Engineering Tripos Part IIA 2005 Paper 3C1
Manufacturing Engineering Tripos Part I 2005 Paper P4A

Solutions

q. 1(a) Transformation hardening involves rapid heating and cooling of the steel from the surface. Steel near the surface forms austenite which is then quenched either by conduction into the cooler bulk and/or into a quenching medium (air/water/oil etc) and if cooling rate is fast enough will form martensite. The hardening is associated with martensite formation. Depth of hardening will therefore be that to which austenite is formed and quenches to martensite so will depend on heating rate, cooling rate and hardenability of the steel (i.e. TTT diagram). Limit to maximum hardness is the maximum hardness of (untempered) martensite – so strongly dependent on carbon content of the steel.

Other (non-coating) methods are carburising (diffusion of carbon into the steel in the austenite phase, followed by quenching and tempering; the higher C content leads to a harder martensite), carbonitriding (as for carburising but involving diffusion of both carbon and nitrogen), and nitriding (diffusion of nitrogen in the ferritic phase, forming nitride precipitates which give a hardening effect – steel must contain nitride-forming elements such as Cr, Al, V). Further details given in lecture notes.

(b) The *equivalent diameter* of a component is the diameter of an infinitely long circular cylinder which, if subjected to the same cooling conditions as the component, would have a cooling rate on its axis equal to that at the position of slowest cooling in the component.

Half-way between the holes, the width of the rectangular section is twice the average radius of the two ends (21mm). Hence:

$T = 10\,\text{mm}$, and $B = 42\,\text{mm}$. So $T/B = 0.24$.

From the equivalent diameter curves for rectangular sections:

$f = 1.72$, so $D_e = 1.72 \times 10 = 17.2\,\text{mm}$

For the semi-circular ends, treat the large end as a tube (as the length is greater than the radial thickness), and the small end as a ring (as the length is less than the radial thickness).

For the large end, allow for the countersunk holes by taking an average tube length of 22mm, with inner radius 6.5mm and outer radius 22mm. Hence:

$x = 13\,\text{mm}$, $y = 15.5\,\text{mm}$, and $z = 22\,\text{mm}$. So $x/y = 0.84$ and $y/z = 0.70$

From the equivalent diameter curves for tubes:

Large end: $f = 1.27$, so $D_e = 1.27 \times 15.5 = 19.7\,\text{mm}$

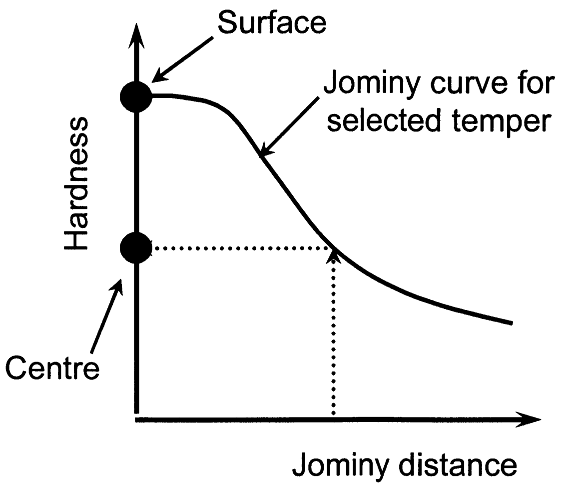
For the small end:

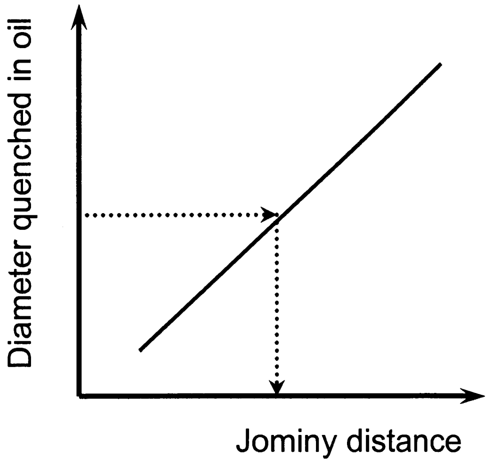
$x = 13\text{mm}$, $y = 13.5\text{mm}$, and $z = 10\text{mm}$. So $x/y = 0.96$ and $z/y = 0.74$

