2013 Manufacturing Engineering Tripos Part IIB
Paper 1 Examiner: Prof Duncan McFarlane

Exam Sample Solutions

Question 1

(a)

(i) Closed-die hot forging: cut billet to correct mass/volume for final component; heat to appropriate forging temperature (avoid overheating which will lead to enhanced grain growth and even local melting); lubricate dies/billet with e.g. graphite; forge between dies; repeat process with different pairs of dies to achieve final shape. Large number of forging steps (e.g. up to 10) may be needed to achieve final shape in some applications. Dies may be pre-heated to reduce local cooling of part.

PM processing with uniaxial pressing: blend metal powder with alloying elements, lubricant, wax binder; fill die; press powder in die (may involve complex motion of multiple punches/dies to achieve uniform density; eject part from die; (optional green machining for additional features); sinter in belt furnace.

(ii) Hot forging would be used for gas turbine disc, and PM route for automotive windscreen disc. Reasons: very large difference in size of part – turbine disc O(10) – O(100) kg whereas windscreen disc O(10) g. PM limited by size of press to ~ 1 kg max. so would be impossible for turbine disc even if quality were acceptable (which it would not be). Production volumes very different – O(100) for turbine disc, O(10^5) for automotive. Turbine disc is safety critical, so need exceptional fatigue strength and integrity, achievable by well-controlled forging; automotive part can be conservatively designed to tolerate range of properties, not safety-critical. Cost is paramount consideration for automotive, whereas performance paramount for turbine disc.

(iii) Materials &Processing Steps:

<u>turbine disc</u>

Materials : Ni-based superalloy.
Processing Steps: very important that non-metallic inclusions are minimized to achieve maximum fatigue life, so alloy would be vacuum melted (VIM = vacuum induction melting) and electroslag remelted (ESR) before casting as billet before forging. The disc blank would be machined after forging to remove chill zones in contact with dies (which would have poor microstructure), and further machined to achieve final shape

<u>windscreen disc</u>

Materials: low alloys steel (Fe + graphite + ~4% Cu for PM blend) for .
Processing Steps: The windscreen disc would not need any mechanical processing after sintering but might well be electroplated (e.g. with Ni) to avoid corrosion in use.

(b) Possible reasons for deviation from intended shape:

- error in the dimensions of the mould cavity;
- residual stresses caused by differential thermal contraction, anisotropy induced by flow orientation of polymer chains,
- differences in crystallinity in different regions of the part due to differences in cooling rate.

Could investigate by:
- accurate measurement of mould (e.g. using CMM);
- cutting part to see whether distortion changes (to detect residual stresses),
- possibly with use of strain gauges on surface;
- if transparent, use polarized light to detect optical birefringence – to show anisotropy and/or residual stresses;
- measure density of small pieces cut from various regions of component to detect variation in crystallinity;
- use computer modelling to study heat flow during cooling to detect regions with anomalously high or low cooling rates; (candidates may have other suggestions).

Various solutions can be suggested depending on the origin(s) of the distortion (and there may be more than one).
- Process conditions might be changed, for example by changing injection pressure, melt temperature, mould temperature, hold-on time, cycle time.
- Mould design might be varied e.g. to change heat paths, cooling rates at various regions.
- Polymer might be changed, radically or simply by use of a different grade.
- A straightforward approach, if the process is otherwise well controlled and reproducible, may be to modify the mould cavity so that the final product conforms to the intended shape even though the cavity does not: i.e. accept that some distortion of the part is inevitable.

Question 1

a) Three possible material options are: [name/properties/uses]

(HDPE) which is the most widely used resin for plastic bottles.

- This material is economical, impact resistant, and provides a good moisture barrier.
- HDPE is compatible with a wide range of products including acids and caustics but is not compatible with solvents. It is supplied in FDA approved food grade. HDPE is naturally translucent and flexible. The addition of color will make HDPE opaque although not glossy.

(LDPE) is similar to HDPE in composition.

- It is less rigid and generally less chemically resistant than HDPE, but is more translucent. LDPE is significantly more expensive than HDPE.
- LDPE is used primarily for squeeze applications.

PET

- provides very good alcohol and essential oil barrier properties, generally good chemical resistance (although acetones and ketones will attack PET) and a high degree of impact resistance and tensile strength. The orienting process serves to improve gas and moisture barrier properties and impact strength. This material does not provide resistance to very high temperature applications—max. temp. 200 °F (93 °C).
- **(PET)** is commonly used for carbonated beverage, water bottles and many food products.

