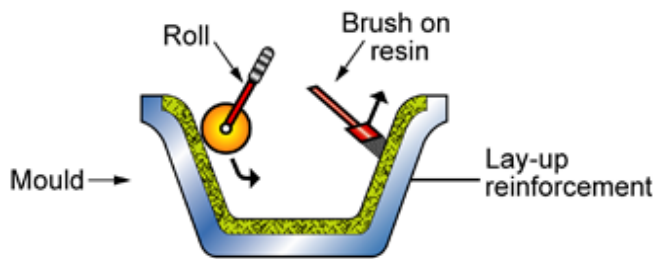Dr G. McShane, Dr H. Shercliff, Prof I. Hutchings

1 (a)
(i) Wet lay-up: Resin impregnated by hand (using rollers or brushes) into fibres (generally in the form of woven cloth). Only suitable for low-viscosity resins (may be warmed). Left to cure at room temperature.


Roller used to spread resin and remove bubbles

Gelcoat (resin only) on mould surface used to obtain good surface finish
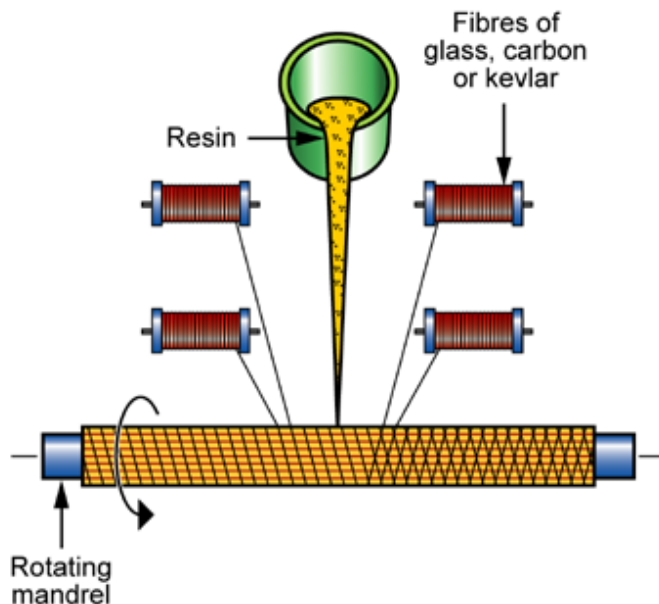
(ii) Vacuum bagging.
Similar to wet lay-up but quality improved by applying hydrostatic (air) pressure through a flexible membrane before and during curing. As shown in the diagram, a vacuum pump is used to reduce the pressure inside the bag/membrane. Mould may be heated or the assembly placed inside an oven or pressurised oven (autoclave); less easily done in the field for on-site repairs.

 (cloth plus uncured matrix resin in sheet or tape form)
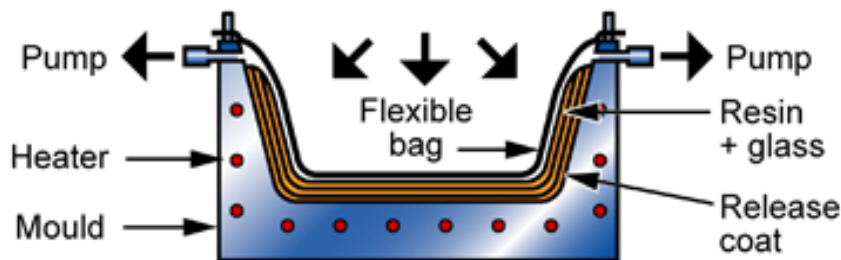
(iii) Filament winding.

Generally used for hollow (circular or oval sectioned) components, though large curved sheets can also be made by carving these up after winding. Continuous fibre tows are passed through a resin bath to impregnate them with resin before being wound onto a mandrel in a controlled orientation.

Fibres of glass, carbon or kevlar

Resin

Rotating mandrel

(b) Pre-preg is pre-impregnated fibres i.e. woven fibre cloth or tow (a bundle of fibres) which is already impregnated with resin. Pre-preg would be suitable for use in the vacuum-bagging process.

(c)
(i) a compressed gas cylinder needs high strength to resist internal pressure. Filament winding on to a suitable hollow former (which would remain inside the cylinder) would allow the orientation of the fibres to be matched to the stress distribution in the wall of the cylinder, to give an efficient structure (maximum strength for minimum mass). Neither wet lay-up nor vacuum bagging would be so suitable for this application .

