Version SH/4

MET 3
MANUFACTURING ENGINEERING TRIPOS PART IIB

Wednesday 23 April 2014 9 to 12

PAPER 1

*Answer not more than **four** questions.*

*Answer **each** question in a separate booklet.*

All questions carry the same percentage of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number not your name on the coversheet.

STATIONERY REQUIREMENTS
8 page answer booklet x 4
Rough work pad

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 Discuss the concept of a ‘*high-performance material’*. [25%]

Describe three examples of how materials can be processed to achieve ‘*high performance*’. For each example:

(a) identify a practical application of the material in a manufactured product;

(b) explain how the production process is used to enhance the properties of the material; and

(c) describe how the enhanced properties are relevant to the performance of the product in the identified application. [75%]

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Q1 CRIB.
Answer

There is no unique definition of a high-performance material as the attribute of 'performance' depends on the application for which it is intended. For example, an aerospace structural material may require high specific strength or stiffness, or a more complex figure of merit which depends on the precise nature of the stress to which it is exposed. For marine applications, or chemical plant, resistance to corrosion may be of paramount importance; for an optical fibre used for data transmission, optical transparency at the right wavelength will be the most important property. High melting point, low density, high density, resistance to creep, toughness, electronic properties (e.g. conductivity, insulation, semi-conduction etc), low wettability, etc. etc. are all possible desirable properties which might lead to a particular material being described as 'high performance'. In many cases the values of the attribute will depend on both the intrinsic properties of the material and on the method by which it is processed to form the component or final product.

Four examples were discussed in the course, but others are certainly possible and should receive full credit for a detailed discussion.

25%

Steel for rolling bearings
Rolling bearings (ball or roller bearings) transmit loads (e.g. in an axial and/or radial direction) while permitting rotation or linear motion at very low friction. As the rolling elements move over their tracks the underlying material and the rolling elements themselves are subjected to high contact stresses. As the applied loads increase so the stresses increase and the cyclic nature of the loading will lead to the initiation and growth of subsurface fatigue cracks, which historically have been the source of failure.

Fatigue cracks initiate at non-metallic inclusions and these are usually oxides. The bearing life depends strongly on oxygen content so the steel is processed to reduce its oxygen content: halving the oxygen content from 10 to 5 ppm increases the life tenfold. Current bearing steels have about 6 ppm oxygen, which is achieved by secondary processing of the steel – vacuum arc remelting (VAR).

25% for each material
Ultra-strong glass
Glass with a high fracture strength is needed for many applications such as safety glazing in transport, architectural uses, containers, drinking vessels, optical systems and consumer electronics (e.g. smart phone screens).

Normal' soda-lime glass is mainly SiO2 with additional sodium and calcium ions as network modifiers (e.g. 70% SiO2 10% CaO, 15% Na2O,5% MgO) . These reduce the softening temperature and allow the glass to be processed more easily.

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The fracture strength of glass is controlled by the size of the largest surface flaw. The flaw size distribution leads to a distribution of fracture stress (e.g. the Weibull distribution). We can strengthen glass either by reducing the flaw sizes (possible in some cases) or by generating an internal compressive stress which opposes the applied tensile stress in the surface – the tensile stress to which the flaws are exposed is then reduced and the fracture stress is increased.

In thermal strengthening the surfaces of hot glass sheet are rapidly cooled and become strong and unable to deform. The core of the sheet cools more slowly and its contraction is restricted by the cooler surface. The result (at room temperature) is a sheet with compressive stress in the surface and tensile stress in the core. This process cannot achieve the very thin strong sheet needed for a phone screen. That is produced by chemical strengthening. The sheet is treated in a molten salt bath which allows potassium ions (K^+) to diffuse into the surface to replace sodium ions. This replacement of small ions by larger ions results in surface compressive stress. Advantages over thermal strengthening are: much less distortion of the sheet; can be used for much thinner sheets (down to 0.5 mm); sheet can be cut after strengthening; can achieve high compressive stress in a thicker surface layer (e.g. >950 MPa in 40 µm, compared with 500 MPa in 20 µm).

Aluminium alloy for drinks cans

The aluminium can is a very efficient container – designed to use the minimum amount of material yet fulfil the design requirements. The internal gas pressure in a fizzy drinks can is 4 bar. Cans are designed so that all failure modes (side splitting, end ‘popping’, lid bursting) occur at the same internal pressure, to give most efficient use of materials. Different alloys are used for the body and lid to optimise properties:

3104 Al 1% Mg 1% Mn for body

5182 Al 4.5% Mg 0.3% Mn for lid

The wall thickness is currently ~75 µm.

Very high ductility is needed in the alloy which is subjected to a drawing and ironing process; the combination of work hardening from the mechanical processing and solution hardening from the alloying elements give the material a strength of ~300 MPa (compared with ~10 MPa for pure Al). The metal content in a standard 300 mL can has fallen steadily to around 13 grams, with a long term target of 10 grams.

Carbon fibre composite for pole-vaulting poles

The function of the pole is energy storage (in bending), to act as a pivoting column, and to provide appropriate stiffness (both sideways and torsional). The world record achieved in this sport increased asymptotically until about 1960 when the previous aluminium alloy poles were replaced by CFRP., leading to a new asymptote – the current world record was set in 1994 and seems to be limited by the pole material. For maximum energy storage in the bending pole we need a constant bending stress along the length of the pole – which in turn requires a stiffness which varies along the length. This is achieved by changing the wall thickness sinusoidally aloing the length: can readily be done with a CFRP tube manufactured by wrapping a pre-shaped sheet f prepreg around a mandrel.

75%

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2 (a) Micro Electrical Mechanical Systems (MEMS) have been identified as one of the most promising technologies for the 21st Century and have the potential to revolutionize both industrial and consumer products. Discuss the main technical and operational attributes of typical MEMS devices. Give specific examples of MEMS devices and applications to support your answer. [30%]

(b) In order to manufacture and apply a successful MEMS device, basic physics and operating principles, including scaling laws, need to be fully understood and appreciated at both macro and micro levels. What are the issues with scaling laws when designing and manufacturing MEMS devices? [30%]

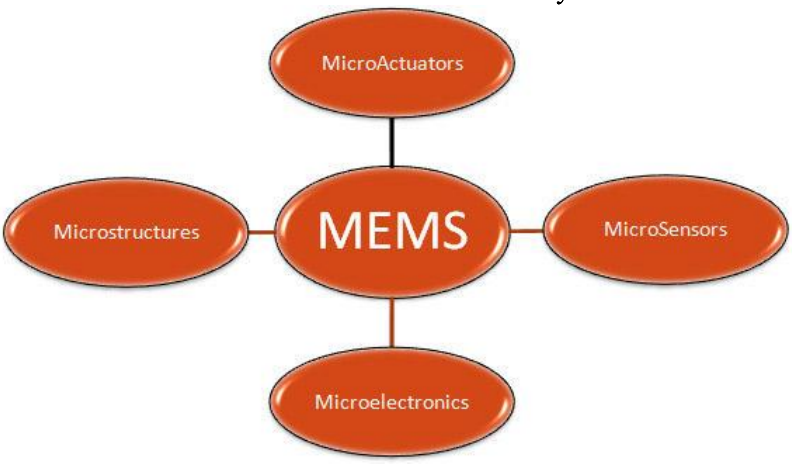
(c) Although MEMS and Nanotechnology are sometimes cited as separate and distinct technologies, in reality the distinction between the two is not so clear-cut. In fact, these two technologies are highly dependent on one another, particularly in terms of production methods. Semiconductor and MEMS device fabrication routes are constantly seeking higher resolutions that go beyond the limits of typical semiconductor fabrication technologies. Explain the factors that limit the current resolution and describe two emerging production technologies that could be applied in the realisation of device resolutions that go below 35nm. [40%]

Q2 CRIB

Answered by around 30% of the class. Most answers were able to describe the main technical and operational attributes of MEMs, with good answers identifying the the principle characteristics of actuation, sensing, and microelectronics in a typical MEMs device. Almost all were able to list a significant number of applications of the technologies in order to showcase the importance of the technologies. Few good answers were seen for the discussion of scaling laws, general discussions were given and high scoring answers were able to discuss the challenges of manufacturing and the considerations of the scaling law physics in device design. Despite its larger share of the questions, most answers gave scant detail in question c) despite being able to cite the emerging production processes.

a) Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as

- miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication.
- The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters.
- MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics.
- The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move.



