite.

For a sphere the total energy change ΔE on changing phase is :-
$$\Delta E = (-4/3)\pi r^3 \Delta G + \gamma 4\pi r^2.$$

The rate of change becomes positive when dE/dr becomes negative so that a small increase in r leads to a decrease in energy.

This is when :-
$r = 2\gamma/\Delta G$

This is the minimum size of nucleus.

(For those who worry about whether we should be using internal energy, enthalpy, Helmholtz energy or Gibbs function you are quite right. We have ignored any heat going in or out so this is rather sloppy thermodynamics. In fact none of these functions can be used in an inhomogeneous system with a surface, we need to use the Availability. However the extra complication is large and the difference in the result small).

Two examples are martensite and glasses. In both cases the non-equilibrium phase is frozen in by rapid cooling.

Grains nucleate where there is a concentration of plastic deformation because of the energy of the dislocations. To provide a nucleus the material must be deformed by plastic deformation. This gives a uniform array of dislocations.

It is then annealed so that the dislocations concentrate in walls which are nuclei for new grains. To make a small grain size the material should be heavily deformed and then annealed so that the dislocations form walls. Because of the heavy deformation these will be close together so that there are many nuclei and the grain size is small. The annealing should not be too long or the grains will grow.

To make a large grain size we put in a small amount of deformation before annealing. This requires careful control as the deformation must be enough to ensure that there is at least one nucleus, but not many more.

Once the material has recrystallised further annealing will increase grain size, but the process is slow.

Comments   A number of candidates talked about the size of precipitates instead of the size of grains.

3)

0.1% Pb solid solution

10% Mainly α solid solution plus a little almost pure tin

61.9% Eutectic, fine mixture of Pb solid solution and tin

90% Eutectic plus tin .

For a given temperature in an AB diagram let the phase boundary compositions be at x1 and x2 %B

If we have a mass M=m1+m2 of a material with composition x%B

Then since the mass of A in each phase must add up to the total:-

m1 x1+m2 x2= (m1+m2)x

Hence m1(x-x1)=m2(x2-x)

This is the lever rule.
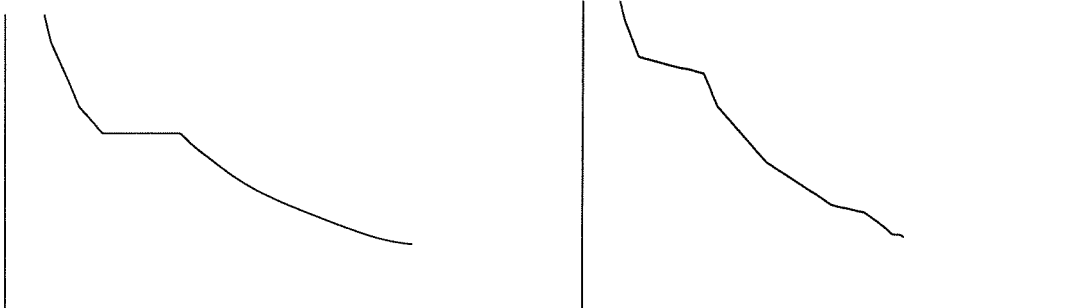
If we apply it to the B component we get the same result

m1(1-x1)+m2(1-x2)=(m1+m2)(1-x).

This is based on conservation of mass. It cannot be applied to atomic percentages since although the number of atoms is conserved we cannot easily define the atomic percentage of a phase in a mixture of phases.

Cooling curves

Temperature

Time   69% 90%

Curves a re basically exponential with a changing rate at phase changes. The eutectic has a single horizontal section. The 90% has a reduced rate over the temperature of the liquid to solid transition and a much smaller discontinuity on crossing into the two solid phase region.

For electrical soldering the eutectic is used. This is because the temperature is lowest, avoiding damage to semiconductors, and also it solidifies like a pure solid avoiding movement of precipitates in the liquid which could damage fine wires.

For plumbing it easier to block holes if you can work with a slush of solid and liquid so a composition well away from the eutectic is used. Since lead is cheaper than tin that side of the eutectic is used.

Comments

Many candidates wasted time in writing down information that was not asked for such as the proportions of each phase. This gains no extra marks.

4)

Creep occurs by atomic diffusion and by thermal activation of dislocations past obstacles by climb.

a) Temperature has a large effect on creep since it is thermally activated. The rate is proportional to $\exp(-U/kT)$ where Q is the activation energy. Typical activation energies are about a tenth of the bond strength, i.e. about 0.1 eV which should be compared with kT at room temperature which is 1/40 eV.

b) Diffusion occurs along grain boundaries so polycrystals creep more rapidly than single crystals. If the grain size is very small the linear creep rate is sufficiently fast to be used to form artifacts, (superplasticity).

c) Creep resistant alloys use a wide range of precipitates to hinder diffusion,

d) The diffusion activation energy depends on the ease with which diffusing atoms, or dislocations, can break atomic bonds and so is directly related to the melting point. In different materials creep mechanisms begin at the same fraction of the melting point.

e) Although there is no direct connection between creep and modulus, the modulus depends directly on bond strength and so high modulus elements have a high melting point and are creep resistant. Precipitates will increase the creep resistance without affecting the modulus.

f) At lower temperatures the main mechanism is dislocation creep so the higher the dislocation density the more rapid the creep.

Problem:-

If the wall thickness is d then $V=2\pi Rd$ and $\sigma=PR/d$ so:-

$d\varepsilon/dt=d^{-1} \, dd/dt = -\alpha(PR/d)^n = -\alpha(PV/2\pi d^2)^n$.

$d^{(2n-1)}dd/dt== -\alpha(PV/2\pi)^n$

$d^{2n}/2n - d_o^{2n}/2n = -\alpha t(PV/2\pi)^n$

For d =0 $t=(1/2n\alpha)(2\pi d_o^2/PV)^n$.

Two effects will reduce this time. One is the effect of the longitudinal stress, which is half the hoop stress. The other is inhomogeneous thinning which will cause necking as in a tensile test. Only if n=1 will the wall thin uniformly. Also cavities form after large amounts of creep strain so that the wall will fail before it reaches zero thickness.

5)

Details in handouts

i) Austenitic stainless steel (fcc). Ferritic steels (bcc) go brittle at low temperatures. Roll sheet and weld under argon, or with e-beam.

ii) Injection moulded thermoplastic, e.g. polypropylene. Disadvantage of high moiuld cost if the production run is short – probably then not feasible to use plastics unless it could be rotationally moulded

iii) Nickel alloy, cast and preferably made single crystal to minimize creep.

iv) Moulded soda-lime glass followed by thermal toughening – plenty of detail in notes/handouts

6)

a) Silicon should be pure to 1 atom in 10^{11} · Single crystals are made by pulling from the melt (Chorkalsky method), and then sliced into wafers.

Doping with impurities begins to have an effect at about 1 in 10^8 and beyond this point te resistivity is determined by the doping. Since the valency of silicon is 4 trivalent dopants add holes, pentavalent impurities add electrons.

The distance diffused $x=\sqrt{(Dt)}$ after a time t.

D is proportional to exp(-Q/RT) and t to 1/D

$t(1000)/t(1200)=\exp(336\times10^{-3}/8.3)(1/1000-1/1200)=852$

b)

Breaking stress $\sigma =K_{IC} \sqrt{(\pi a)}= 0.86$ GPa

Strain $\varepsilon=\sigma/E = 1.9\times10^{-3}$ Bend radius $R= y/\varepsilon=1mm/\varepsilon=.525m$

Deflection $=R(1-\cos(L/2R))=0.21$ mm