

A CRIB

ENGINEERING TRIPOS PART 1B

Tuesday 5 June 1997 9 to 11

Paper 3

MATERIALS

Answer not more than four questions.

The paper consisted of 6 questions from which the candidate was asked to attempt 4 questions. Each question covered a major theme of the Materials Course. The answer to the first part of each question was descriptive; subsequent parts were either numerical requiring a proof and calculation and/or the application of a procedure in materials selection and design or method of microstructural control. A number of questions included aspects of microstructural manipulation and methods of fabrication and processing. The various parts of each question involved making links or connections between these aspects of materials behaviour and component performance and reflected the nature and philosophy of the Course. Each part of every question could be attempted without having done a previous part.

Word of Caution: the following answers to the descriptive parts of questions may be longer than the candidate would have time to complete but an ideal answer should include many of the points below, even if simply given as a list. Sketches have not been included here for the sake of space but refer to Ashby and Jones "Engineering Materials" Volume 2, Pergamon Press that illustrate clearly many of the points.

ANSWER TO QUESTION 1.

(a) The properties of ceramics are highly dependent on their texture at the microscopic and macroscopic levels. Texture links fabrication and properties. Raw materials, the way they are processed and fired all affect texture. Fabrication conditions have to be adjusted to optimize the important properties. Consideration must be given to the form and design of the component (see part (b)).

The fabrication process is generally based on converting particulate raw materials into the useful object. This usually means forming the particulate matter into the desired shape, followed by a sintering stage at high temperature. This involves joining the original particles together, often accompanied by a reduction in volume and free space, i.e., the density of the porous part increases.

The most wide-spread process is sintering in the presence of a liquid phase. To attain the best mechanical properties it is often necessary to resort to hot-pressing or

reaction-sintering. In the simplest form, it involves the compaction of fine (1 micron) pure particles at ambient temperature followed by heating to 0.5 to 0.8 of the absolute melting point. The driving force for the reaction is a decrease in surface area by fusing together the particles; the larger particles grow at the expense of smaller ones. An example is the fabrication of uranium dioxide for nuclear fuel. The final structure consists of individual grains, grain boundaries, and some residual porosity.

Hot-pressing produces higher density parts and finer grain sizes may be achieved at lower temperatures. This results from an increased driving force caused by stresses at points of contact between particles. Pressing times can be short.

Because of expense and difficulty of working at high temperature, sometimes small amounts of additives that form plastic phases are added which allow sintering at lower temperature. Examples include magnesia added to silicon nitride or to alumina. Resulting microstructure can be single phase, uniform grain size, virtually no porosity.

Another method of increasing technological importance involves sintering by chemical reaction. This is not logical for oxide production and is more suitable for silicon-based ceramics, e.g., silicon nitride, silicon carbide. Nitrogen reacts with silicon at high temperature and bonding occurs simultaneously. In this example, the article can be formed by flame spraying of silicon onto a former- useful for a shell or hollow structure; isostatic pressing of silicon powders; or mixing of silicon powder with plastic binders, then plastic-forming, e.g., by rolling, extruding or pressing. The component is fired in a nitrogen atmosphere below the melting point of pure silicon; once the skeleton of the nitride has formed the temperature can be raised above the melting point. Porosity can be as high as 30%. Silicon carbide could in principle be made in a similar way.

(b) The microstructures of components made from such a wide range of methods possess a number of common features: one or more crystalline phases; maybe a glassy phase; wide range of grain sizes, 1-1000 microns; porosity, fine or coarse, open or closed; grain boundaries that can act as sites for pores or cracks or act as a source or obstacle to a propagating crack. This leads to a variety of phenomena including variations in tensile strength due primarily to large variations in inherent flaw size, e.g., porosity content, pore size and shape, and crack shape, length and orientation (transgranular or intergranular cracks), and impurities. Crack tip blunting by plastic flow processes is essentially absent except at only the highest temperatures; hence ceramics are brittle.

Factors that affect the fracture stress include processing which influences phase distribution and grain size; firing which influences pores and cracks; finishing which affects surface condition, size of surface crack, for instance.

A mismatch between the coefficient of thermal expansion of neighbouring grains can set up thermal stresses which result in crack formation at internal grain boundaries, e.g., in anisotropic alumina and BeO which are hexagonal in structure. Their coefficients vary with crystal orientation. Variations also in elastic properties of two phases can result in cracking during cooling and the size of the crack may be influenced by the grain size which can vary from specimen to component. The coalescence of porosity can lead to variations in fracture stress. Finally, external conditions can effect the size of pre-existing cracks, e.g., environmental (chemical)-assisted crack growth.

A component operating under known conditions of stress-state and environment, for example, can be designed with regard to lifetime and acceptable probability of failure. Considerations of statistical variations of strength and the variations of strength with time can be presented on a strength/probability/time diagram. (A complete answer may include a brief description of Weibull statistics including the effect of component volume on strength and state of stress on strength although this would not be expected in any detail).

(c) In a proof test the stress intensity factor K_p on the surviving sample is:

$$K_p = \sigma_p \pi^{1/2} a_p^{1/2} < K_c$$

In service at σ_a the corresponding stress intensity factor K_a is:

$$K_a = \sigma_a \pi^{1/2} a_p^{1/2}$$

Thus: $K_p \leq \left(\frac{\sigma_a}{\sigma_p}\right) K_c$ (where $R = \frac{\sigma_p}{\sigma_a}$).

