1   (a)   Carbon equivalent is an empirical measure of both the hardenability and weldability of steels, accounting for the alloying elements present. A high alloy concentration results in a high carbon equivalent. The higher the carbon equivalent, the higher the hardenability and the lower the weldability. A higher carbon equivalent increases the likelihood of brittle phases being present in the microstructure.

(b)   (i)   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 (air cool, oil quench or water quench) would have a cooling rate on its axis equal to that at the position of slowest cooling in the component.

(ii)   Aspect ratio $T/B = 10$ mm / 50 mm $= 0.2$. Reading from Fig. 1, using the curve for $T = 10$ mm, the factor $f = 1.66$.
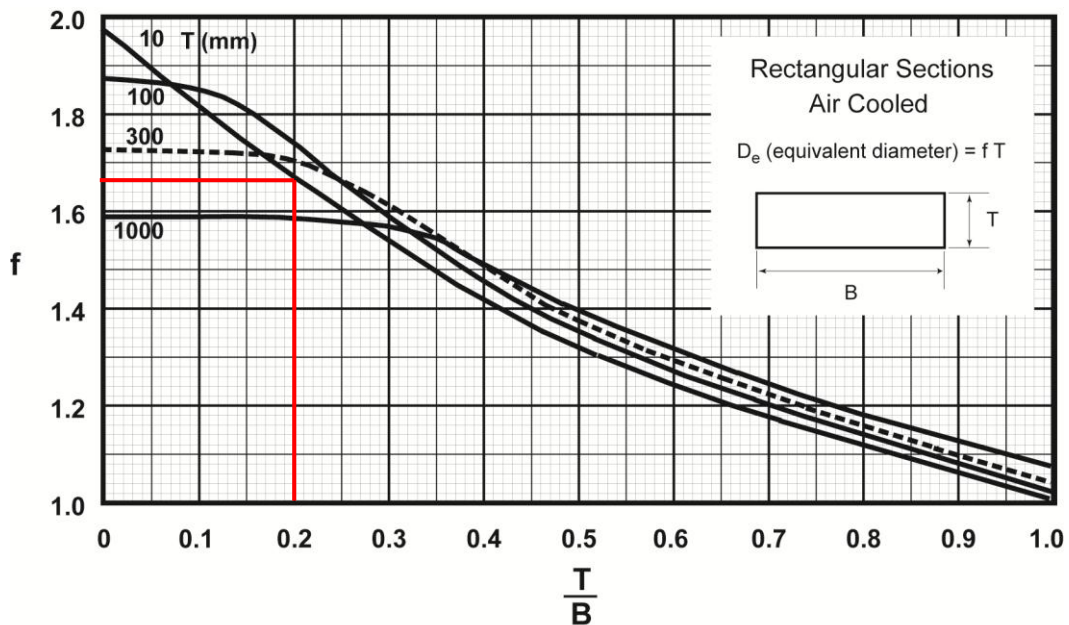

Figure 1

The equivalent diameter: $D_e = fT = 1.67 \times 10$ mm $= 16.6$ mm

Using Fig. 2 (below), the microstructure and hardness in the centre of the bar can be read off by interpolating the correct equivalent diameter from the air-cooled axis. The microstructure is 50% bainite, 50 % martensite. The hardness is 520 HV.

For air cooling, the properties on the surface of the specimen can be assumed to be identical to those in the centre. (For more rapid water or oil cooling, the properties on the surface of the specimen could be found by assuming the fastest cooling rate available in Fig. 2.)