(ii) the wheelchair seat would presumably be a shell-like structure so could be made by either wet lay-up or vacuum bagging. But the fact that it is a prototype suggests that a manual wet lay-up into a cheap mould would be the most cost-effective method; the added complexity of vacuum bagging would not be justified for a one-off product, and the additional performance (strength/stiffness/mass ratios) which could be obtained by that process would probably not be needed for this application. Filament winding would not be suitable for this geometry.
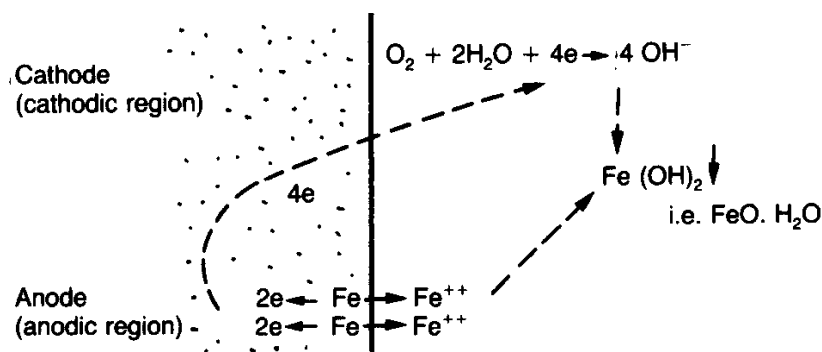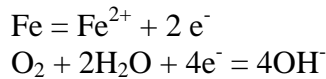
(iii) this is a high performance, safety critical component where the costs of mould fabrication and processing involved in vacuum bagging are justified. The performance of a composite made by wet lay-up, as well as the quality control aspects, would be totally inadequate for this application, and filament winding would not be appropriate for the geometry.

(d) Decrease in stiffness suggests degradation of the glass fibres since they make the major contribution to the stiffness and could also arise from degradation of the fibre-matrix interface as this transmits the load between matrix and fibres. During temperature cycling the difference in thermal expansion coefficient between glass and epoxy resin will lead to cyclic stresses at the fibre-matrix interface (CTE for epoxy is about 12 times that for glass). This can lead to fatigue failure of the interface so that is one mechanism. Once cracks form at the interface this will allow water to penetrate by capillary action ('wicking' - n.b. blade is exposed to rain) and water can cause environmental stress cracking (static fatigue) of the glass fibres; transverse cracks in the fibres will reduce the effective fibre length and so reduce the stiffness of the

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composite: a second mechanism. Less important in reducing stiffness would be fracture of the matrix (which might also happen under extremely wide temperature excursions).

2.

(a) Corrosion of the mild steel is here concentrated at the lap joint so is likely to be crevice corrosion, which is caused by difference in oxygen concentration within the crevice (here between the two sheets in the joint) compared with outside. Corrosion of steel or iron in water in the presence of oxygen takes place by the reactions:

$$Fe = Fe^{2+} + 2\,e^-$$
$$O_2 + 2H_2O + 4e^- = 4OH^-$$

Cathode (cathodic region)

$$O_2 + 2H_2O + 4e \rightarrow 4\,OH^-$$

4e

$$Fe\,(OH)_2$$
i.e. $FeO.\,H_2O$

Anode (anodic region)

$$2e \leftarrow Fe \rightarrow Fe^{++}$$
$$2e \leftarrow Fe \rightarrow Fe^{++}$$

The two reactions occur at different regions of the steel surface, depending on the local oxygen concentration, and electrons are transported

between the two through the metal.

The oxygen level is highest outside the joint, and the lowest oxygen level is deep inside the joint and crevices. Corrosion (the anodic process) will be concentrated within the joint where the oxygen concentration is lowest.

The joint is formed by spot welding so that there is not a continuous seam along the edge of the sheet, but a series of spots of weld at intervals. So a change to the joint design by adding a sealing bead along the edge (e.g. a polymer sealant or even a thicker continuous paint film) would prevent water/oxygen ingress and thus prevent crevice corrosion. Using a continuous weld rather than an intermittent spot weld (for example by resistance seam welding or laser welding) would also prevent crevice corrosion. Use of stainless steel (e.g. an austenitic stainless steel) would also prevent corrosion, but would be considerably more expensive than mild steel.