While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, as shown above, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured mechanical signal into an electrical signal.

15%

<u>Applications.</u>

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Over the past several decades MEMS researchers and developers have demonstrated an extremely large number of **microsensors** for almost every possible sensing modality including

- temperature,
- pressure,
- inertial forces,
- chemical species,
- magnetic fields,
- radiation,
- etc.

Remarkably, many of these micromachined sensors have demonstrated performances exceeding those of their macroscale counterparts. That is, the micromachined version of, for example, a pressure transducer, usually outperforms a pressure sensor made using the most precise macroscale level machining techniques.

MEMS devices have demonstrated a number of **microactuators** including:

- microvalves for control of gas and liquid flows;
- optical switches and mirrors to redirect or modulate light beams;
- independently controlled micromirror arrays for displays,
- microresonators for a number of different applications,
- micropumps to develop positive fluid pressures,
- microflaps to modulate airstreams on airfoils,
- etc

15% (3 marks each)

b)

Sometimes there are a number of advantages and disadvantages in terms of design, production, operation and performance of MEMS devices due to the scale at which they operate. Size/weight, reliability and cost can be gained with a MEMS device. Increased surface area (S) to volume (V) ratios at microscales have both considerable advantages and disadvantages.

Design Criteria

- Friction is greater than inertia. Capillary, electrostatic and atomic forces as well as stiction at a micro-level can be significant.
- Heat dissipation is greater than heat storage and consequently thermal transport properties could be a problem or, conversely, a great benefit.
- Fluidic or mass transport properties are extremely important. Tiny flow spaces are prone to blockages but can conversely regulate fluid movement.
- Material properties (Young's modulus, Poisson's ratio, grain structure) and mechanical theory (residual stress, wear and fatigue etc.) may be size dependent.

Production Criteria

- Integration with on-chip circuitry is complex and device/domain specific. Lab-on-a-chip systems components may not scale down comparably.

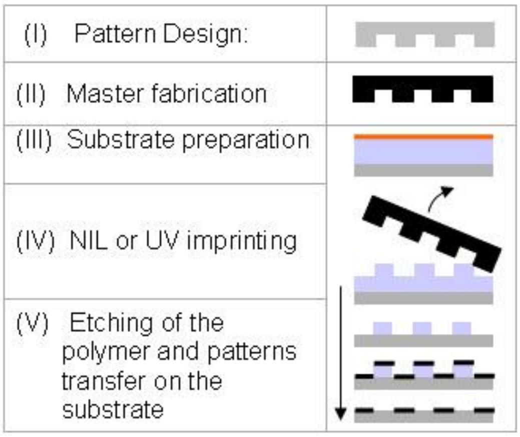
- Miniature device packaging and testing is not straightforward. Certain MEMS sensors require environmental access as well as protection from other external influences.
- Testing is not rapid and is expensive in comparison with conventional IC devices.
- Cost – for the success of a MEMS device, it needs to leverage its IC batch fabrication resources and be mass-produced. Hence mass-market drivers must be found to generate the high volume production.

30% (3 marks per sub-set answer + 6marks for additional answers)

c) There are a number of technologies that were discussed in the lectures that could deliver device resolutions less than 35nm. These are

Nanoimprint Lithography

The key advantage of this lithographic technique is the ability to pattern sub-25 nm structures over a large area with a high-throughput and low-cost. Nanoimprint lithography has two basic steps as shown in the Fig. 1. The first is the imprint step in which a mold with nanostructures on its surface is pressed into a thin resist cast on a substrate, followed by removal of the mold. This step duplicates the nanostructures on the mold in the resist film. In other words, the imprint step creates a thickness contrast pattern in the resist. The second step is the pattern transfer where an anisotropic etching process, such as reactive ion etching. RIE is used to remove the residual resist in the compressed area. This step transfers the thickness contrast pattern into the entire resist. During the imprint step, the resist is heated to a temperature above its glass transition temperature. At that temperature, the resist, which is thermoplastic, becomes a viscous liquid and can flow and, therefore, can be readily deformed into the shape of the mold. The resist's viscosity decreases as the temperature increases. Unlike conventional lithography methods, imprint lithography itself does not use any energetic beams. Therefore nanoimprint lithography's resolution is not limited by the effects of wave diffraction, scattering and interference in a resist, and backscattering from a substrate.



Nano Imprint Lithography Process

Extreme UV (EUV) Lithography

EUV stands for "extreme ultraviolet" and refers to the light source that is used in the lithography machine. The previous generation of lithography machines used light in the

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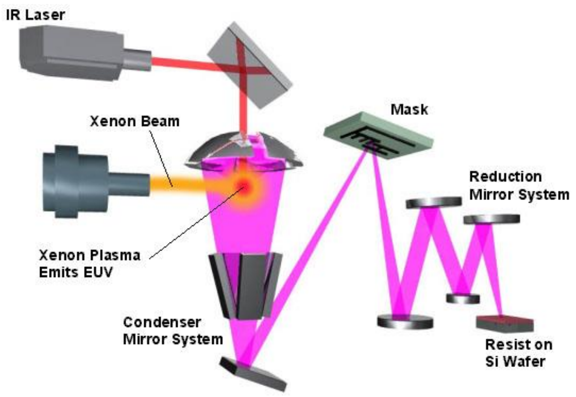
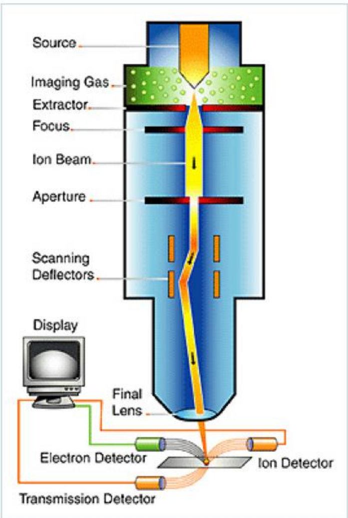
"deep ultraviolet" spectrum. Ultraviolet light has a shorter wavelength than visible light. With a wavelength of only 13.5 nm, EUV sits in the spectrum between visible light and X-ray. Since lithography is an optical technology, one of the things that limit the resolution of the equipment is the wavelength of the light that is used. Shortening the wavelength of the light means higher resolution and smaller features. Lithography machines have gone from using ultraviolet light with a wavelength of 365 nm to "deep ultraviolet" light of 248 nm and 193 nm, improving the resolution at every step. EUV is the next step, with light of a wavelength of 13.5 nm. (An analogy is painting: we use a smaller brush to paint the finer details). The current lithography technology has been pushed further than many would have thought possible even five years ago, but this has come at the cost of increasing complexity and shrinking margins of error. The industry has had to reach deep into a bag of tricks to continue shrinking feature sizes. Double Patterning in particular is costly because it increases the amount of lithography exposures per wafer, and thus either reduces Fab output or requires more equipment. With EUV, chip makers will return to the former situation in which they expose a critical layer in just one single step. EUV also has a credible path to a resolution of less than 10 nm. The system is shown in the figure. A IR laser source, of power level in the range 5kW is used to strike plasma in a xenon gas, or tin droplet. The emission from these plasma is centred around a wavelength of 13nm, which is then directed to a contact mask or reflective mask which is minimised with reflective optics and sent to the Si wafer to expose the resist.