<u>Other answers may include the following</u>, although these are less common

(PVC) is naturally clear, has extremely good resistance to oils, and has very low oxygen transmission. It provides an excellent barrier to most gases and its drop impact resistance is also very good. This material is chemically resistant, but it is vulnerable to solvents. PVC is an excellent choice for salad oil, mineral oil, and vinegar. It is also commonly used for shampoos and cosmetic products. PVC exhibits poor resistance to high temperatures and will distort at 160 °F (71 °C), making it incompatible with hot filled products. It has attained notoriety in recent years due to potential health risks.

(PP) is used primarily for jars and closures and provides a rigid package with excellent moisture barrier. One major advantage of polypropylene is its stability at high temperatures, up to 220 °F (104 °C). Polypropylene is autoclavable and offers the potential for steam sterilization. The compatibility of PP with high filling temperatures is responsible for its use with hot fill products. PP has excellent chemical resistance, but provides poor impact resistance in cold temperatures

(PS) offers excellent clarity and stiffness at an economical cost. It is commonly used with dry products including vitamins, petroleum jellies, and spices. Styrene does not provide good barrier properties, and exhibits poor impact resistance.

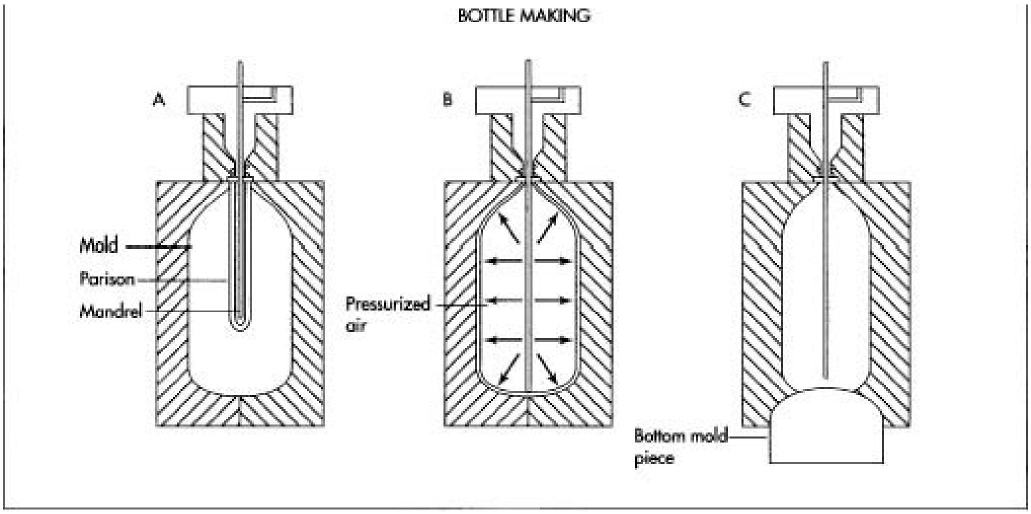
b)

PET has established itself worldwide as a material for the production of drinks bottles. As a thermoplastic, in this application (high pressure capability, i.e. gas permeability, complex shape, good looks, transparent etc), it offers numerous advantages

- It is easily moldable and thus allows production of individual bottle shapes
- It has good chemical stability – the drink may have long use by date
- It is lightweight – needs to be portable
- Bottles can be made completely from PET, which simplifies recycling considerably.
- Its crystallization level can be increased, thereby producing varying physical properties such as stiffness, and increased gas permeability. The higher the crystallization, the better the properties of PET in relation to gas permeability and resistance to heat and aggressive materials.

Hence it is suitable choice

c) Process Choice: Injection Stretch blow molding (IBM), aka Stretch Blow Moulding, but definitely NOT just Blow Moulding



The molten PET is fed into a manifold where it is injected through nozzles into a hollow, heated perform mould. The perform mould forms the external shape of the bottle neck and thread, and more importantly, precisely gauges how much material will be used in the blow moulding stage to produce the finished bottle. The perform is clamped around a mandrel (the core rod) which forms the internal shape of the preform. The preform consists of a fully formed bottle/jar neck with a thick tube of polymer attached, which will form the body. The preform mould opens and the core rod is rotated and clamped into the hollow, chilled blow mould. The core rod opens and allows compressed air into the preform, which inflates it to the finished article shape. The preform is stretched with a core rod as part of the process. The stretching of some polymers, such as PET results in strain hardening of the resin, allowing the bottles to resist deforming under the pressures formed by carbonated beverages, which typically approach 60 psi after a cooling period the blow mould opens and the core rod is rotated to the ejection position. The finished article is stripped off the core rod and leak-tested prior to packing. The preform and blow mould can have many cavities, typically three to sixteen depending on the article size and the required output.