(b) Unstabilised austenitic stainless steels like this one can suffer from 'weld decay' in which areas of the heat-affected zone (HAZ) are susceptible to pitting corrosion. This is likely to be the reason for the corrosion in this case. Heating of the steel during welding causes the carbon (present in this alloy) to react with chromium to form precipitates of chromium carbide on grain boundaries in the HAZ, depleting the neighbouring metal of chromium. The steel is then said to be 'sensitized'. Localised corrosion occurs, with the grain boundary region being anodic. Sensitization can be avoided by using a low-carbon alloy (e.g. type 304L), or a 'stabilized' stainless steel containing carbide-formers such as Ti or Nb which react with the carbon in preference to chromium.

(c) Sudden failure of high strength steel in tension by intergranular fracture after electroplating suggests hydrogen embrittlement: the source of the hydrogen is the electroplating process, which can generate atomic hydrogen which migrates readily into the steel and concentrates at grain boundaries, lowering the fracture toughness of the steel. Possible changes which would avoid hydrogen embrittlement:

- o Use a lower-strength alloy, which is less susceptible. Steels with yield stress lower than about 700 MPa are generally resistant to hydrogen cracking.
- o Avoid electroplating
- o If electroplating is used, bake the component to remove any dissolved hydrogen (e.g. 150-200° C for 1 - 2 hours).

(d) Liquid mercury in contact with aluminium alloys (used for aircraft structures) leads to liquid metal embrittlement. The symptoms are that the metal component which is in contact with the liquid metal suddenly fails by intergranular fracture. The mercury penetrates along grain boundaries forming cracks. It then diffuses a limited distance into the host metal. It reduces the bond strength at the crack tip, and so the fracture toughness falls dramatically.

3. (a) Cross-sectional area $A = 2w \times 2h$, so $w = A/4h$
   $A = 0.1 \times 0.2 = 0.02$ m^2

$2h$ (mm)	$2w$ (mm)	$2h_o - 2h$ (mm)	F (MN)	Work done in this step (kJ)
200	100	0	2.629	0
167	120	33	3.227	97.60
133	150	67	4.205	123.87
100	200	100	6.148	172.55
			TOTAL WORK DONE	394 kJ

Forging force against distance moved by platen
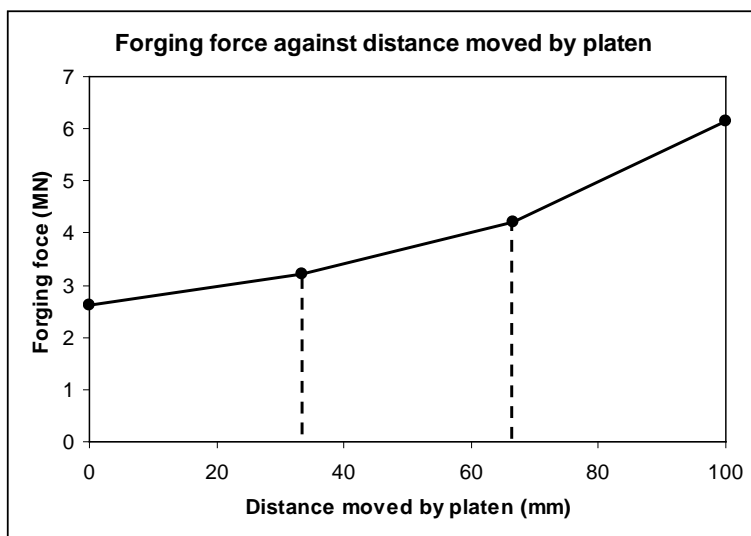
Work done in each step
= area of trapezium
= $0.5 \times (F_1 + F_2) \times (0.1/3)$

4

Assume adiabatic heating, with no heat transfer to the tooling or air.
Assume uniform temperature rise.

Average temperature rise = energy / (volume × density × specific heat capacity)

Volume = $0.5 \times 0.2 \times 0.1 = 0.01$ m^3
Density $\rho = 2700$ kg/m^3
Specific heat capacity $C_p = 950$ J/kg.K

Temperature rise = 394×10^3 / ($0.01 \times 2700 \times 950$) = 15^oC

Relatively small temperature rise, but will not be uniform as some of the heating will be localised to the workpiece-platen interface due to friction. But at the same time, in practice the platens will be cooler than the billet, with intimate thermal contact, cooling the surface.

(b) In Al alloys during hot deformation, *dynamic recovery* occurs. Dislocations annihilate at the same time as they accumulate by work hardening – a balance between the two leads to a stead-state, constant flow stress.