EUV processing system

Foucsed Ion Beams

The FIB instrument is similar to a scanning electron microscope (SEM), except that the beam that is rastered over the sample is an ion beam rather than an electron beam. Secondary electrons are generated by the interaction of the ion beam with the sample surface and can be used to obtain high-spatial-resolution images. In most commercially available systems, Ga ions are used, and their sputtering action enables precise machining of samples. In conjunction with the gas-injection capabilities on these systems, which enable ion-beam activated deposition and enhanced etching, a range of sample fabrication schemes are possible. The size and shape of the beam intensity profile on the sample determines the basic imaging resolution and micromachining precision. Generally, the smaller the beam diameter, the better the achievable resolution and milling precision, although the requirements for the two applications are not exactly the same. For the energies, currents, and acceptance angles used in typical FIB systems, the beam spot size is limited mostly by the chromatic aberration that results primarily from the energy spread of the beam due to space charge effects at the ion source and secondarily from the spherical aberration of the lenses. However, the ultimate spatial resolution for FIB imaging is, in fact, limited by sputtering and is thus sample-dependent. In modern FIB systems, the imaging resolution determined by the sputter-limited signal/noise usually is about 10 nm. Whilst FIB systems are deemed to be slow for conventional micro-machining, when processing materials at sub 35nm, they can infact be extremely fast, require no masks or secondary stages such as resists, and can process a wide range of materials that are relevant to both Si devices and multi-material MEMs devices.



Focused Ion Beam System

Resolution (10 marks), (15 each for good process description)

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3 The environmental impact of polymer packaging in the food and drink industry is the subject of some controversy. Public perception is based on information which is often incomplete, even when it comes from reputable sources.

(a) The main functions of packaging in the food and drink industry may be summarised under the headings of product handling, mechanical protection, barrier function, provision of information, and tamper-evidence. Give examples of how these functions are achieved, and discuss their resulting environmental implications. [25%]

(b) How may polymers be recycled at end-of-life? Why is recycling of post-consumer polymer packaging generally regarded as problematic? What are the environmental consequences (benefits and penalties) of the different end-of-life disposal options for polymer packaging? [30%]

(c) Bio-polymers may be defined as polymers originating from renewable feedstock. One of the commonest bio-polymers is PLA (polylactic acid), which is derived from corn. What are the advantages and disadvantages of using PLA for food packaging? To what extent can the environmental impact of biopolymers be assessed using Life Cycle Analysis (LCA)? [30%]

(d) What steps can be taken to minimise the environmental impact of packaging? [15%]

Q3 CRIB

(a)

Function	Achieved by	Example	Environmental consequences
Product handling	Containers for loose goods and liquids; clustering of small items	Bottle, box, bag (liquids, powders). Tray, bag (meat, cheese, loose foods, other products)	**Positive**: Reduction in product wastage by damage etc. **Negative**: Packaging material required. **Verdict**: Unless excessive packaging used, expect small positive impact.
Mechanical protection	Impact-resistant packaging for fragile items; surface protection for many items.	Egg box; blister pack; plastic film wrapping	**Positive**: Reduction in damage so less product wastage. **Negative**: More packaging material. Increased bulk reduces transportation packing efficiencies. **Verdict**: Generally large positive impact.
Barrier function	Prevents contact between atmosphere/environment and product; selective passage of gases; protect from light; prevents odours escaping; enables inert gas atmosphere	Plastic bag for foods. Multi-layer packaging for meat and cheese	**Positive**: Product life increased by orders of magnitude, so reducing wastage. But by enabling longer supply chains it promotes globalization of food production – with both **positive** and **negative** environmental consequences **Negative**: Complex multi-layer films very difficult to recycle **Verdict:** Huge positive impact
Provision of information	Writing and pictures on packaging	Labels attached to product, or inkjet-printed onto packaging	**Negative**: Stuck-on labels may impair recyclability if appropriate materials not chosen. **Verdict:** Negligible impact
Tamper-evidence	Sealed container	Tamper-evident tabs; sealed lids	**Positive**: Some reduction in wastage.

Overall summary: Packaging is typically responsible for between 0.5 and 5% of the energy footprint of packaged foods: most of the impact comes from the food itself. So

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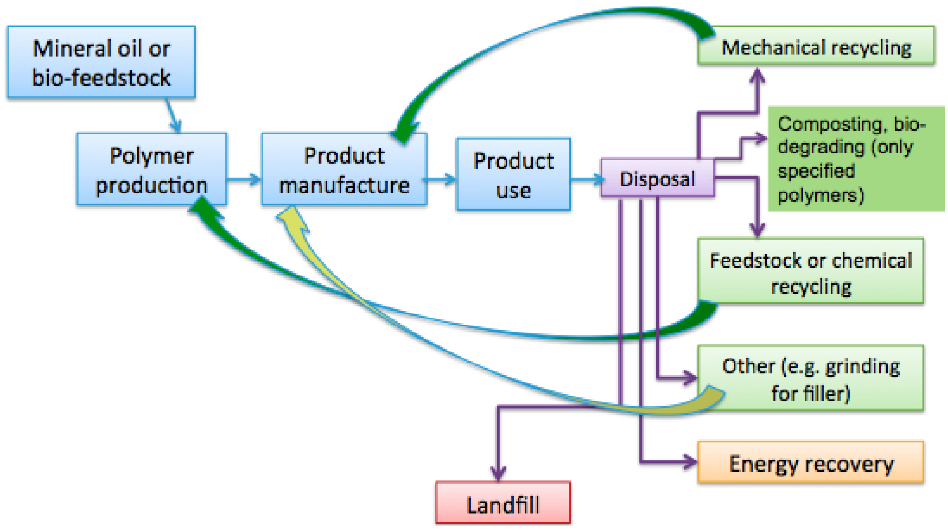
using a small amount of packaging to reduce the food wastage by (typically) at least 50% makes it environmentally very beneficial. The overall environmental consequence of whether packaging can be recycled at end-of-life is small. However, this is something which consumers focus on as a negative environmental influence of packaging.

4% each discussion point + 5% comment

(b)
Mechanical recycling: Sort, shred, clean, melt/reprocess (extrusion, pressing)
Chemical recycling: Polymers broken down into constituent monomers which can be used in refineries or in petrochemical production
Energy recovery: Burning



10%

Polymers are difficult to recycle for technical reasons:

- Polymers cannot be purified, so quality of input waste stream is critical. Polymers need to be cleaned thoroughly, and then sorted very accurately into different polymer types – including segregating by colour.
- Polymer properties depend not only on 'chemical formula' but also on chain length and configuration, so polymer from different sources may have very different properties.
- Polymers contain a range of additives (e.g. to improve processing, surface modifiers etc) which may compromise quality of recycled material.
- Polymers tend to decompose on heating and can be degraded by processing.

But there are other reasons why polymer recycling is often not favoured:
Economic:

- Polymer quality often low, so recycling usually means *downcycling*: applications are limited, so re-sale value low
- Oil prices still comparatively low, so virgin polymer prices low (often not much more expensive than recycled polymer)
- The recycling business has slender profit margins: polymer collection and processing are expensive.

Social:

- Worries about safety of recycled polymers – e.g. dioxins, additives

10%

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Eco-impact: Most important factor is whether polymers can substitute for virgin polymers so potentially saving virgin polymer production. Improves as supercleaning technologies allow polymers to be recycled to food-grade applications (particularly PET, HDPE), and legislation is relaxed to permit this.