Under constant applied stress σ_a the time to failure of the window is:

$$t_f = \int_{a_p}^{a_c} \frac{da}{da/dt}$$

where $\frac{da}{dt} = A(\sigma_a \sqrt{\pi a})^n$
and $da = \frac{2K}{\sigma_a^2 \pi} dK$

Now: $\int_{a_p}^{a_c} \frac{da}{a^{n/2}} = A(\sigma_a \pi^{1/2})^n \int_0^{t_f} dt$

By substituting the maximum initial value of K_a we can estimate the minimum time to failure of the window:

$$t_f = \frac{2 K_c^{2-n} \left(\frac{\sigma_a}{\sigma_p}\right)^{2-n}}{A \sigma_a^2 \pi (n-2)} \quad \left(R = \frac{\sigma_p}{\sigma_a}\right)$$

Therefore:

$$t_f = \frac{2 K_c^{2-n} (R^{n-2})}{A(n-2) \pi \sigma_a^2} \quad (n \gg 1)$$

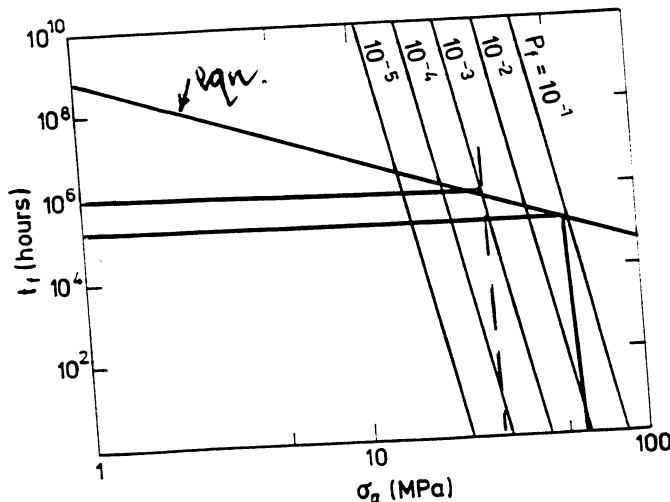


Fig. 1 Time-to-failure diagram for silica windows

(d) (i) Guaranteed lifetime is about 20 years and about 10% would fail the proof test.

(ii) Reduce the working stress to 25 MPa (for $R=2.5$).

ANSWER TO QUESTION 2.

(a) The strain energy stored in a deformed crystal is a manifestation of the number or density and arrangement of dislocations in that crystal. When cold-worked aluminium is annealed the free energy (dominated by the strain energy) can be decreased through dislocation annihilation and rearrangement. This is called Recovery and results in a decrease in yield strength. The initial gradual recovery with time is due to several different kinds of recovery mechanisms. The sharp drop which eventually occurs is caused by Recrystallisation and the formation of small relatively dislocation-free (there are still plenty of them) new grains. These new grains grow with time.

Recovery is by the annihilation of dislocations of opposite sign on the same slip plane. Dislocations of opposite sign annihilate by a process of cross-slip (screw dislocations) or by climb (edge dislocations). Recovery may also occur by rearrangement of dislocations by forming a low-angle grain boundary.

Aluminium-copper alloys can strengthen by a precipitation process of a second phase in the form of finely-spaced, hard particles. A supersaturated solution of copper dissolved in aluminium undergoes transformation with time at moderate temperature. The second phase precipitates out at a measureable rate. Holding the alloy at a fixed temperature is referred to as ageing the alloy. First, atoms of the solute begin to cluster by diffusion, forming nuclei of the second phase precipitate. The strength increases a modest amount because the small precipitate offers little resistance to dislocation motion. As the number and size of the precipitates increase, more work is necessary to force the dislocations passed these precipitates. Consequently, the yield strength increases with time of ageing.

(b) (i) Eventually, it becomes sufficiently difficult for the dislocation to cut through the particles it is easier to bow between them. Further ageing causes these precipitates to grow at the expense of their number and the spacing between them decreases. The strength falls further. An alloy that has been aged beyond the point of maximum strength is said to be overaged. For practical purposes, aircraft alloys based on aluminium that operate at elevated temperature may be deliberately underaged by a small amount. The skin of Concorde can exceed 100 C in flight. Overaging can result in a decrease in strength and creep resistance input design requirements for an aircraft alloy.

(b) (ii) Quite simply, the precipitates can be dissolved by heating to sufficiently high temperature that results in a single phase solid solution. Hence, the rivets are heated to an appropriate temperature that can be determined by observation of the Al/Cu phase diagram, typically 550 C, quenched to produce the supersaturated solution of Cu in Al, followed by ageing once more at the ageing temperature for an appropriate time to give peak strength or just below maximum hardness.

ANSWER TO QUESTION 3.

(a) The way molecular chains are assembled in a polymer affect greatly its mechanical properties, e.g., strength and ductility and other characteristics. Polymers in bulk are never totally crystalline; some are completely amorphous (polystyrene and epoxy resin, the former is a thermoplastic, the latter a thermoset); others are partly crystalline ranging from a few percent to 90%. Organisation at the atomistic and microstructural levels is important because it affects the properties of the solid polymer.