From the equivalent diameter curves for rings:

Small end: $f = 1.22$, so $D_e = 1.22 \times 10 = 12.2\,\text{mm}$

To find the hardness at the crank centre, the equivalent diameter for oil quenching is converted to the Jominy distance which has the same cooling rate, and the hardness read off the appropriate tempered Jominy curve at this distance (schematic below). For the surface hardness, it is assumed that the hardness with an oil quench is the same as that obtained at the centre of a very small bar, i.e. the hardness at the quenched end of the Jominy bar.



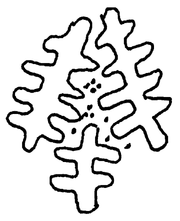


For air quenching, the cooling rate is limited by the poor surface heat transfer, and the cooling rate is essentially the same everywhere in the cross-section. In this case, the centre and surface hardness would be the same, as given by the equivalent diameter for air cooling, and the appropriate conversion from diameter in air to Jominy distance.

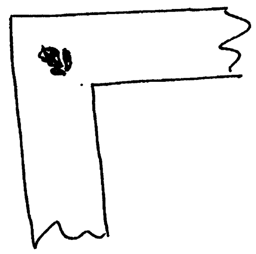
Examiner's comment:

This popular question was generally well done, and students who could handle the quantitative part obtained good marks.

q.2 (a) (i)



microporosity



macroporosity

Macro-porosity: Significance of alloy: very long semi-solid range, so there will be high shrinkage on undergoing the liquid-solid transition. The contraction of liquid is very much greater than that of solid. On cooling from about 600°C to 425°C the total contraction comes from not only the liquid-solid transition, but also the contraction of liquid. Since material in the semi-solid state has very low strength, it is liable to form large cavities and tears if it is put under tensile stress by the surrounding material. This is liable to occur in variable section castings such as this, since the thicker section (the centre of the corner of the box) solidifies more slowly than the surrounding thinner parts. There is no feeder to supply a source of liquid metal to be sucked into the last part of the casting to solidify.
Remedy: "chills" (blocks of metal) around the thick section to encourage early solidification. Alternatively, a feeder head could be used to supply liquid metal to this region.

Micro-porosity: Gas which is in solution in the liquid comes out in the form of bubbles as the solid forms. The bubbles are pushed to the regions which solidify last, so are found as microporosity in between dendrite arms and at grain boundaries. In the gun-metal, these microcavities will expand to accommodate some of the very large amounts of solidification shrinkage, and some extra cavities will form. The amount of microporosity can be reduced by out-gassing the metal before casting (e.g. by vacuum), but the problem will still remain.

Porosity from other sources: If the sand is damp, then there may be some cavities formed as the water vapourises in the presence of the liquid metal. These are generally quite small (sub-mm size), and very close to the surface of the casting.

(ii) The inoculant will increase the amount of nucleation within the melt. This will reduce the grain size and increase the proportion of equiaxed grains. This means that the amount of columnar growth is limited. Porosity in columnar regions is likely to be interconnected, forming channels parallel to the long grains. Decreasing the grain size means that the porosity is likely to be smaller and on average more evenly distributed through the casting, with less interconnection.

(iii) Macro-porosity: Al-12%Si is a eutectic alloy, so immediate liquid-to-solid transition. Shrinkage problems are greatly reduced, though there is still some danger of shrinkage cavities forming.

Micro-porosity: Amount of out-gassing porosity expected to be similar to gun-metal, but because of the reduced shrinkage the total will be very much less.

(iv) Because this is a net-shape casting, the possibilities for post-processing are limited. Heating alone has very little effect on porosity: gas-filled pores won't shrink because the gas can't diffuse through the solid. However, HIPing (Hot Isostatic Pressing) is sometimes used to squeeze out porosity in Al alloys, and provides significant improvement in mechanical propreties. It is ineffective for porosity which connects to the surface.