	Suitable waste streams	**Energy and resource usage**	**Comments**
Mechanical, primary or closed-loop recycling	Clean, well-characterised industrial or post-consumer thermoplastics.	Low	Post-consumer recycling normally limited to bottles (HDPE, PET or PVC)
Chemical or feedstock recycling (depolymerisation; partial oxidation; cracking)	More mixed and impure polymer streams. Specialist polymers.	High	High volumes needed to be economic
Energy recovery	Most; chlorine-containing polymers excluded	Negative	Legislation limits some waste streams. Public opposition.
Other material re-use (e.g. as fillers)	High-volume examples include electronics thermosets; rubbers	Variable; generally low	Potential for increasing amounts, but material is low-value
Landfill	Any	Low	

10%
(c)
PLA has physical properties similar to polystyrene, and can be modified to resemble PE and PP. All these are commonly used in packaging. The grease resistance (another important attribute) is comparable to PET. So the material is basically suitable, although properties aren't always optimized at present.
After use, the PLA degrades by hydrolysis in a commercial composting operation (but not in domestic composting, or in the open air). If included in the recycling stream for mixed polymers, PLA is difficult to distinguish from some petrochemical polymers and can contaminate conventional polymers.
A rationale for using biodegradable polymers (which are not necessarily bio-derived polymers, so there is immediately consumer confusion here) for food packaging is that food and packaging can be disposed of together at end-of-life by composting. The alternative is generally agreed to be environmentally more negative: often landfill, or in some cases energy recycling.

Problems with biopolymers:

- Biopolymers are expensive compared with conventional polymers (perhaps factor of 2 for PLA).
- Resource scarcity: wide-scale commercialization of biopolymers is held back by high production costs.

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Environmental credentials of biopolymers are controversial. Production is energy and resource intensive: such large-scale monocultures involve intensive agriculture, requiring fertilisers, pesticides, fuel for farming equipment, irrigation. So even though they are a renewable resource, they carry a big fossil fuel burden. Some studies indicate that the environmental impact of biopolymers is greater than that of conventional fossil-derived polymers.
Assessing the environmental impact can be done through an LCA, but the assumptions which must be made to do this lead to a large range of answers. LCA provides a standardised framework for determining the environmental impact of a product or process, to allow comparisons to be made.

- *But interpretation varies, and users can select different options while still remaining within the framework*

- Should cover the entire life-cycle of the product
    - *But many published biopolymer studies don't do this*
- Presents environmental impact results by category
    - *Many studies don't look at all categories*
- Location specific
    - Transport requirements, incineration efficiencies, farming practices
    - Energy production is country-specific: very different environmental impacts (e.g. coal-fired; hydro etc)
- Impact in several disparate categories should be computed and combined, including:
    - Contribution to climate change (including CO2)
    - Resource depletion
    - Ozone depletion
    - Energy and water use
    - Acidification, eutrophication, smog formation, human and ecosystem toxicity? Nitrogen emissions from fertiliser use? Etc?

But not all studies examine all impacts, so comparisons are difficult.

30%

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(d)

Feature	Achieved by	Positive consequences	Negative consequences
Reduced weight of packaging	Reduce film thickness by using multi-layer film	Less material required; material production energy saved	Increased complexity of manufacture means higher failure rates so more wastage
		Reduced transport costs	Recyclability impaired or prevented
Reduced volume of packaging	Polymer bags rather than trays	Volume of packaged item reduced: better packing density enabled Transport used more efficiently (e.g. fuller lorries: fewer needed) Refrigeration costs reduced	Trays potentially easier to recycle than bags
		Reduced pressure on end-of life facilities (landfill)	
		Less material required; material production energy saved	

Packaging has a small eco-impact compared with the goods being packaged
Plastics are very efficient for packaging; eco-impact of other materials greater
Only a small proportion of packaging is recycled to products which save production of virgin polymer, so end-of-life considerations for packaging are *currently* of secondary importance.

Priority should be to minimise amount of material in single-use disposable packaging
Biodegradable plastics may help – but aren't the magic solution of popular perception

For the future:
Increase amounts of closed-loop recycling to food-grade polymers
Restrict range of polymers used for food packaging
But only where this can be done without significant eco-impact increase

Re-usable packaging? e.g. milk bottles, collected by supermarket and returned by them to dairies for washing and refilling. Re-usable PET bottles (Mainland Europe): Fizzy drink bottles collected, returned to production plant for washing, re-filling and re-labelling
Complex logistics
Requires uniform bottles (no product-specific bottles e.g. Coke)
Economics are generally unfavourable

15%

4 A consumer electronics company is launching a new tablet based computer. You have been asked to design an automated system that will perform the final assembly of the product. The assembly process will require an electronics module comprising of a Liquid Crystal Display (LCD) and an integrated single board computer to be positioned in a plastic tablet casing and fastened in place with four screws. A snap-fit plastic bezel will then be positioned and pushed into place on the front of the tablet. This will form an attractive front for the tablet casing, framing the edge of the LCD and concealing the inner workings of the tablet. Fig. 1 shows an exploded assembly drawing of the tablet.

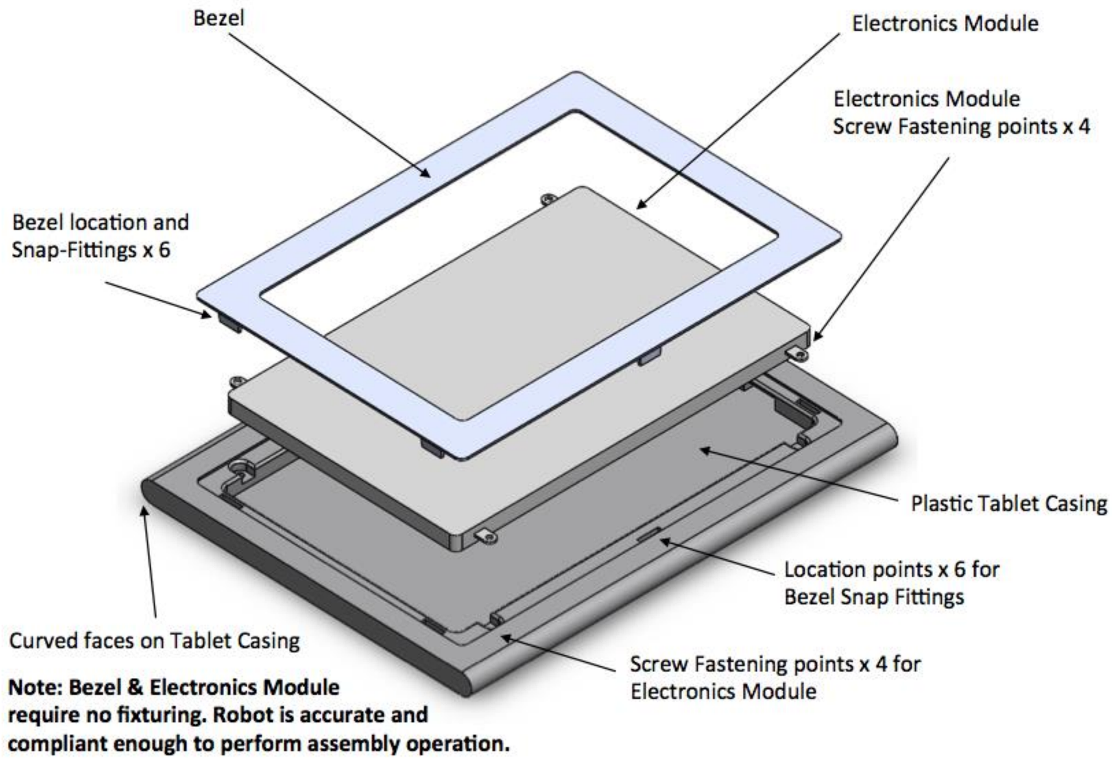


Fig. 1 Exploded assembly drawing of tablet.

The assembly station will consist of two SCARA Robots and a single assembly fixture. One SCARA robot will manipulate in-coming parts (tablet casing, electronics module and bezel) and out-going parts (assembled tablet) between kitting trays on a conveyor and the assembly fixture. The second SCARA robot will perform the screw fastening operation.