d) Mould tools in the case of ISBM would be manufactured using a high grade tool steel such as H10 or H13, the reasons for this choice are as follows

- The product will require a good surface finish, with high levels of transparency, therefore a high quality tool steel will be required to obtain and maintain the optical finish when subject to 1Million shots per year

- High hardness and toughness required for such a large volume requirement to minimize tool wear through repetitive pinching
- Easy to deliver complex features to the tool halves by machining in the annealed state, followed by heat treatment to transform the steels properties
- High chemical resistance to release agents used in the moulding process
- High heat conductivity for mould tool cooling and reducing cycle times (essential for such high volumes)

Question 3

(a) Primary Food Packaging functions and environmental benefits:

Function	Example	Environmental benefits of polymers
Product handling	Containers such as bottles, boxes or bags for loose goods and liquids.	Light weight. Can be tough. Flexible or rigid as required. Shrink-wrap is possible. Packaging closure can be obtained by heat seal.
Barrier; hygiene	Prevents contact between environment and product. Selective passage of gases (e.g. allowing cheese to ripen in package while keeping odour in). Protection from light.	Polymers have a range of barrier capabilities which can be tailored to the required function.
Mechanical protection	Impact-resistant packaging for fragile items e.g. egg boxes. Surface damage prevention e.g. shrinkwrap on cucumber.	Light weight. Versatile.
Increased product life	Barrier function; inert atmosphere; reduced handling.	Very significant reduction in food wastage achieved with small amounts of packaging material
Tamper-evidence	Sealed container (including bottles and bags). Pop-off tags. Improved quality assurance provides reduced wastage: customers can be confident that goods reach them in the same condition as they left the manufacturer	Easily incorporated into different types of plastic packaging
Information, advertising	Writing or pictures	Can be printed directly onto polymer

(b) End of Life Options for polymer food packaging:

1. End-of-life process	Suitable waste streams	Energy and resource usage	Comments
2. Mechanical recycling	Clean, well-characterised waste streams such as bottles from food use. Limited range of polymers allows reliable sorting.	Low	Environmentally beneficial for bottles. Some can be recycled to food use; most are downcycled.
3. Chemical or feedstock recycling	More mixed and impure polymers.	High	High volumes needed to be economic. Not favoured for packaging.
4. Energy recovery (energy-from-waste)	Most; chlorine-containing polymers excluded (because of decomposition releasing HCl gas)	Negative (energy recovered)	Must be carefully controlled to avoid e.g. dioxins. Legislation limits some waste streams. Public opposition.
5. Other material re-use (e.g. filler)	Cleaned mixed polymers	Variable; generally low	Potential for increasing amounts, but material value is low
6. Landfill	Any	Low	Landfill space is limited;

			taxes increasing. Not an environmentally favoured option.
7. Composting	Biodegradable polymers	Low	Polymer identification problematic. Polymers degrade in industrial systems but temperatures are not high enough in domestic systems. Industrial compost is low-quality.

Reasons for non economic viability of most packaging includes

- insufficient volumes
- cost
- degradation levels and lack of purity
- difficulty in sorting / differentiation of types
- consumer mentality limiting effectiveness of recycling

(c)

PLA is produced from maize (corn) by wet milling to produce glucose, fermentation to lactic acid then lactide, and then polymerization. Its properties can be modified so that the polymer can substitute for PS, PE, PP. It degrades by hydrolysis in commercial waste disposal operations, by composting (58º needed) and under anaerobic conditions (when is generates methane).

PROS

If the polymer is composted along with waste food, then there can be environmental benefits (avoids landfill). Also, the decomposability of the packaging enables the decomposition of the contents.

CONS

It is unlikely to degrade in the natural environment. It can contaminate a conventional polymer recycling stream because of difficulties with polymer identification. Production of the maize is agriculturally intense, so an environmentally questionable operation. It is a large-scale monoculture, requiring agrochemicals (e.g. pesticides), fuel for farming equipment, irrigation. The land requirements compete with food crops. The production of the polymer is energy intensive – comparable to production of conventional polymers.
The LCA for biopolymers is generally less favourable than for oil-based polymers.
It is not expected that enough maize could be grown to substitute for conventional polymers in commercial food packaging. The competition with food production agriculture is a major worry here.

Question 4

(a)

Programmed maintenance (or planned/preventive maintenance) is maintenance planned and done at regular intervals on a continuous basis, intended to repair the slow degradation before it leads to failure, and to restore the plant to its undegraded state.