(b) (i) Surface detail and good tolerance imply we need a zero shrinkage alloy. Graphite expands on formation, so counterbalances the shrinkage of the metal. Either of the two grey cast irons would satisfy this criterion. However, the SG cast iron has much improved mechanical properties (strength and toughness) because of the spheroidal morphology of the graphite (Mg poisons growth of the graphite, so prevents the formation of flakes). So this will be the material of choice.

(ii) Material needs to absorb vibration; mechanical properties are relatively unimportant as it is under compression. The flake graphite in grey cast iron acts as cracks, which have a vibration damping effect.

Examiner's comment:

Weaker students regurgitated their notes and failed to apply their knowledge to the specific aspects of this question; they did not obtain high marks for this.

q.3 (a) (i) All three processes involve melting the thermoplastic feedstock supplied as granules, and then extruding the melt. Melting and extrusion are achieved in a screw extruder in which both mechanical work and external (electrical) heating result in melting.

In injection moulding a charge of melt is injected into a shaped dismountable metallic mould cavity under high pressure, either directly (by moving the extruder screw relative to the barrel) or indirectly by moving a piston in a separate cylinder which has been filled with melt from the extruder. The process is discontinuous, since the melt has to cool in the mould before the component can be removed; cycle times are of the order to tens of seconds to a minute or more, depending on the size of the component. Used for 3-D parts, often with complex shapes, usually thinner in one dimension than the other two to achieve sufficiently rapid cooling.

Extrusion is a continuous process in which the melt is forced through a shaped die to produce a linear product, which can also be hollow (eg tube/pipe) by use of a plug die. Also used for coating wire (electrical insulation).

Film blowing involves inflating a 'balloon' of molten polymer with air, produced by forcing polymer melt through a ring-shaped die. The resulting polymer cylinder is drawn upwards as it is inflated and also cooled, giving a thin sheet product. Used for producing thin sheet or film (thin in one dimension).

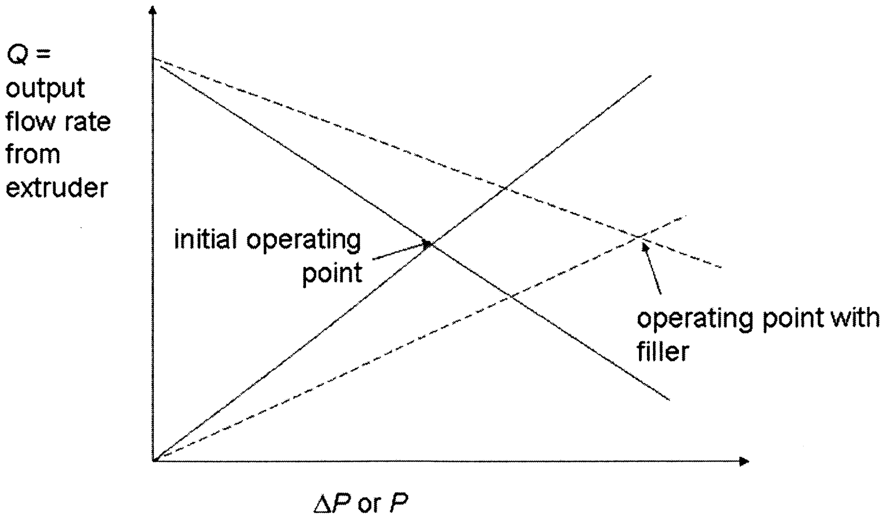
(ii) Molecular alignment results from extensional flow which occurs when the melt is subject to drag from solid walls – eg in channel flow and also in extrusion through a die. Molecules become aligned parallel to the flow direction, and extended from their natural randomly coiled conformation. Shear flow (dominating in injection moulding) gives much less alignment.

An advantage of alignment is the increase in yield stress of the solid polymer in the alignment direction(s) – this is exploited in film blowing where the combination of air inflation and drawing produces biaxial alignment (in both hoop and axial directions) in the cylinder of film.