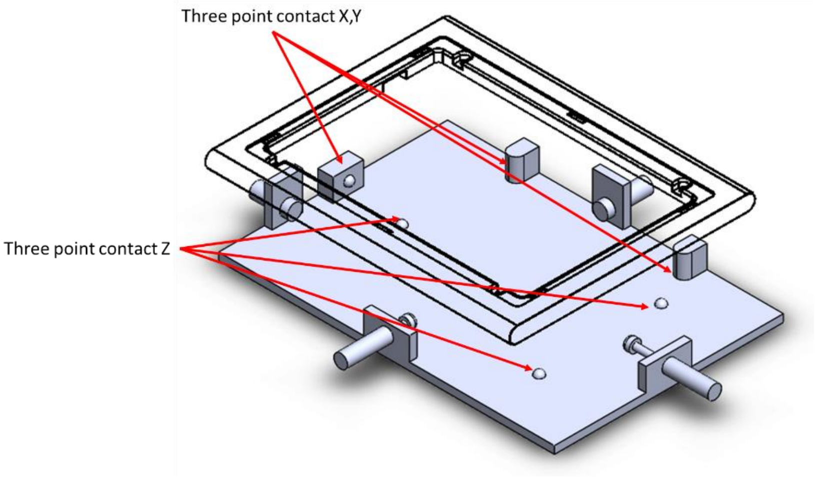
(a) Provide detailed designs of the fixture and robot end effector used to manipulate parts during the assembly of the tablet. Describe the overall operation of the fixture and end effector, listing aspects of the mechanical design that enable them to work reliably. [40%]

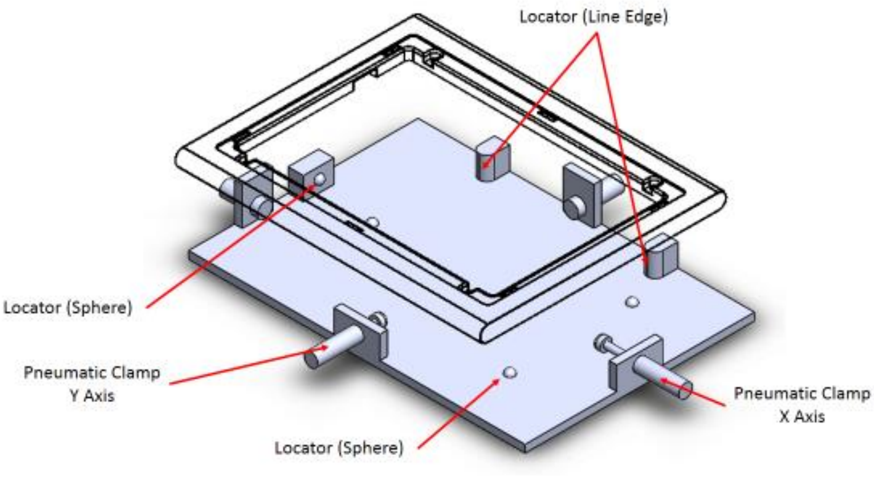
(b) Describe the type, location and functionality of sensors required to ensure the reliable operation of the fixture and both end effectors. [40%]

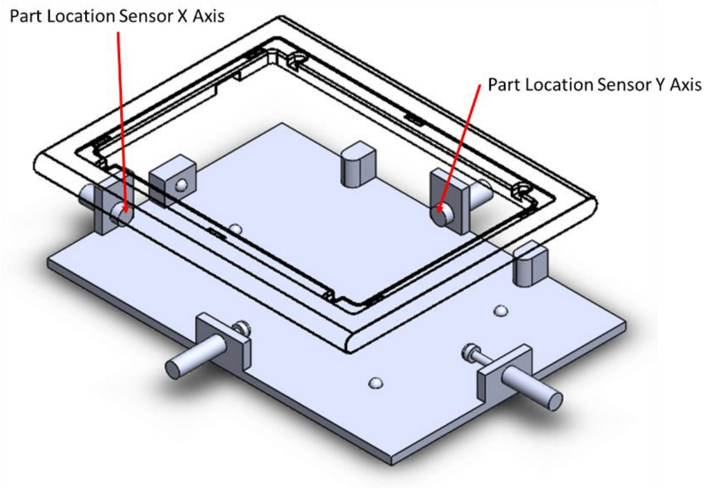
(c) Describe the approach that should be taken to test the assembly station. Discuss details of the different test phases and types of tests that should be carried out in each phase. [20%]

Q4 CRIB

a. The fixtures would be designed as shown below:







The fixture has an initial condition with all clamps retracted, providing maximum space for parts to enter the fixture. Once the table casing has been placed in the fixture the clamps are fired, pushing the casing against the fixed stops. The sensors are triggered allowing operations to continue. The bezel and electronics module have no fixturing and rely on the accuracy and compliance of the assembly robot.

The following table lists the key features of the fixture that are important for its operation.

Feature	Description of Functionality
Three point contact in Z Axis	To locate the components accurately in three dimensions it is important that kinematic principles are followed. This requires three points of contact in the Z axis. (Note the three points of contact should be spread to ensure screw fastening forces in the Z plane can be catered for.
Three point contact in X, Y Axis	To locate the components accurately in three dimensions it is important that kinematic principles are followed. This requires three points of contact in the X,Y axis. Note Y fixed locations have been designed with an edge contact to cater for the curved surface on the edge of the tablet casing. X fixed location point has been designed as a point location to cater for the flat surface of the tablet casing.
Pneumatic Clamps	To ensure that the components are located against the reference points and held in position pneumatic clamps are used. These are positioned correctly to ensure clamping forces don't skew the parts or cause deformations.
Pusher Pads	Even though a single point of clamping is theoretically preferred, this can cause damage to the surface of the components so a pusher pad is used to spread the load. (Pusher pads on the Y axis need to have a large enough flat

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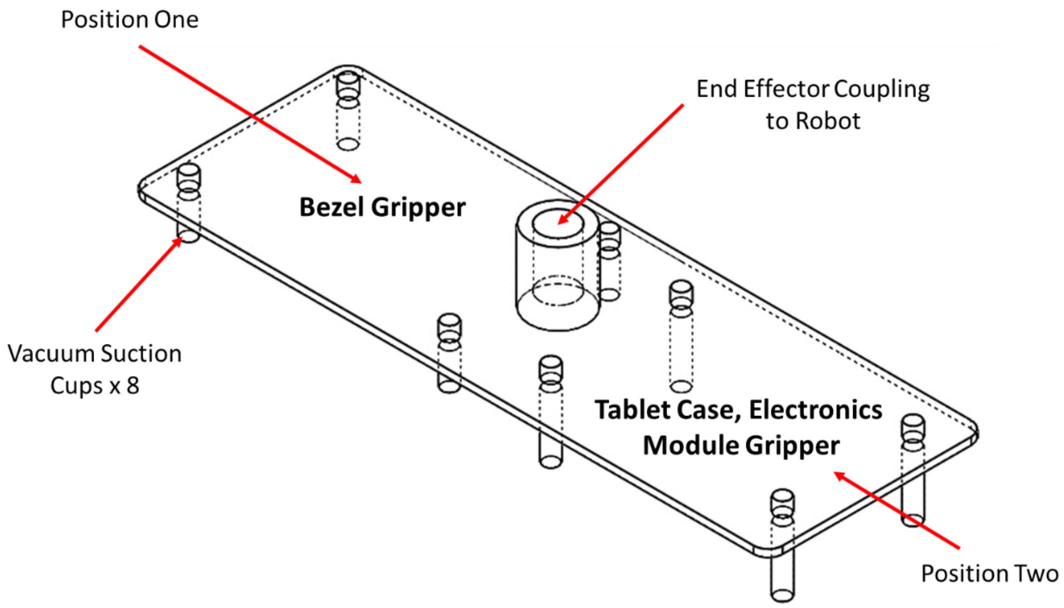
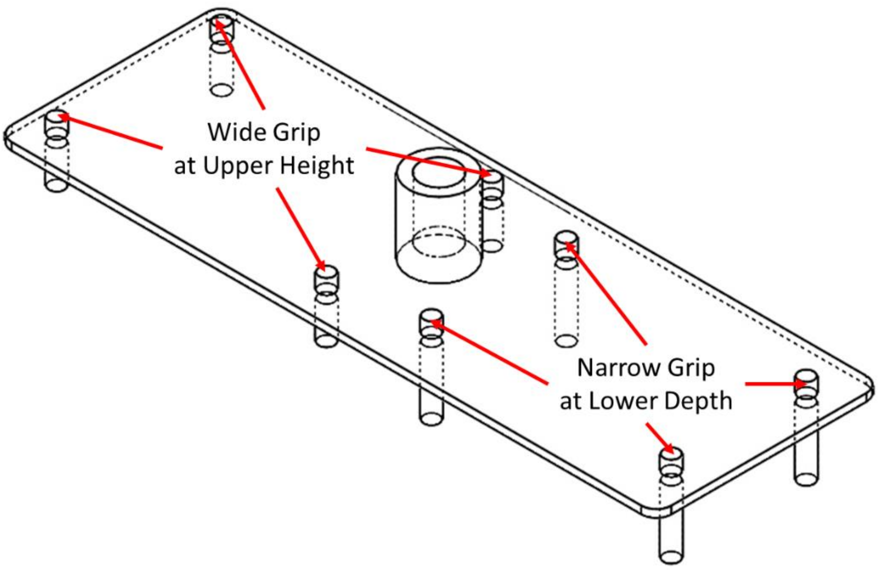
	surface to cater for curved surfaces on the edge of the tablet casing.
Sensors	Sensing is critical to ensure the correct operation of the fixture. Sensors have been positioned to register the presence of a correctly clamped component. Additional sensors can be added to the pneumatic pistons to register if they are in an extended or retracted position.
Operation	It is important that when the clamps on the fixture are in the retract position enough clearance is available to ensure that parts can be placed in the fixture while accounting for the tolerance of the robot and kitting trays.