Response maintenance does still include a small level of programmed maintenance work (lubrication is an example) but most effort is put into having a well structured response mechanism that handles failures of all kinds.

The factors that determine whether or not programmed maintenance is called for are:

- cost of programmed maintenance
- probability of failure (failure rate)
- cost of unforeseen/unplanned failure
- cost of unplanned maintenance
- cost of holding spares (response maintenance might require holding of more spares)

(b)

standard response, when an item fails, engineers go and establish the scope of the problem and needed response, and produce a scoping report, by mid-day on the day of the failure. They then schedule the repair for 5 days from the failure date, and order the necessary resources to do the repair. On the repair date the repair team execute the repair with no disruption. The plant is then handed back to operation.

imperative response is still planned before execution begins. When an item fails, the work is scoped, the resources are ordered and the repair is planned, but an imperative response is allowed to override other work to draw people to complete it in faster than the 5 days of the planned response work.

The decision between the two responses is made by

- comparing the cost of "creative maintenance", i.e., extra cost incurred in speeding up the maintenance process to the total cost of production + maintenance.
- Other considerations include environment and safety issues.

(c)

(i) The task duration time can be obtained by using the critical path method. The **Critical Path** is longest sequence of activities in a project plan which must be completed on time for the project to complete on due date. An activity on the critical path, by definition, cannot be started until its predecessor activity is complete. If the critical path is delayed for a day, the entire project will be delayed for a day. If a day is removed the entire project will be completed a day earlier unless another path becomes critical.

The critical path for this question is A-B-C-F-G. Hence the task duration is 6.5 days.

(ii) This part requires thinking about a combination of approaches such as SMED, Critical Path, as well as maintenance. In order to reduce the task duration, we must first look at the critical path and focus on the activities in the critical path.

- The first point of investigation is to examine if any of the activities in the critical path can be moved “offline” – according to the SMED philosophy.
- It is easy to note that resourcing the spare part could potentially be done in advance of occurrence of any failure – if the cost/risk implications of carrying the spare is not prohibitive.
- If activities B and C can be eliminated from the critical path, the new critical path becomes A-D-F-G. We can now examine whether any of these activities can be done quicker (e.g., by adding more manpower). Again this should be done in due consideration to the costs involved – linking to the comparison between standard and imperative response.

Question 5

a) The following is a list of appropriate sensors that should be installed on the light switch production system:

(i) carousel

Location	Sensor Type	Functionality / Operation
Carousel	Incremental shaft encoder, referenced from an inductive sensor at a zero point.	Rotary Position of Carousel has to be determined to ensure that switch face plates are located correctly under work stations. It will also be necessary to keep status on individual carousel pockets as they may contain reject products that failed operations at particular stations.
Carousel (Station 3)	Retro reflective sensor. This type of sensor could be fitted at station 3 looking down onto the carousel. (Switch face plates are typically plastic)	Detect if the carousel fixture located at station 3 has components present. This may be an independent check carried out at station 3 or information may be sourced from the carousel and the high level control system.

(ii) robot end effector / screw driver

Screw Driver (Vacuum)	Vacuum sensor to be plumbed into controlled vacuum line connected to screw pick-up attachment.	This sensor would be used to detect an increased vacuum pressure generated when a screw has been picked up by the screw driver and the screw head is engaged on the screw driver bit. (In an error condition such as dropping a screw during robot motion this sensor would not be triggered at the final fastening location)
Robot/ Screw Driver (Slide-way top location)	Inductive proximity switch would be mounted to detect if screw driver is at the top of slide way motion.	This sensor would be used to detect that the screw driver was positioned at the correct height before a fastening operation is performed. (Once the robot has moved to the correct location for fastening operation this sensor should also be triggered)
Robot / Screw Driver (Slide-way bottom location)	Inductive proximity switch would be mounted to detect if screw driver is at the bottom of slide way motion.	This sensor would be used to detect that the screw driver has moved to a lower position at the end of fastening processes. (In an error condition such as cross threading this sensor would not be triggered)
Robot / Screw Driver (Motor Torque)	Current flow to motor will have to be detected or micro switch added to mechanical torque clutch.	This sensor would be used when the fastening operation had reached the required torque setting. (In an error condition such as cross threading this sensor value could be crossed checked with the slide way location of the screw driver. In the case of stripped threads a timer function would also be required)

(iii) screw feeder

Screw Feeder (Buffer)	Inductive proximity Switch. Mounted on the plastic side wall of the screw buffer. (Presence of metallic screws would trigger sensor)	This sensor would be used to detect if the screw quantity in the buffer is low and a replenishment process needs to be triggered.
Screw Feeder (Pick-up Location)	Inductive proximity switch would be situated to detect the presence of a screw at the pick-up location.	This sensor would be used to detect if a screw is ready to be withdrawn from the screw feeder.

b) Testing the operation of a newly developed production system can be timely and repetitive. It’s critical that a structured test plan is developed to sequence and record test scenarios carried out, both for normal operations and error conditions. Typically test plans are broken down into a number of phases, these include:

Unit Test: (Units of automation that have a standalone capability are tested to ensure they operate correctly and at predicted level of performance. Internal error trapping and recovery processes perform correctly.)