A disadvantage of alignment is the resulting tendency of the molecular chains to revert to their random conformation, causing distortion of the product – important in extrusion where high alignment within the die can be followed by subsequent distortion of the product after it leaves the die (die swell')

(b) (i) The LHS of the equation relates to the rate of flow of the polymer through the barrel; the RHS is the rate of flow through the die. Mass balance requires that the operating point is when the two flows are equal.
$A\omega$ is the term describing drag flow of the polymer, as a result of rotation of the helical screw down the centre of the barrel. ω is the rotation rate of the screw; A contains geometrical factors.

$B\Delta P/\eta$ describes the back-flow of the polymer in the channel. B contains geometric factors. ΔP is the pressure drop across the metering zone. η is the polymer viscosity.
CP/η describes the flow through the die. C contains geometric factors. P is the polymer pressure at the die, which is about twice the value of ΔP . η is again the polymer viscosity.
The main factor which is ignored is leakage: some polymer will flow back past the flights of the screw, so reducing the total output. This may reduce the flow rates by as much as 20%.



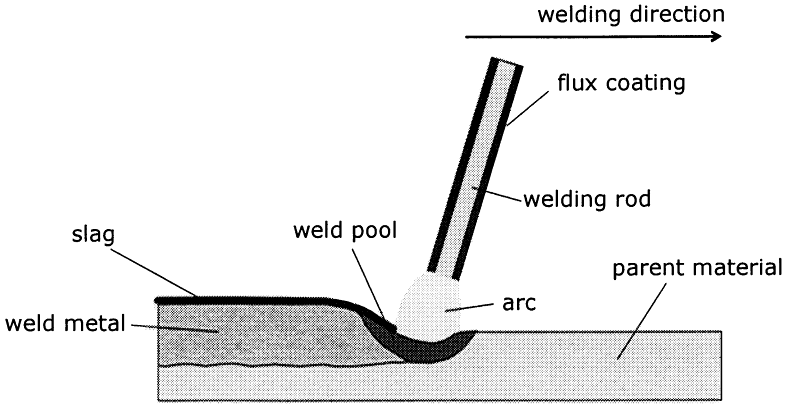
(ii) Adding filler increases melt viscosity, so affects back flow and flow through the die, changing the gradients of both lines as indicated by the broken lines. The operating point shifts to increased pressure drop, but the output is likely to change little (the exact behaviour depends on gradients of lines and so on values of geometric constants B and C).

Examiner's comments:

The most popular question, generally quite well done.

q.4

(a) MMA welding

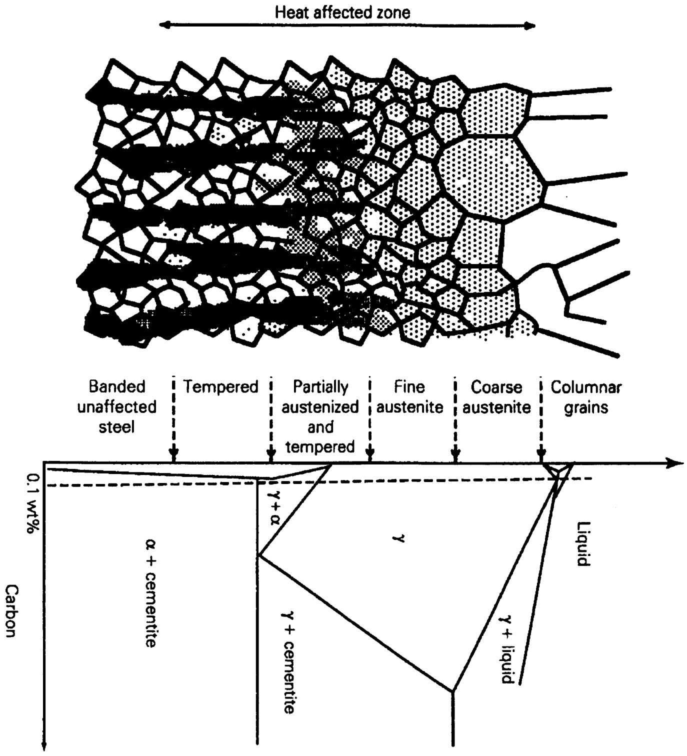


Electric arc struck between welding rod and work supplies heat to melt both rod (acts as filler) and work. Resulting weld pool solidifies to form weld metal. Welding rod is coated with flux which melts and forms layer of inert slag on top of weld pool and cooling weld metal – slag protects the molten/hot steel from oxidation by air, and is removed after cooling.