These long chained molecular solids consist of links or covalent bonds along their length between, for example, carbon and carbon atoms or between carbon and nitrogen; they can have short or long side groups (or branches) of large or small atoms, of hydrogen and oxygen, for instance. The covalent bond is weaker than the C-C bond found in diamond because of the presence of hydrogen side groups and there is an unexpected van der Waals bond within the chain which permits rotation about the axis of this C-C bond. This mechanism imparts some ductility and toughness to the polymer. A combination of these elements arranged carefully in these ways produces Nylon. An unbranched chain results in the polymer having low yield stress and melting point; the polymer made of branched chains is stiffer and less flexible and has a higher melting point. These branches can be irregular and of variable length and atomic complexity.

There are 3 key factors that determine the mechanical behaviour: chemical composition of these building blocks; the possible shapes of the polymer chains they can produce including crystal growth and the formation of a crystalline structure; and the alignment of these chains within the final product. Different combinations of these factors can produce polymers with ductility at low temperature or brittleness even at elevated temperature; low melting point polymers or polymers that begin to burn before even softening. Shape of the polymer chain varies according to the size of the molecules used, the smaller the molecule the more flexible the polymer and resulting product, like polyethelene bags. A large grouping like a benzene ring or molecule as part of the backbone of the long chain imparts rigidity and high melting point, polycarbonate for example.

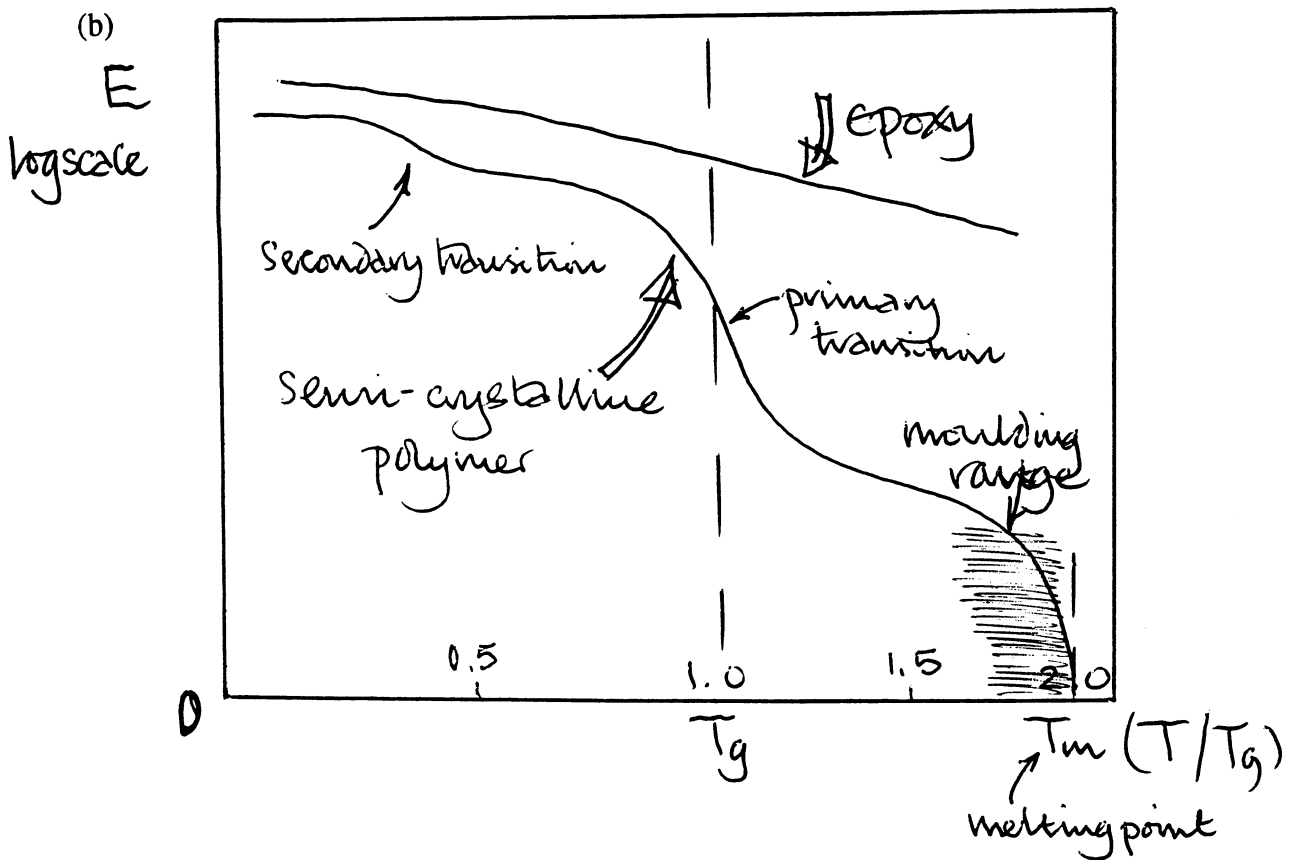
A simple polymer chain can have added as well as branches, cross-links. An unbranched chain of high-density polyethelene becomes low-density PE when side branches are added which has lower yield strength and rigidity and lower melting point. But when cross-links are introduced the polymer is at its strongest and least flexible with the highest melting point.