Test	Test Type	Goal of Test
Error Condition Missed screw pickup	Unit Test	To test the operations of the robot and screw driver in station three. To ensure that three repetitive screw pick-ups are attempted before a non-recoverable error is flagged.
Normal Operation Cycle time of station 3	Unit Test	To measure the cycle time of station three. This would make use of a dummy part and representative robot motions to allow the performance of station 3 to be gauged and tuned before integration into the overall system.

System Test: (Units of automation are integrated together to allow system tests to be performed. This ensures that data and mechanical interfaces between units of automation work correctly. It allows system level behaviours and error recovery strategies to be tested. Critical to good system testing is a platform of robust unit testing, reducing the confusion and complexity of error debugging at a systems level.)

Test	Test Type	Goal of Test
Normal Operation Cycle time of station 1,2,3 & 4	System Test	To measure the overall production cycle time of station 1, 2, 3 & 4.
Error Condition Faulty part presented to station 3	System Test	To test the operation of station 3 when it is presented with a faulty assembled part from station 2. Station three should wait for carousel to be incremented to the next part.

Bonus: On commercial projects (less relevant in this case) two further levels of testing are undertaken to ensure that contractual performance agreements are achieved:
Factory Acceptance Test (FAT): System meets performance level at integrators factory.
Site Acceptance Test (SAT): System meets performance level at final factory site.

Question 6

a)

The purpose of a functional specification is to

- specify what the automation will achieve.
- It will form the basis of the contract between the automation vendor and the customer, and will form the basis for the acceptance trials.
- It will minimise specification creep and
- be a base from which requested changes during the project can be identified and appropriately costed.
- It forms the main means of communication between customer and vendor to minimise the chances of disappointment and/or nasty surprises!

b)

The functional specification should focus on what the system has to deliver, not on how this should be achieved. It should specify the

- form, quality and method of delivery of the incoming material, and the
- form and method of delivery of the finished product.

This will require iteration with the material suppliers and customers.

The following additional areas should be covered:

- The context within which the automation will operate, eg.skill levels of operators, reliability of interfacing equipment outside the control of the vendor.
- Cycle Time
- Some measure of availability, usually expressed as output over a specified period.
- Form and extent of manual intervention
- Scheduled periods of operation and maintenance
- Levels of defects, and what to do when defect is detected
- Error detection and recovery, recoverable and non recoverable errors. Form of error logging.

All the statements in the functional spec should be testable, and so vague wording should be avoided. For example, "The system should operate reliably" is not acceptable, some measure of reliability should be provided.

c)

Overall, this is a very poor FS. It starts OK by allowing the system vendor to specify how the raw material should be supplied and outlines the main function. It then deteriorates.

- What is 'Perfect alignment'?
- It also strays from the 'what' (the function to be performed) to the 'how'. This is bad practice The system vendor should be allowed to decide how the function is to be performed. For example, vision may not be the best way to ensure alignment.
- The next set of requirements are hopelessly specified. None of this is testable.
- What does efficiently mean?

- What are the shift lengths? Is this 3x8 hours i.e. continuous operation, or are there breaks? Does it include weekends? What time is allowed for maintenance? What is minimal manning?
- What constitutes a reject? Is this total scrap, or is it rework? What happens to a reject? Is it identified? Does the system carry on?

An improved spec. should be something like:
“The incoming parts will be supplied in a form to be specified by the system vendor. The system will assemble the cover plate to the main housing and secure with the specified bolts. Position, alignment and bolt fastening torques are to be as specified on the accompanying drawing. The system will operate with a cycle time of one minute, and achieve a minimum output of 55 units per hour, averaged over a 7.5 hour shift. The system should operate for three shifts, six days /week, and two shifts on the 7th day. The system should require no more than three manual interventions/hour, averaged over three shifts. The system should log any errors in alignment and any bolts not correctly torqued, should indicate an error situation and should pause operations awaiting manual intervention. ”