(b)

Diagram from lecture notes for a banded steel – in answer would expect sketch with similar features without the banding and including the following moving out from the weld centre-line:

- cast microstructure with columnar grains, epitaxial growth from neighbouring solid material
- coarse austenite grains which may then form martensite or ferrite/pearlite or bainite (depending on cooling rate)
- finer austenite grains ditto
- region which has been partially austenitized
- tempered zone
- unaffected microstructure



(b) continued

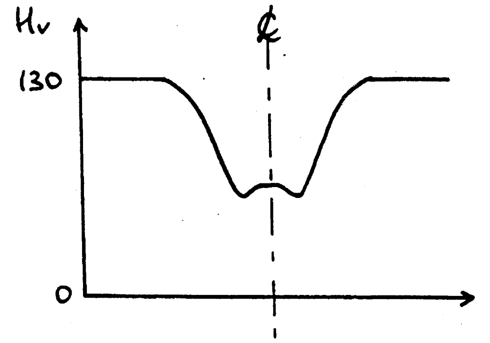
Formation of martensite (associated with high hardenability – favoured by large austenite grains) leads to high hardness, and low fracture toughness. The maximum hardness corresponds to the minimum toughness in the HAZ, which is an important design criterion to avoid fast fracture.

(c) (i) preheating of plates will reduce cooling rate after welding and reduce the tendency for martensite formation (sketch of CCT diagram would get extra mark); beneficial since martensite is hard and brittle and would lead to a low toughness weldment. The critical cooling range is from 800 to 500 °C.

(ii) heat treatment after welding can be used to temper any martensite which has formed and also reduce residual stresses; again beneficial in achieving a strong, tough weld.

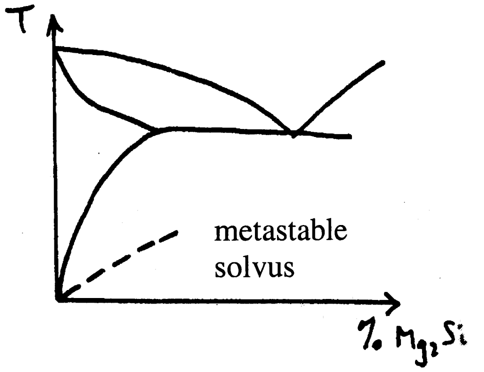
(d) EB welding involves a much higher power input so would expect a much narrower weld region and heat-affected zone. The resulting cooling rate is much higher so that there is a greater tendency to form martensite. Process is therefore less applicable to steels with high hardenability (sketch of CCT diagram helpful here).

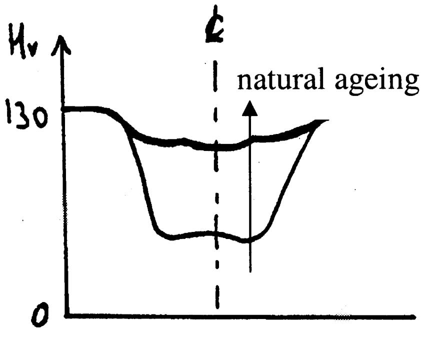
(e) (i) For age-hardened Al alloy, the hardness profile immediately after welding would be:



the weld metal is softened since the cast weld metal is now a supersaturated solution of the solute (e.g. Cu), and the precipitates have also dissolved in the HAZ ('reversion').

(ii) After several days at room temperature precipitation (natural ageing) would have occurred in the HAZ and weld metal by formation of new precipitates, leading to restoration of much of the original strength. (Full explanation of these processes would involve sketch of phase diagram showing the metastable solvus for the precipitates – heating above this leads to dissolution)





Examiner's comments:
Some good answers, but a disappointingly large number of candidates who had only a hazy idea of how arc welding was carried out, or of the microstructures to be expected around a weld in steel.