a. **The end effector would be designed as shown below:**





The end effector is formed by two sets of four vacuum suckers. Each set of vacuum suckers can be used independently when the end effector is rotated into either of its two operational positions. Position two is used to pick up the tablet case and the electronics module. The vacuum suckers are positioned closer together and at a lower depth so that they fit inside the lower recess of the tablet case. Position one is used to pick up the bezel. The vacuum suckers are positioned further apart and higher up so that they can pick up the bezel.

The following table lists the key features of the end effector that are important for its operation.

Feature	Description of Functionality
Operational Configuration	The easiest way to pick up flat components of this type is to use vacuum suckers. Due to the narrow and curved front face of the tablet case, the inner flat recess will be used. The same sucker configuration can be used for the electronics module. The bezel will be picked up on a wider sucker pitch. A complication occurs at the bezel assembly place position as there will be no recess to accommodate the suckers previously used to pick up the case and the electronics module. (When picking up the case the wider pitch suckers used for the bezel would collide on the outer face of the case.) To overcome this problem a double headed end effector is used with two separate sucker configurations. Configuration one for the Bezel (Position One),

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	Configuration two for the Case and Electronics module (Position Two).
Operational Control	The vacuum end effector will have two pneumatic circuits, one for the four suckers used in configuration one for picking up the Bezel and one for the four suckers used in configuration two for picking up the Case and the Electronics Module. Each pneumatic circuit will have a solenoid valve to either apply vacuum or vent to atmosphere. This will be controlled by the robot controller. Upstream of the solenoid valve will be a vacuum sensor to detect the vacuum pressure. This will be used to sense the presence of a part on the end effector.
Vacuum Suckers	The vacuum suckers used for this application will have minimum bellows to get the highest positional accuracy and internal grip faces to reduce part slippage during high speed moves. Three sucker points can be used to meet kinematic principals, but four may be better to ensure z force can be applied directly above bezel clips during the assembly process.

b. The sensors are located as shown above in the fixture diagrams.

It should be noted that the tablet casing is made from plastic and so limits the choice of sensors to either being optical or capacitive proximity. I would recommend capacitive as they have less maintenance requirements e.g. cleaning of optics. Sensing the status of the pneumatic pistons can either be done by a range of sensors monitoring dogs on the shafts of the pistons or by using specialised magnetic sensors that can be clamped onto the outside of the clamp cylinders. The inner components (electronics module and bezel) could be detected with optical diffused sensors mounted on the periphery of the fixture. State information on these components could be logged from end effector sensor information. By testing the status of both the part presence sensors and the status of the clamp sensors it is possible to determine whether the tablet case is correctly positioned and clamped. (Inner components may need additional assembly status information.)

b. The sensors that should be used on the end effector (Assembly).

The assembly end effector uses a vacuum sensor to check the vacuum pressure present in the pneumatic circuits on the end effector. The sensor can be neatly integrated into the vacuum manifold for the two pneumatic solenoids. The checks performed on the vacuum sensor would have to be integrated into the operation of the pneumatic solenoids. Once one of the pneumatic solenoids has been opened and a part is present and sealing the pickup suckers, a vacuum pressure will build. Once a vacuum threshold level has been reached the sensors output will change state. Missing parts or dropped parts will stop a vacuum pressure being generated. Optical or Capacitive sensors could be mounted on the end effector to sense the presence of parts but this can constrain / complicate the end effector design.

b. The sensors that should be used on the end effector (Screw Driver - Fastening).

The screw fastening end effector has a number of states to be detected. These are listed in the table below.

State (Error)	Sensors
Screw Driver Up	Inductive Sensor (Z + Position)
Screw Driver Down	Inductive Sensor (Z – Position)
Screw Present / Aligned on Screw Driver	Vacuum Sensor on Screw Pick Up Head
Screw at Torque	Air Pressure Sensor from Screw Driver Motor Torque Sensor from Screw Driver Motor
Correctly Fastened Screw	[Screw Driver Down + Screw at Torque]
Miss-Threaded	[Screw Driver Not Down + Screw at Torque]
Screw Thread Stripped	[Screw Driver Down + Over Run Timer]

c. Test Phases to be undertaken in testing the assembly station.

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There are two main test phases that will be undertaken in commissioning the system:

Unit Testing (Low Level Module) **Assembly Robot** **Fastening Robot** **Fixture** **Conveyor**	Each sub-module of the system will be tested in isolation to ensure that: a) Its operation agrees with functional specification. b) It operates reliably and provides operational status information. c) It captures and declares error conditions. d) It performs the correct hand shaking with high level controller.
System Testing (Production Components)	Each sub-module of the system is integrated with the high level controller in a controlled fashion to allow a test strategy to be undertaken: a) Test production components b) Test Hardware / Software Interfaces c) Test Error / Recovery Strategies

Answered by almost all of the class. Most answers were able to offer detailed designs on the jig fixtures and end-effectors required to automatically assemble the components. Marks were lost for cursory descriptions of the system operation and components. Higher scoring answers offered detailed diagrams and clear descriptions of the overall system. Many answers failed to offer sufficient details of the sensory systems employed, or their operation states in order to assess the status of the operations. Part c) was not answered in full by many candidates, with the common answer being simply a list of sequences rather than more detail on unit testing and system testing actions.

5 (a) Describe the basic principles that underpin design for assembly. [30%]

A company is proposing to manufacture large area lightweight aluminium flooring for the next generation of high-speed train. The design requirements are that the floor must be light, stiff, have surfaces that remain flat with no protrusions, and must not contain adhesives. A section of the initial design is presented in Fig. 2. It consists of top and bottom plates made from aluminium sheet that are secured to a series of extruded aluminium spacers that run the length of the floor section. Both top and bottom plates are secured to the spacer at intervals with screw fixings.