Figure 2
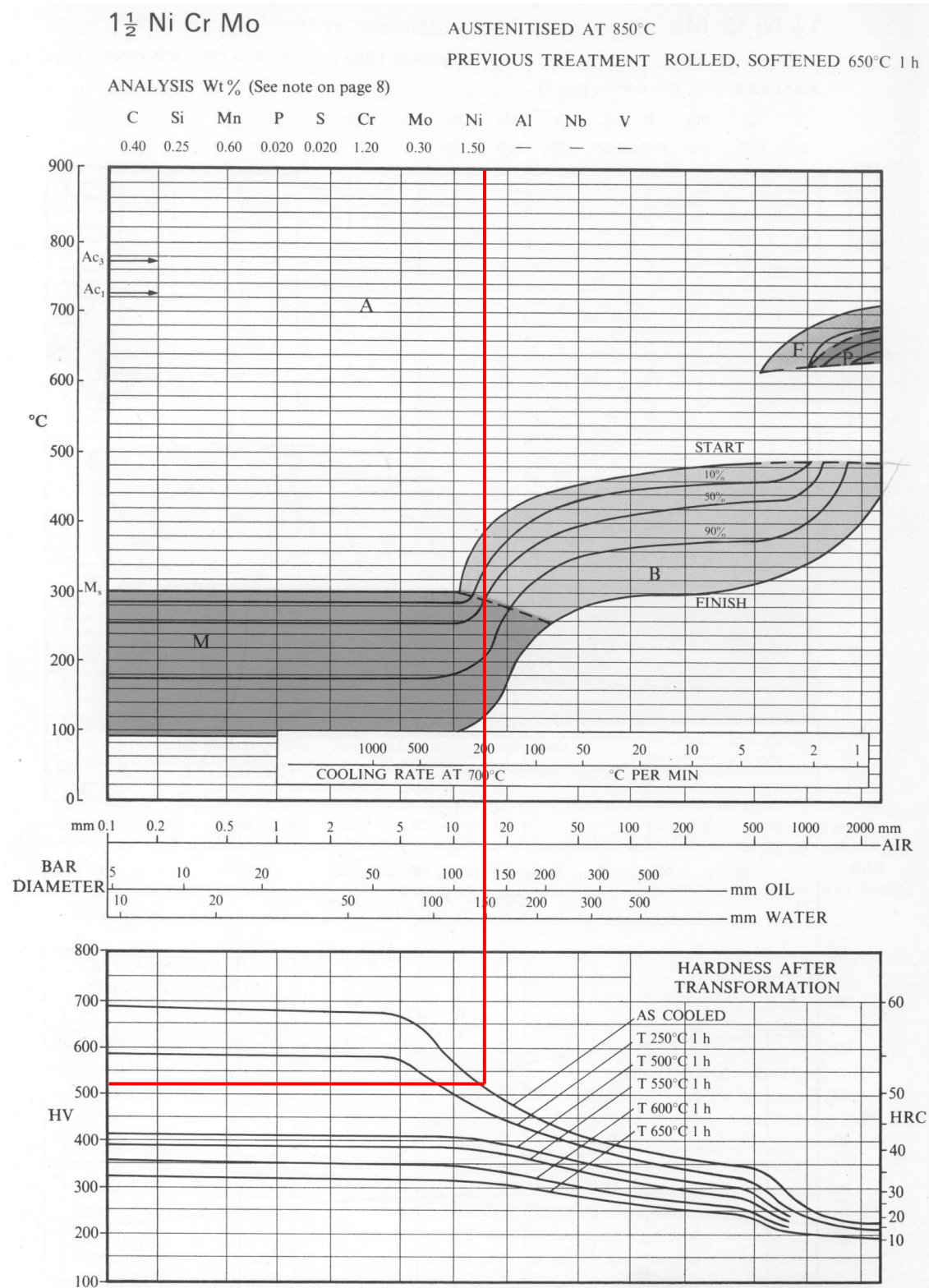
(c)   (i)   MIG welding is an example of arc welding. In arc welding processes, an electrical discharge is generated between an electrode and the work piece. MIG welding uses a consumable electrode (rod or wire), which provides the filler material, and a supply of inert shielding gas to prevent oxidation of the melt pool.