Of the 2 major kinds of polymers, "thermoplastics" indicate that the material softens on heating and hardens on cooling in a virtually reversible manner; they can be moulded by extrusion, injection or compression moulding, and are used to make fibres and fabrics and literally thousands of other products. Their giant molecules have no strong links between the individual molecules. The other big family is described as "thermosetting" and is made up of substances which polymerise irreversibly under heat or pressure with or without a catalyst to form a hard rigid, infusible mass. The building units are small organic molecules that polymerise in a heated mould to its final shape. Structurally, the thermosetting polymer is characterised by the 3-D cross-link network through covalent bonds making it hard, inflexible and low toughness. By varying the frequency of these cross-links or intermolecular bonds it is possible to impart some ductility and toughness. Synthetic rubber cross-linked (vulcanized) with sulphur retains its elasticity when deformed. Essentially, the properties of thermoplastics are time (rate) dependent; thermosetting polymers show much less dependence.

Alignment of chains within a polymer has a direct bearing on the density and properties of the final product. Chains which can align themselves closely like those of HDPE produce stiff and heat resistant synthetics. Both rubber cement and synthetic rubber are made from flexible, unaligned polymers giving them desired qualities of elasticity. However, the cement's shorter, unbranched molecules are far less rigid than a tyre's longer, cross-linked molecules to resist curb pounding and ground friction.

Whilst a number of competing mechanisms account for yield phenomena of thermoplastics, crazing, shear banding, for instance, thermosets generally show little ductility up to fracture which occurs by the propagation of preexisting flaws. Only the inclusion of a second phase such as an elastomer into a thermoset can shear banding pre-empt the onset of brittle fracture.

The ease with which alignment of chains can take place within the polymer will affect its ability to form crystalline regions of the product. The amount of crystallinity determines the yield strength, ductility and toughness as does the size of the crystals or spherulites made of these regularly ordered densely packed long chains. Cooling-rate of the polymer in the mould will determine the degree of crystallinity and the size of the spherulite (see part (c)). Thermoplastics can exhibit some or no crystallinity; thermosets are completely amorphous. A partly crystalline polymer undergoes (at least) 2 thermal transitions, the first at what is known as the glass transition temperature when the weaker bonds between neighbouring chains "melt" and the second when the temperature of the crystalline portion of the polymer "melts". Thermosetting polymers do not exhibit either of these temperatures but char or burn above about 275 C (see part (b)).



(c) For a semi-crystalline polymer, the chill effect of a cold mould wall can inhibit the formation of a crystalline region on the outside of the moulding. The interior of the moulding where the cooling-rate is slower is likely to be crystalline. The depth of the surface layer of amorphous polymer depends on melt temperature, mould temperature and cooling-rate. In practice, this can result in the formation of residual stresses being set up through the thickness of the moulding. It is not uncommon in a moulding to have a residual stress that can be compressive on the surface and tensile in the centre, the magnitude of these stresses depending on the processing variables. The size of spherulite will also vary depending on cooling-rate.

- (d) (i) amorphous thermoplastic--polymethylmethacrylate
 (ii) semi-crystalline thermoplastic--polyethelene
 (iii) thermosetting resin--epoxy resin.

For (i) the rigidity and yield stress (or stress to initiate a craze) is sufficiently high and when combined with transparency makes it suitable for commercial airplane window. Increased toughness can be achieved by biaxial stretching of the polymer at elevated temperature to align the long chained molecules. The hot pressing of a stack of PMMA sheets produces a tough window suitable for combat aircraft. Delamination by bird impact might cause some loss of transparency without catastrophic fracture.

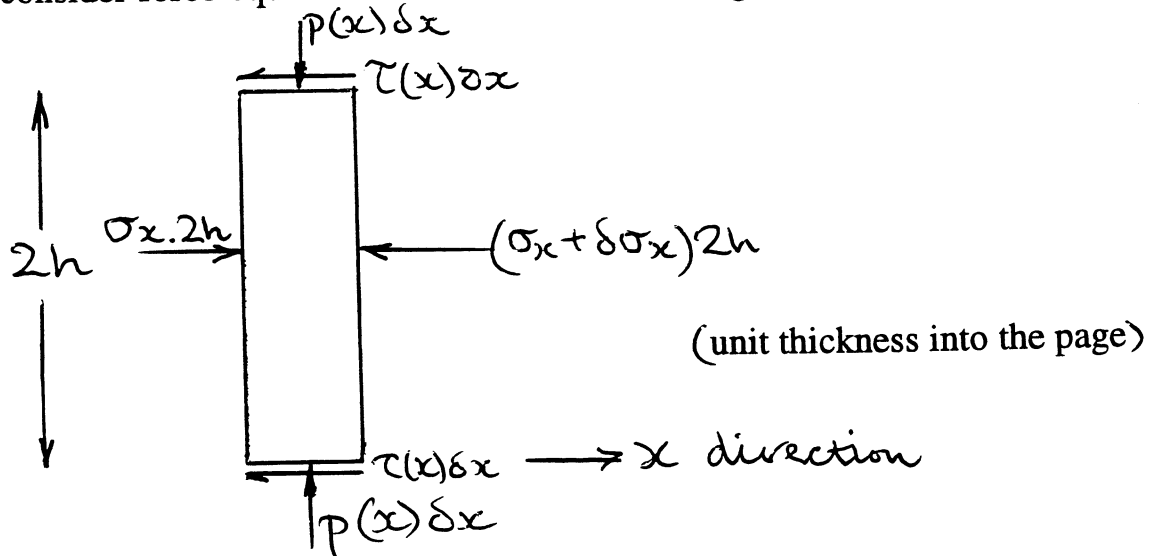
For (ii) increasing the crystallinity content (short side branches allow alignment of the long simple C-C chains) produces a sufficiently high yield strength and tough material and when combined with low coefficient of friction (good wear resistance) is an excellent material for the cup of a total hip joint replacement. It also inert in the hostile environment of the human body.