In the subsequent heat treatment, static *recrystallisation* is expected, with new grains nucleating an completely replacing the deformed grain structure. The final grain size is affected by:
- initial grain size before forming
- plastic strain
- deformation strain-rate and temperature
- temperature of subsequent heat treatment
- second phase particles of intermetallics (which may lead to particle-stimulated nucleation, PSN)

Reasons for recrystallisation:
- soften the material, and restore high ductility, ready for further deformation
- control grain structure and properties
- may also reduce impurity segregation (by new boundaries redistributing some impurity atoms by solute drag)

4. (a) Permanent mould: mould shaped in high melting point material (usually tool steel, copper, or ceramic) and used repeatedly for many castings.
Permanent pattern: wooden or metal pattern used to produce mould from a brittle ceramic/sand material; mould is separated into two parts to remove pattern, then re-assembled for casting into the cavity. Mould destroyed to remove casting.

Shape:
Permanent mould: simple shapes without re-entrant surfaces (to enable removal of parts from mould). Permanent pattern enables more intricate shapes – must be able to remove the pattern, but the mould will be destroyed to remove the casting itself.

Economics:

Permanent mould: expensive moulds, high production rates (suitable for large number of parts)

Permanent pattern: low setup costs, low production rates (large parts, or small production runs)

Examples:

Permanent mould: gravity and pressure die casting

Permanent pattern: sand casting, investment casting

(Note: investment casting uses a permanent pattern to make the low cost mould in which the many wax parts are formed, before assembly into a single wax pattern around which the mould is built. This wax pattern is then destroyed, as is the ceramic mould, so at first sight this process does not appear to be permanent pattern or permanent mould).

     (b)   A dendrite is a solid crystal that characterizes a growth instability in solidification. The crystal grows out into a liquid during solidification, with a characteristic "fir-tree" shape: an initial long, thin stem, and then with transverse primary branches, off which secondary arms grow. The whole dendrite has the same crystallographic orientation.

In pure liquids, dendrites are a result of a negative temperature gradient close to a solid nucleus. The liquid is initially super-cooled below the melting point, then the formation of the solid nucleus releases latent heat, raising the nucleus temperature to the melting point and setting up a temperature gradient that falls from the solid-liquid interface. Liquid at the interface has zero undercooling, whereas liquid away from the interface is supercooled – solid protruding locally into this region grows rapidly outwards, giving the dendrite structure.

In alloys, segregation can lead to dendrite formation by "constitutional supercooling". Segregation of solute occurs from the initial solidification from the mould wall, leading to a build-up of solute ahead of the solid-liquid interface. At steady-state, this "bow-wave" of solute moves with at the same speed as the interface, with the solid forming at the same composition as the alloy (C_o) but with the peak concentration ahead of the interface being raised to C_o/k (where k = partition coefficient between solidus and liquidus). The solidification temperature of the alloy rises ahead of the interface, following the concentration profile in inverted form. Cooling of the casting through the mould imposes a thermal gradient. If this gradient is sufficiently low, a region ahead of the solid-liquid interface has a temperature profile below the depressed melting point profile – solid protruding locally into this region grows rapidly, giving dendrites.

Dendrite growth leads to fine-scale segregation and micro-porosity. Small pockets of liquid become trapped between the dendrite arms, so that impurities and dissolved gas are released and trapped in small quantities as these pockets solidify, distributing them over the whole casting. This prevents significant build-up of impurities/gases being swept over large distances in the casting, leading to macro-porosity or very weak grain boundaries at the centre of the casting – this being the case if planar or columnar growth is maintained throughout.

(c)   Sulphur: comes from the hydrocarbons used to heat blast furnaces and reduce the iron oxide, and prone to segregation and formation of brittle FeS on grain boundaries. Alloying addition of Mn leads to formation of a dispersion of MnS particles throughout the cast steel, preventing segregation to the grain boundaries.

Oxygen: comes from the oxygen blast in steel-making, used to burn off the excess carbon and reduce the C content from that of blast furnace iron to that of carbon steel. Leads to excessive porosity if left in solution during casting. Solution is addition of elements (such as Al) that are strong oxide formers, leading to a dispersion of oxide particles (known as "killing" the steel).

(d)   Grey cast iron: carbon forms as elongated graphite flakes (+ some iron carbide within the surrounding iron matrix, depending on the composition and heat treatment). In white cast iron, the carbon forms iron carbide (cementite).

Advantages of grey cast irons:
  - if C content sufficient (> approx 3.5 wt% C), expands on solidification. One composition gives zero volume change, useful for producing castings directly to final size and shape, and reproducing the surface detail of the mould.
  - graphite is a natural lubricant, so grey cast iron can be machined without any liquid lubricant.
  - graphite flakes are brittle, and this provides good damping against mechanical vibration (useful for the mounting beds of large machine tools).