Δt_{8-5} is the time taken for the material to cool from 800°C to 500°C, the temperature range over which most diffusive phase transformations occur in steels. The lower Δt_{8-5}, the more likely it is that hard and brittle phases such as martensite will be present in the microstructure.

(ii) The cooling rate can be estimated as $(800 - 500) / \Delta t_{8-5} = (800 - 500) /100 = 3$ °C/s $= 180$ °C/min. Using Fig. 2, and interpolating on the cooling rate axis, the microstructure is 70% bainite and 30% martensite. The material has a high hardenability, which makes it difficult to avoid brittle phases when joining using this process.

(iii) The cooling rate can be reduced by pre-heating the plate before welding. A post-weld heat treatment could be used to temper any martensite that is present and relieve any residual stresses.

2   (a) Sink marks

(i)   Injection mouldings often suffer from sink marks (dimples or other irregularities on the surface of a component) when there are section changes.
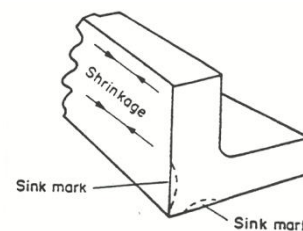
(ii)   The low molecular mobility in polymers means that high-temperature structures can become 'frozen in' on cooling. Polymer in thicker sections cools more slowly so has more time to shrink. The problem is worse with crystallisable polymers: thicker sections have more time to crystallise, and crystalline regions have higher density so shrink more.

(iii)   Unless dimensional tolerances are stringent, the main problem is aesthetic, being particularly noticeable on shiny polymer surfaces.

(iv)   The main way is to avoid section changes (suggestions illustrated). The aesthetic problem may be mitigated by using matt finishes for articles, so that the sink marks are less visible.
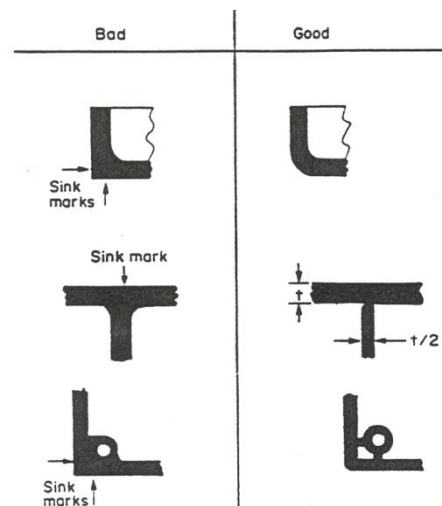
Weld lines

(i) When two polymer streams meet, weld lines can form. These can be seen as lines on the surface of injection moulded articles, often also associated with surface irregularities. Weld lines can also form in extrusion of pipes or hollow sections where the polymer flows around the 'spider' holding the mandrel in place.
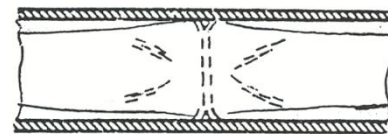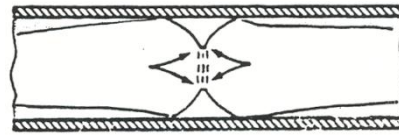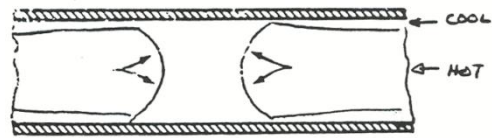
(ii) Weld lines are the result not only of incomplete fusion but also from molecular alignment variations: there is some extensional flow at the surface of the melt causing polymer chains align parallel to the melt surface.

(iii) Weld lines are lines of weakness, which may cause immediate failure (splitting), or may be the sites for subsequent failure in service as the polymer typically loses toughness as a result of environmental degradation. When Environmental Stress Cracking can occur (specific combinations of polymer and some chemical in the environment) weld lines are the usual sites for failure.