For (iii) the adhesive is suitable for bonding metal parts instead of rivetting, for bonding composite parts, themselves having an epoxy matrix, to metals as in the fixing of a composite drive shaft to the metal end fixture. As a matrix it is highly suitable for bonding fibres together for the transfer of applied load to the fibre. It's initial liquid state before polymerising allows the resin to be applied liberally over a fibre preform to produce an resin impregnated fibrous shape which can be moulded under pressure and temperature to produce rigid strong light weight parts.

ANSWER TO QUESTION 4.

A Model for Forging

(a) To calculate the pressure distribution $P(x)$ on the strip consider force equilibrium on an element of height $2h$ and width dx :



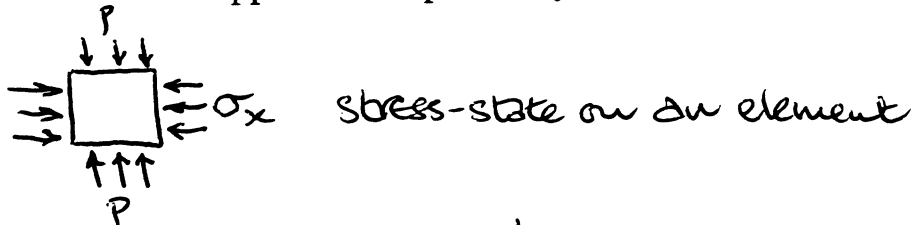
Consider x greater than 0. Deforming material slides; frictional shear stress is set up at interface and equilibrium of forces in x -direction gives:

$$(\sigma_x + \delta\sigma_x)2h - (\sigma_x 2h) + 2\tau \delta x = 0$$

$$\frac{\delta\sigma_x}{\delta x} = -\frac{\tau}{h} \quad (1) \quad (\tau = m.k)$$

(where m is a friction factor between 0 & 1 and k is the shear strength = 0.5 yield stress).

Now consider what happens at the point of yield:



(ii) By the Tresca criterion: $P - \sigma_x = \sigma_Y$

$$\frac{dP}{dx} - \frac{d\sigma_x}{dx} = 0 \quad (2)$$

Combining (1) & (2):

$$\frac{dP}{dx} = -\frac{\tau}{h}$$

Now use: $\tau = m.k = m \frac{\sigma_Y}{2}$ to get: $\frac{dP}{dx} = -\frac{m}{2} \cdot \frac{\sigma_Y}{h} \quad (3)$

Boundary Conditions.

At edge of strip $x = w$ and $\sigma_x = 0$

Yield criterion gives

$$P - \sigma_x = \sigma_Y$$

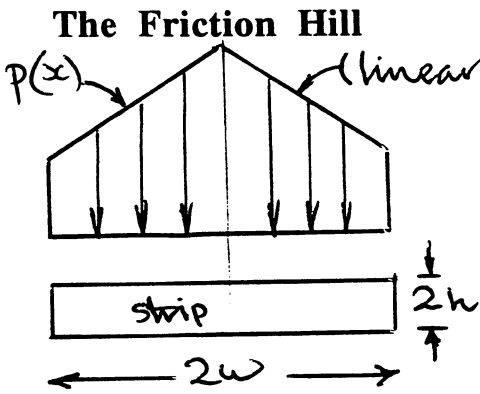
$$P = \sigma_Y \text{ at } x = w$$

Integrating (3):

$$\int_{p(x)}^{\sigma_y} dp = \int_x^w -\frac{m}{2} \frac{\sigma_y}{h} dx$$

$$p = \sigma_y \left[1 + \frac{m}{2} \left(\frac{w-x}{h} \right) \right] \quad x > 0$$

$$p = \sigma_y \left[1 + \frac{m}{2} \left(\frac{w+x}{h} \right) \right] \quad x < 0$$