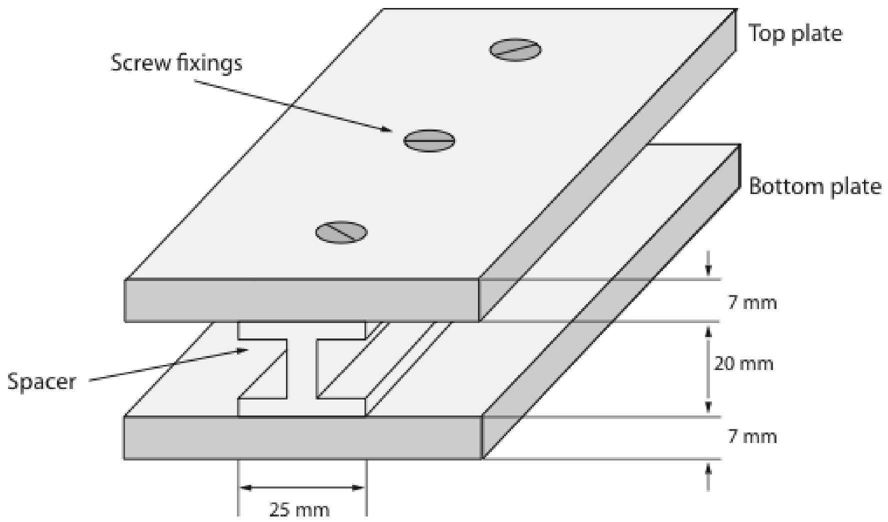

Fig. 2 Floor section

(b) Discuss the extent to which this design and manufacturing route align with the principles outlined in section (a). [30%]

(c) Develop an improved design and suggest three alternative manufacturing routes. Select your preferred route and provide a detailed description of the manufacturing processes and operations employed. [40%]

Q5 CRIB

Q2 Crib

a) 1. Simplify the design and reduce the number of parts Because for each part, there is an opportunity for a defective part and an assembly error. The probability of a perfect product goes down exponentially as the number of parts increases. As the number of parts goes up, the total cost of fabricating and assembling the product goes up. Automation becomes more difficult and more expensive when more parts are handled and processed. Costs related to purchasing, stocking, and servicing also go down as the number of parts are reduced. Inventory and work-in-process levels will go down with fewer parts. As the product structure and required operations are simplified, fewer fabrication and assembly steps are required, manufacturing processes can be integrated and lead times further reduced. The designer should go through the assembly part by part and evaluate whether the part can be eliminated, combined with another part, or the function can be performed in another way.

2. Standardize and use common parts and materials to facilitate design activities, to minimize the amount of inventory in the system, and to standardize handling and assembly operations. Common parts will result in lower inventories, reduced costs and higher quality. Operator learning is simplified and there is a greater opportunity for automation as the result of higher production volumes and operation standardization.

2. Design for ease of fabrication. Select processes compatible with the materials and production volumes. Select materials compatible with production processes and that minimize processing time while meeting functional requirements. Avoid unnecessary part features because they involve extra processing effort and/or more complex tooling

3. Mistake-proof product design and assembly so that the assembly process is unambiguous. Components should be designed so that they can only be assembled in one way; they cannot be reversed. Notches, asymmetrical holes and stops can be used to mistake-proof the assembly process. Design verifiability into the product and its components.

4. Design for parts orientation and handling to minimize non-value-added manual effort and ambiguity in orienting and merging parts.

5. Minimize flexible parts and interconnections. Avoid flexible and flimsy parts such as belts, gaskets, tubing, cables and wire harnesses. Their flexibility makes material handling and assembly more difficult and these parts are more susceptible to damage.

6. Design for ease of assembly by utilizing simple patterns of movement and minimizing the axes of assembly. Complex orientation and assembly movements in various directions should be avoided. Part features should be provided such as
chamfers and tapers.

7. Design for efficient joining and fastening. Threaded fasteners (screws, bolts, nuts and washers) are time-consuming to assemble and difficult to automate. Where they must be used, standardize to minimize variety and use fasteners such as self- threading screws and captured washers. Consider the use of integral attachment methods (snap- fit). Evaluate other bonding techniques with adhesives. Match fastening techniques to materials, product functional requirements, and disassembly/servicing requirements.

8. **Design modular products to facilitate assembly** with building block components and subassemblies. This modular or building block design should minimize the number of part or assembly variants early in the manufacturing process while allowing for greater product variation late in the process during final assembly.

9. **Design for automated production.** Automated production involves less flexibility than manual production. The product must be designed in a way such that it can be handled with automation.

b) One the basis of the guidelines given in part a) one can state the following.
Guideline-1. This is not met since there are a minimum of parts required to provide a stiff structure, which are the top and bottom plates and a spacer. Considerable part cost, production complexity and processing time is introduced when using screw fixings.
Guideline-2. This is met since there are common parts such as plates, extrusions, and screws.
Guideline-3. This is met since parts are symmetrical (spacers and plates)
Guideline-4. This is met since parts are symmetrical (spacers and plates) and can be handled with the correct equipment.
Guideline-5. This is met since there are no flexible parts.
Guideline-6. This is met since patterns of movement are provided by Cartesian motion systems.
Guideline-7 This is not met since joining in this manner requires many extra processing operations such as plate drilling, spacer drilling and tapping, countersinking, screw positioning, placements, and locating. In addition to the need for a wider range of production machines, tools and fixtures for each operation.
Guideline-8. This is met since the part components are basic building blocks.
Guideline-9. This is met since large production operations can al be performed automatically once work pieces are positioned into their jigs and fixtures.

In summary, the current design meets 7 of the 9 guidelines. Whilst at first sight this appears to be a high level acceptability, failure to meet guidelines 1 and 7 in this case will render this design and manufacturing approach unacceptable in terms of cost, productivity, and acceptability for the transport sector. Any redesign must address these issues.

c) Given the design constraints and the issues indentified in part b), there are a number of potential routes, some more appropriate than others. The use of plates and extruded spacers offers stiff structure and this design feature should be retained.

Addressing **Guideline-One** of the primary objectives is to remove the need for fasteners (, since this will reduce cost, increase stiffness, and reduce the number of manufacturing process steps. It is therefore appropriate to implement joining technologies (addressing guideline-7) whilst maintaining the basic structure of the design. Since adhesives cannot be used there are a number of options.

<u>Options</u>

There are few fusion based joining technologies appropriate for Al. The only possible route in this case would be MIG welding. One of the difficulties with fusion welding these structures is that the high heat input leads to distortion. Manufacturers learn how to control and correct this to some extent, but extra costs can be incurred and there may remain the need to use filler to ensure a satisfactory cosmetic appearance to the rolling stock.

An alternative is laser stake welding. Although this is particularly difficult since welds are often left brittle due to the high reactivity of molten Al, which requires significant levels of environmental controls using shielding gases. Even if this were possible, the likelihood of weld failure is high, and there remains the need for finishing operations to correct for distortion and improve cosmetic appearance.

Brazing could be employed although this will require high levels of heat input and will suffer from low bond strength and the need to correct for distortions in expensive post-treatment operations.

Friction stir welding is another option, and one that has been applied in this application.

Detailed Process Operation.
A non-fusion, solid-state joining technology is Friction Stir Welding (FSW). Manufacturers report a range of benefits from using FSW:

- Reduced cost,
- Less distortion and excellent mechanical properties of FSW compared with MIG welding
- A single FSW pass may be all that is needed to replace multiple MIG welding passes required for thicker sections.
- No weld spatter. The surface and root of the joint are clean and their cosmetic appearance so good they need not even be painted. This provides potential for further cost reduction.
- No weld fume during manufacture, which is increasingly important as health and safety standards tighten.
- The process can operate in any orientation, because gravity has no influence.
- Energy efficient.
- Consumables like gas or filler wire are not needed.
- No porosity in the welds.
- Excellent mechanical properties.
- FSW is its potential to contribute to the crash worthiness of aluminium vehicles that could otherwise fail in the heat affected zone along weld seams.

This was not a popular question, with only one attempt. The design for assembly component was well answered, in addition to the assessment of the alignment of the existing design. A good set of alternatives were given in part c.