(iv) Good design of moulds ensures that polymer streams are hot enough to fuse properly when they meet. In extrusion of hollow sections, temperatures need to be high enough.

(b) (i) The uniaxial plies are very stiff parallel to the fibres, so the multi-ply composite deforms *anisotropically* and internal stresses are created in a composite as it is loaded.

- Strain of composite block is intermediate between theoretical strains of the two laminae stressed in isolation;

- Composite block will suffer **out-of-plane distortion**s, as shown below (mainly because of Poisson ratio effects).

Elastic distortions can be minimised by making multi-ply composites with a balanced layup. In this case, the layup can be balanced by adding a third ply so that the stacking sequence is 0-90-0. More complex sequences can also be used, so long as the stacking is symmetric in this way.
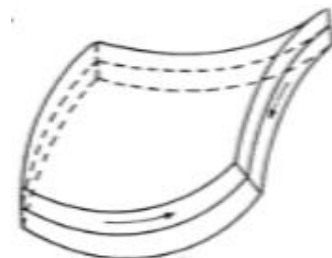
(ii) The composite under bending will suffer high stress at the interfaces between between the laminae. This will tend to cause delamination failure, and promote environmental degradation by 'wicking' of liquids between laminae. Water may therefore make its way all the way into the interior of the composite. The epoxy resin should

be fairly stable in the presence of water, but some degradation may occur under prolonged contact.

Under thermal cycling, the differential thermal expansion between the fibres and matrix leads to internal stresses. This can result in cracking: cracks will extend along the fibre-matrix interface, and there will perhaps also be cracking of the fibres.

The effect on mechanical properties is a steady degradation in strength, toughness and elastic modulus.

3   (a) (i) The powder is mixed with a polymer binder. This provides the feed stock for an injection moulding process. The powder-binder blend is injected under pressure into a mould, defining the geometry of the product.

        (ii) A more uniform compaction of the powder is achievable for complex geometries using PIM. This will result in a lower and more uniformly distributed final porosity. The polymer binder reduces friction and wear on the die.

        (iii) The polymer binder is removed using either a solvent or by heating the green compact. The binder removal process limits the maximum section thickness achievable. This 'brown' component is then sintered. During sintering the particles fuse by diffusion across particle interfaces, and the porosity reduces. Some final machining of the sintered part may be required.

        (iv) Porosity can be controlled by adjusting the sintering temperature and time. The initial density of the compact in the green state, affected by the size and shape of the powder particles, will affect the final porosity. The initial particle size will also affect the sintering rate.

(b)   (i) Powder injection moulding (PIM): The high melting temperature of the ceramic makes it unsuitable for investment casting. As a ceramic, the required process is PIM rather than MIM.

        (ii) Investment casting: the thickness makes MIM unsuitable, as it is too large for removal of the binder.

        (iii) Investment casting: a single crystal is needed for creep resistance, whereas a powder process will tend to lead to a fine-grained component.

        (iv) Either investment casting or MIM: both would be suited to the complex geometry and small component dimensions.

(c)   Sintering occurs by atomic diffusion, which leads to the formation of bridges between particles and a reduction in particle surface area through competitive growth of particles and the shrinkage of pores. Diffusion is a thermally activated process, with a rate exponentially dependent on temperatures (Arrhenius law). The reduction in particle surface area provides a driving force for sintering, so smaller particles sinter faster. Diffusion distances are also smaller for small particle sizes. Liquid phase sintering increases the sintering rate by speeding up diffusion between particles. The liquid phase, which is glassy at room temperature, can re-melt at high temperatures, reducing the mechanical properties of the component.

4   (a) During indirect extrusion, there is no relative motion between the material and the die between points A and B. This reduces the work done against friction. The extrusion force can also be reduced by lubricating the material-die interface, and increasing the temperature of the material to reduce its yield strength.