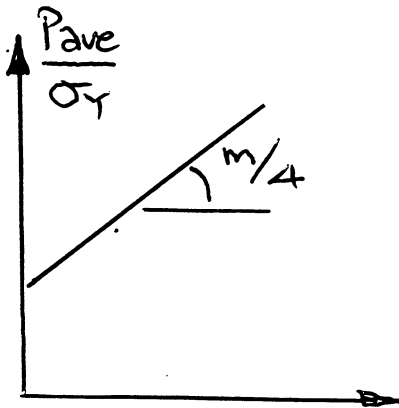


P_{max} occurs at $x=0$
 where $P_{max} = \sigma_y \left[1 + \frac{mw}{2h} \right]$

$$P_{ave} = \frac{\text{total work force}}{2w}$$

$$P_{ave} = \sigma_y \left[1 + \frac{mw}{4h} \right]$$

(effect of τ)



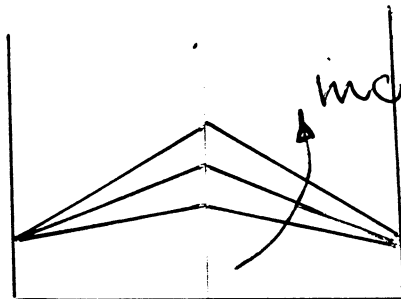
(b) Substituting for $w = 6h$ and $m = 0.1$:

$$F = 13.8 \sigma_y h$$

w/h (workpiece ratio)

(c) F increases with σ_y

(c) (i)



F_{max} increases with τ

(ii) From sketch above, increasing $\frac{w}{h}$ by reducing h increases force F .

ANSWER TO QUESTION 5.

(a) Iron is unusual; it undergoes 2 solid state phase changes with temperature. Up to 1183 K its structure is bcc; above this temperature but below 1663 K it is fcc. Despite the greater unoccupied volume in bcc, the largest interstitial holes in bcc are smaller than those of fcc. More carbon is soluble in the higher temperature form of solid iron, up to 2 % by wt. at 1400 K. In fact at room temperature under equilibrium conditions there is very little carbon in solution in bcc iron. This is not the case should the iron be cooled very quickly from its fcc state to room temperature; carbon is retained in solution by distorting the fcc lattice. A much slower cool from high temperature results in the precipitation of the carbon from solution. At room temperature nearly all of the carbon has precipitated out in the form of the compound iron carbide known as cementite. The nature and appearance of the microstructure depends on the cooling rate and names have been given to a variety of structures that can be formed, pearlite, bainite, martensite, (a mixture of all 3 is possible, see part (c)). A wide range of properties are attainable depending on the structure which is related to thermal history.

(b) A plain carbon steel shaft of small diameter when quenched from high temperature (austenitic state) will transform completely to martensite when quenched in water. This cannot be said of a similar steel shaft of large diameter when only the outer layer some 3mm or so in depth is likely to cool fast enough to convert to martensite. (The cooling rate must be sufficiently fast that there is insufficient time to allow the diffusion controlled pearlite reaction from taking place). The outside of the shaft could crack owing to differential volume expansion effects between surface layer and interior of the shaft. The addition of alloying elements to the steel slows down the time for commencement of the pearlite reaction, i.e., the curve in a TTT diagram which depicts the start time of the pearlite reaction is shifted to the right (as a result of depressing the pearlite or eutectoid equilibrium temperature).

For a low alloy steel the bainite reaction is possible but both the pearlite and bainite reactions are retarded by an amount that depend on the alloy composition. The degree to which the cooling rate of the austenite can be reduced yet still ensure a fully martensitic product such as the steel shaft is a measure of the "**hardenability**" of the steel. It can be expressed as the depth at which the hardness characteristic of martensite has dropped to its mean value characteristic of a non-martensitic structure. Shifting the curve in the TTT diagram to the right can be controlled by the choice and amount of alloying element(s). There is a synergistic effect in that combinations are more potent than separate individual additions which is why Ni, Cr, Mo and V are often added in pairs or threes. (Mn is invariably present). It is these substitutional alloying additions which produce the "hardenability" of the steel.

In welding, a molten pool forms between two plates, for example. During the welding process heat is conducted into the adjacent plate where temperatures can be sufficiently high that austenite forms in a zone (heat affected zone) adjacent the weld pool. A large plate acts as a heat sink and as the weld pool solidifies the cooling rate may be such that martensite is able to form in the HAZ. Volumetric changes can result in localised stresses being sufficiently high to cause cracking of the brittle HAZ. The HAZ of a welded low carbon steel is unlikely to cool fast enough that martensite can form.

(c) There is a linear temperature gradient of 900 C over 100 mm or 9 C/mm. Thus, the temperature and structure at each of the 7 locations is as follows:

- (i) 285 C; 30% martensite+retained austenite
- (ii) 375 C; 100% lower bainite
- (iii) 465 C; 75% upper bainite+retained austenite
- (iv) 645 C; primary ferrite+100% fine pearlite
- (v) 690 C; primary ferrite+75%pearlite+retained austenite
- (vi) 825 C; all austenite
- (vii) 915 C; all austenite.

A water quench after 2 hours would result in any austenite phase transforming to martensite, the remaining phases unaffected.

(ii) All martensite present would transform to ferrite with the precipitation of fine particles of cementite. There would be little time at this modest temperature for coarsening of the remaining structures or for grain growth.