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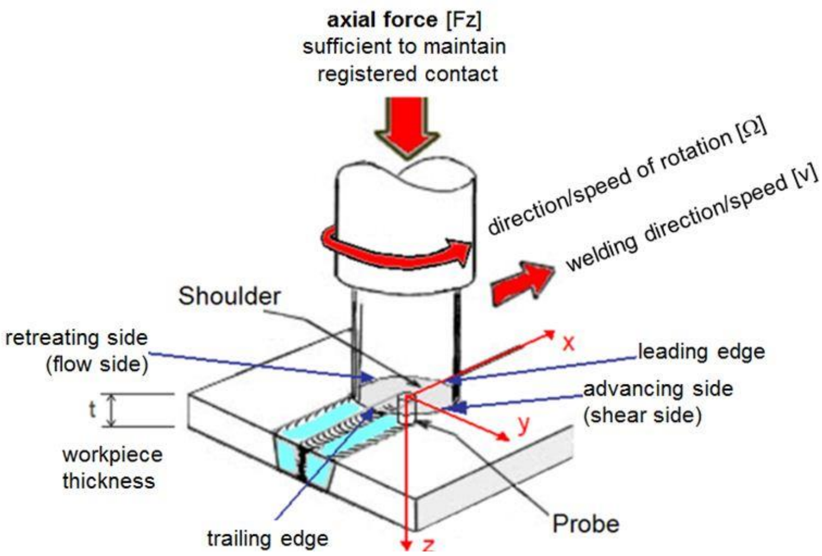
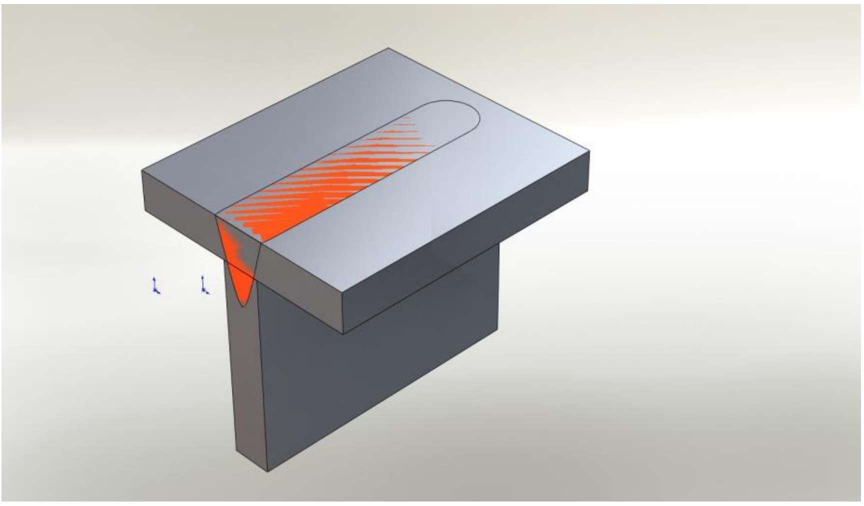

axial force [Fz]
sufficient to maintain
registered contact
direction/speed of rotation [Ω]
welding direction/speed [v]
Shoulder
retreating side
(flow side)
leading edge
x
advancing side
(shear side)
y
t
workpiece
thickness
trailing edge
z
Probe



Version SH/2

6 A manufacturing company underwent inspection by the Health and Safety Executive (HSE) and was found to be in violation of a number of safety regulations. The HSE ordered the company to do the following: alter some existing machinery to make it safer; purchase new machinery to replace old machinery; and relocate machinery to make safer passages within the factory. The HSE gave the company 33 weeks to make the changes. Failure to meet these changes within the timescale would result in the company being fined £300,000. The company prepared a project plan identifying the activities required and the estimated completion times. This data is shown in

Table **1**.

Table 1

Activity	Description	Predecessor	Time estimate (weeks)		
			Minimum (l)	Most Likely (m)	Maximum (h)
a	Order new machinery	-	1	2	3
b	Plan new physical layout	-	2	5	8
c	Determine safety changes	-	1	3	5
d	Receive equipment	a	4	10	25
e	Hire new employees	a	3	7	12
f	Make plant alterations	b	10	15	25
g	Make changes in existing machinery	c	5	9	14
h	Train new employees	d, e	2	3	7
i	Install new machinery	d, e, f	1	4	6
j	Relocate old machinery	d, e, f, g	2	5	10
k	Conduct employee safety orientation	h, i, j	2	2	2

Project crashing is a method for shortening project duration by reducing the time of one or more of the project activities to less than its normal activity time. After implementing project crashing, the project manager has calculated the cost of each activity, and estimated the mean duration of activities and their costs. This data is shown in Table 2.

(TURN OVER

Table 2

Activity	Activity duration after crashing (weeks)	Cost	
		Normal (£)	After crashing (£)
a	1	100,000	101,000
b	2	1,000	3,000
c	1	500	750
d	4	500	1,500
e	3	1,500	1,800
f	10	5,000	8,000
g	5	500	1,500
h	2	2,500	3,000
i	1	5,000	6,000
j	4	5,000	5,500
k	2	1,000	1,000

(a) Construct the project network and determine the expected project duration without project crashing. [40%]

(b) Calculate the risk to the company arising from missing the deadline posed by the HSE without crashing the project. [30%]

(c) Assuming that the variances of activity duration remain the same after crashing the project, identify the activities that must be crashed to achieve the best cost-risk balance. [30%]

(a) The mean duration and the variance of activity durations can be calculated by the following equations:

Mean duration $t = \frac{l+4m+h}{6}$

Variance $\sigma^2 = \left(\frac{h-l}{6}\right)^2$

The results are shown in the table below:

Activity	mean	variance
a	2.00	0.11
b	**5.00**	**1.00**
c	3.00	0.44
d	11.50	12.25
e	7.17	2.25
f	**15.83**	**6.25**
g	9.17	2.25
h	3.50	0.69
i	3.83	0.69
j	**5.33**	**1.78**
k	2.00	0.00

Use the mean times to calculate the earliest start, earliest finish, latest start, latest finish times, and the slack of each activities, the results of which are shown in the table below.

Activity	mean	ES	EF	LS	LF	Slack
a	2.00	0	2.00	7.33	9.33	7.33
b	**5.00**	**0**	**5.00**	**0.00**	**5.00**	**0.00**
c	3.00	0	3.00	8.67	11.67	8.67
d	11.50	2.00	13.50	9.33	20.83	7.33
e	7.17	2.00	9.17	13.67	20.83	11.67
f	**15.83**	**5.00**	**20.83**	**5.00**	**20.83**	**0.00**
g	9.17	3.00	12.17	11.67	20.83	8.67
h	3.50	13.50	17.00	22.67	26.17	9.17
i	3.83	20.83	24.67	22.33	26.17	1.50
j	**5.33**	**20.83**	**26.17**	**20.83**	**26.17**	**0.00**
k	2.00	26.17	28.17	26.17	28.17	0.00

The expected duration of the project is 28.17 weeks.

(b)

The critical path activities are those with zero slack: b-f-j-k
The variance of the project is 9.03 weeks (sum of the variances of the critical path activities)
The standard deviation of the project is 3.004 weeks
Hence the probability that the project will not be completed within 33 weeks = 0.054 (using standard normal distribution tables)
The risk to the company = 0.054 * 300000 = £16154

(c)

The objective here is to crash the activity on the critical path that incurs the least crash cost per unit time such that the crash cost does not exceed the risk reduction. The critical path activities are b-f-j-k. The approach is to crash the activity that incurs the minimum cost per time to crash.

Activity	Crashing cost per unit time
b	**666.67**
f	**514.3**
j	**375**
k	NA

The first activity to crash is activity *j* with an additional cost of £500, reducing the expected duration of the project by 1.33 days. The risk to the company is now reduced to £6019.76.

The next activity to crash is activity *f* with an additional cost of £3000, reducing the expected duration of the project by a further 5.83 days. The risk to the company is now reduced to £9.75.

Crashing activity b now would be more expensive (it would cost the company £2000) compared to the residual risk involved. Hence the company should not crash any more activities.

This question was high scoring for the majority of candidates. Almost every candidate answered part a correctly, and most made very good attempts at part b and c. The methods employed were clearly well understood by most candidates, although marks were lost for errors in the calculations.

END OF PAPER