(b)   (i) Consider the stresses acting on a small element of material:
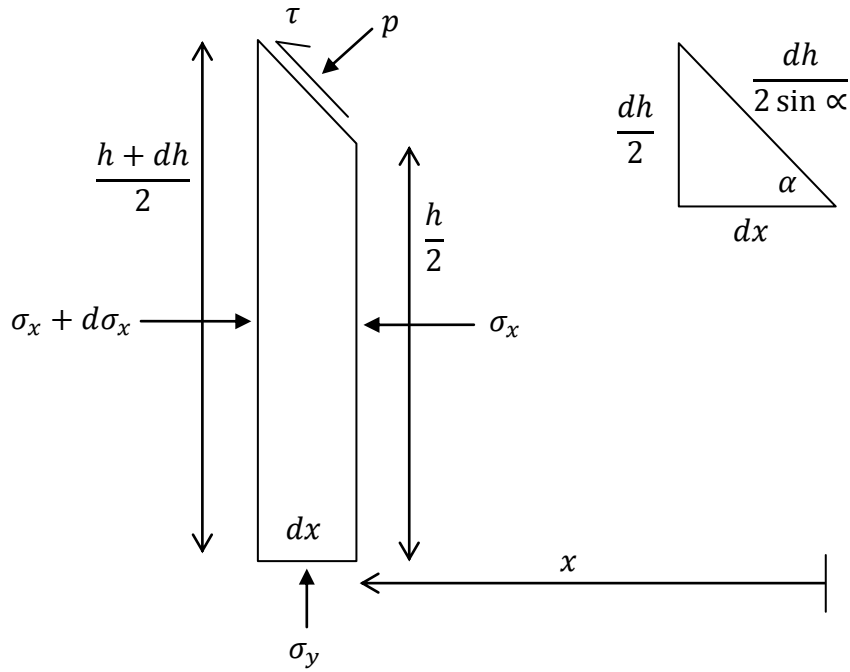
Resolving forces horizontally:

$$(\sigma_x + d\sigma_x)\left(\frac{h + dh}{2}\right) - \sigma_x\left(\frac{h}{2}\right) - p\left(\frac{dh}{2\sin\alpha}\right)\sin\alpha - \tau\left(\frac{dh}{2\sin\alpha}\right)\cos\alpha = 0$$

$$\therefore h\,d\sigma_x + \sigma_x dh - p\,dh - \frac{\tau}{\tan\alpha}dh = 0$$

$$\therefore h\frac{d\sigma_x}{dh} + \sigma_x = p + \frac{\tau}{\tan\alpha}$$

Assuming Coulomb friction:

$$\tau = \mu p$$

$$\therefore h\frac{d\sigma_x}{dh} + \sigma_x = p + \frac{\mu p}{\tan\alpha} = p\left(1 + \frac{\mu}{\tan\alpha}\right)$$

(ii) There is no shear stress acting at the interface between the material and the die. Therefore a force balance on an element of material shows that $d\sigma_x / dx = 0$, and the x-component of stress is therefore constant. Horizontal equilibrium at plane AA' requires that $\sigma_x = F / h_1$.

(iii) If friction is neglected, the differential equation reduces to:

$$h\frac{d\sigma_x}{dh} + \sigma_x = p$$

The Tresca yield criterion gives:

$$p - \sigma_x = Y$$

(as the third principal stress will be intermediate between these two, according to the Levy-Mises flow rule). This gives:

$$h \frac{d\sigma_x}{dh} = p - \sigma_x = Y$$

Integrating from exit (2) to inlet (1) gives:

$$\int_0^{F/h_1} d\sigma_x = Y \int_{h_2}^{h_1} \frac{dh}{h}$$

(where the value of the stress at the inlet, point A , is the same as at point B, which is equal to F / h_1 , due to the fact that the stress is constant between A and B). Evaluating the integrals:

$$\frac{F}{h_1} = Y \ln \frac{h_1}{h_2}$$

$$\therefore F = h_1 Y \ln \frac{h_1}{h_2}$$