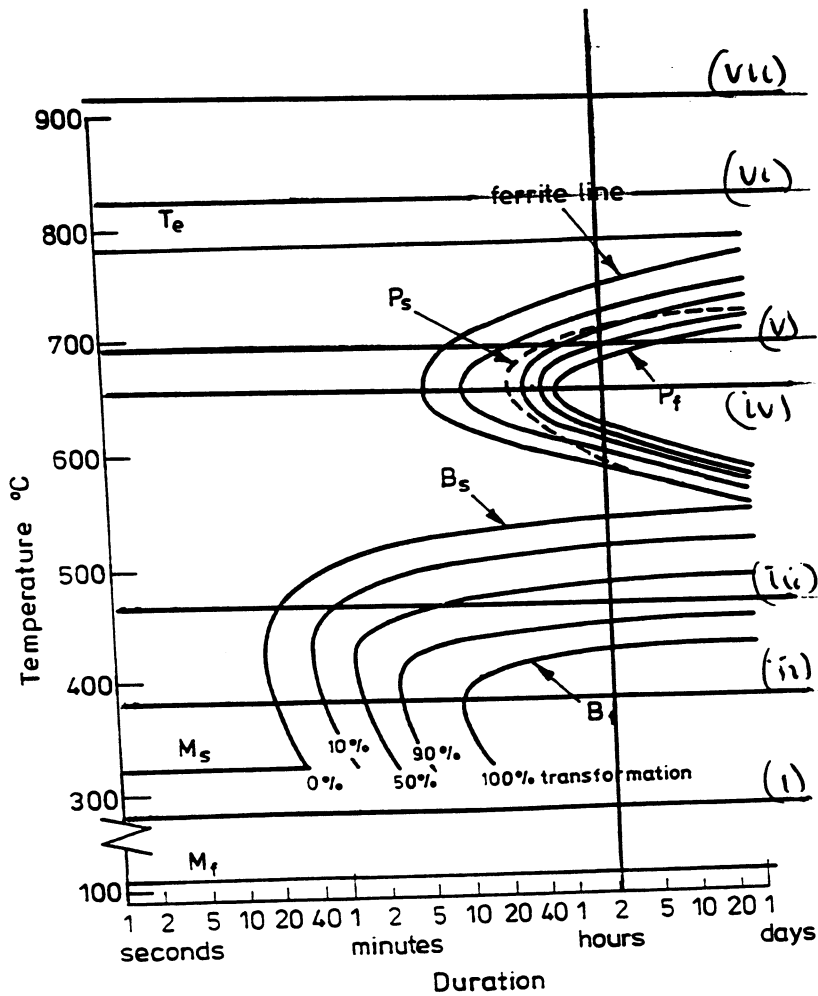


Fig. 3 TTT diagram for a low-alloy steel

ANSWER TO QUESTION 6.

$$(a) M_1 = \left[\frac{1}{A \alpha R} \right] \left[\frac{1}{\rho} \right]$$

↑ fixed

∴ maximise $\boxed{\frac{1}{\rho}} = M_1$

$$(b) \sigma = \frac{\rho \omega^2 R^2 \alpha (2 - \alpha)}{2}$$

where: $Q = A \omega R^3$

$$\omega^2 = \frac{Q^2}{A^2 R^6}$$

Eliminating for ω^2 :

$$\sigma = \rho \frac{R^2 \alpha (2 - \alpha)}{2} \frac{Q^2}{A^2 R^6}$$

$$= \frac{\rho Q^2 \alpha (2 - \alpha)}{2 A^2 R^4}$$

Now: $S_f = \sigma_f / \sigma \dots$ (safety factor)

$$\sigma_f = \frac{\rho Q^2 S_f \alpha (2 - \alpha)}{2 A^2 R^4}$$

$$\text{Or: } Q = \left(\frac{2 A^2 R^4}{S_f \alpha (2 - \alpha)} \right)^{1/2} \left(\frac{\sigma_f}{\rho} \right)^{1/2}$$

↑ fixed

∴ Maximise $M_2 = \boxed{\frac{\sigma_f}{\rho}}$

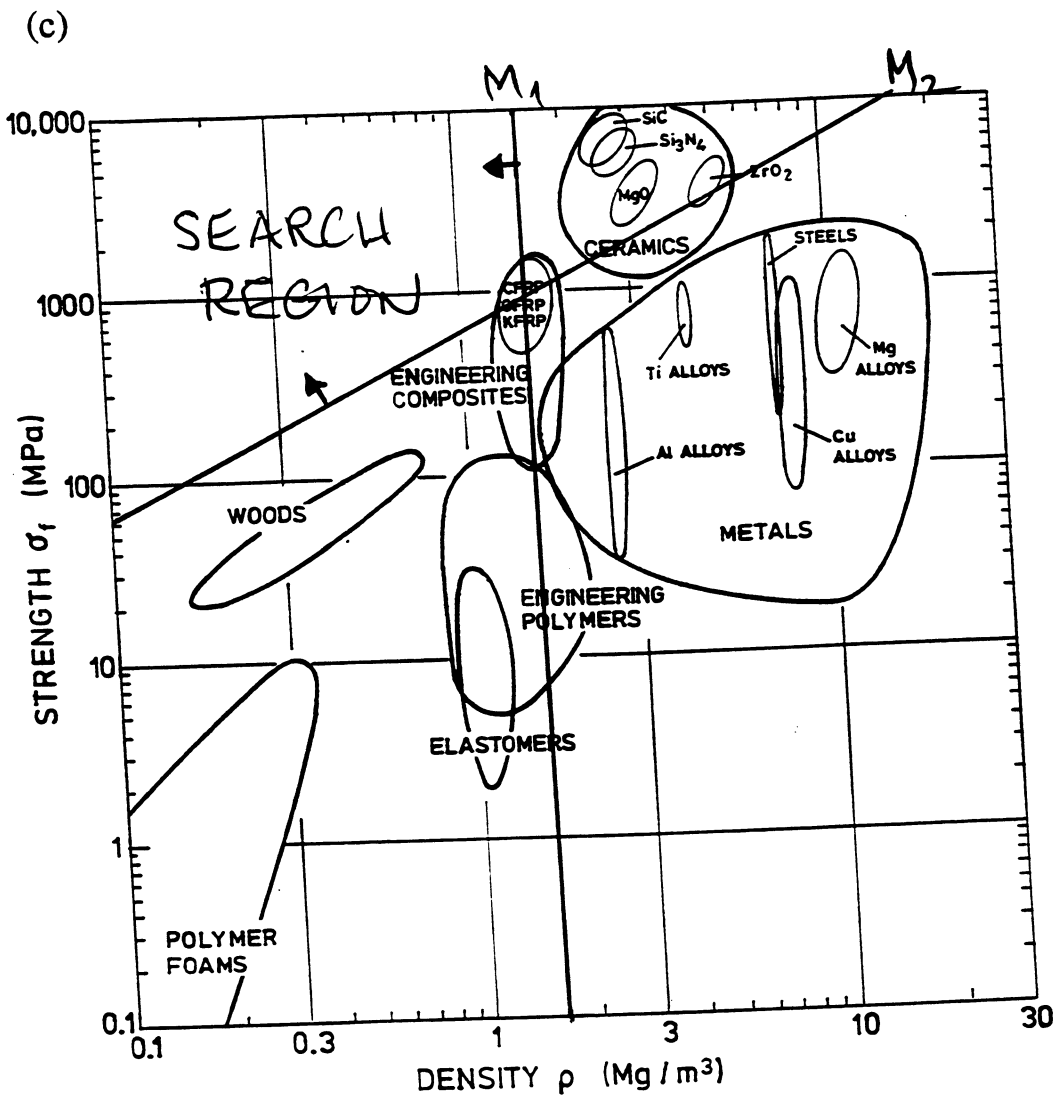


Fig. 5 A Materials Selection Chart of Strength vs Density

(d) If the 2 merit indices shown in the figure above are maximized by increasing strength and reducing density (or weight) they indicate that engineering composites and ceramics would be the primary choice. Whilst there may be sound reasoning for developing ceramics for the blades that operate in the high temperature part of the engine (they are considerably smaller than the compressor blades at the front and run much hotter), the latest compressor blades made by General Electric are of carbon fibre-epoxy. Here, light weight, high strength, stiffness and rigidity is required. The operating temperature range is modest, 50 C maximum quite within the capability of plastics particularly thermosetting resins. Fatigue resistance and toughness are essential requirements and also wear resistance particularly at the leading edge. Resistance to foreign object damage, e.g., bird impact is necessary.

Ceramics are extremely fragile and rule themselves out immediately. Carbon fibre composites are the stiffest of all polymer composites. Although glass fibre can be made stronger than carbon fibre on a specific strength basis glass-epoxy comes out worse than carbon-epoxy. Also, glass-epoxy is less resistant to attack from water than carbon-epoxy. Whilst Kevlar-epoxy has a high specific tensile strength it is poor in compression. Its tensile modulus lies somewhere between between glass and carbon. Its toughness is superior to all the polymer composites. Carbon fibre-epoxy compressor blades were first made by Rolls-Royce in the late 60's but failed the bird impact test because of their low toughness. However, General Electric's 2 metre blades are stitched through the layers of the blade to overcome this problem. Do clearly separate fragility from brittleness; ceramics are fragile and carbon fibre composites are brittle but it doesn't necessarily mean they fracture catastrophically when impacted.

(e) Consider a carbon fibre blade. Fibres are initially impregnated with the appropriate epoxy resin to form an aligned (unidirectional) pre-preg tape. This tape is partially cured to eliminate the tackiness and covered both sides with a non-stick coated paper. The required number of pieces are cut from the prepreg; the backing paper peeled off and the laminate stacked according to the design as specified by the designer, i.e., the correct number of layers are positioned in the specified directions to produce the anisotropic material of chosen elastic constants. A stitching process through the thickness will improve through thickness properties and enhance toughness.

The layup is positioned in the mould and using an autoclave to provide heat and pressure individual blades can be fabricated. The factors affecting the choice of manufacture include: ease of process including ability to arrange the plies in desired order and direction straightforwardly; low temperature and pressure requirements; essentially the blade is made in a single operation; large parts can be made by this process; little or no waste or finishing needed; good precision and surface finish; cost originates with the mould and autoclave, the fibre and resin are not that expensive compared to the cost of the engine; labour skill required not that high; large volume not required so rapid production not necessary.

Peter WR Beaumont
1st July, 1997