MET II 2010 P1 CRIB

1(a) production of CFRP

Outline: start with a bulk petrochemical: acrylonitrile. This is polymerised to form PAN which is then spun into fibres, which are then oxidized and carbonized, chemical processes that take up to 4 hours. The plants are relatively big: ~300 m long lines.

PAN fibre is produced from a concentrated solution ('dope') and the solvent is recycled which needs a lot of energy.

The spun fibre is wound into large 'cheeses' weighing 70 – 250 kg.

The PAN fibre is oxidized (burned) and stretched in air in a series of furnaces, for a long time (30 – 120 min) then heated further (800 – 1400 C) in nitrogen for a short period. It is then wound up on to reels (max size currently 20 kg).

Problems in increasing production volume of CF are investment in new plant. Typically takes 1-2 years and needs to match capacity for both polymer and carbonization. Danger of overcapacity if prediction of demand is wrong, with serious consequences for financing of new plant (not only does demand fall but price may also fall). Demand will not increase unless supply of CF is assured, but supply cannot be assured without demand – vicious circle. CF plants are usually ca. 1000 tonnes per year and cost about $30 million. Worldwide capacity is about 35,000 tonnes per year. It is possible to increase production through higher efficiency: eg increase line capacity, but there is a fundamental mismatch between the production rates of PAN (typically 400 m/min) and CF (400 m/h). There is effort to increase width of machines (but limited by need for manual threading of fibre, and needs stiffer rolls), reduce fibre breakage, automated reel handling, longer ovens etc. etc.

(b) Value for aerospace and automotive applications.

CFRP has benefits over more traditional materials such as steels (automotive) and Al alloys (aerospace) in terms of mechanical properties (stiffness, strength), density (and combination properties i.e. specific stiffness, specific strength). These have significant benefits for automotive but even more for aerospace where aircraft lifetime costs can be reduced substantially by reducing structural mass. It is also an advantage for some applications that CFRP in long-fibre form is anisotropic and so with appropriate design tools its properties can be tailored closely to the applied stress distribution (e.g. in an aircraft fuselage the stress due to internal pressure is predominantly in the hoop direction). In the automotive application the manufacture of body panels and substructures involves pressing of sheet metals with associated high tooling costs which favour high production volumes; CFRP in contrast is well suited to short runs or small production volumes as the moulds can be cheap and readily varied. Ability to make complex shapes as a single part from CFRP reduces the number of components, for example from 200 or so for a typical conventional car down to 30 or fewer for a CFRP version.

(c) Processes for manufacture of aerospace components from CFRP

Based on prepreg (preimpregnated fibre composite material) which consists of sheet or tape containing a high volume fraction of CF (either unidirectional or woven fabric) in a thermoplastic or (more usually) thermoset polymer matrix. The component is formed by building up layers of prepreg into a mould and then heating under pressure to bond/cure. Vacuum bagging and/or autoclaves used for curing. Laying the prepreg is done by hand or machine (e.g. automated tape layer, automated fibre placement).

Manufacturing process involves significant waste. During prepreg manufacture in solvent evaporation, cutting/forming prepreg (offcuts etc), backing sheet, shipping/handling aids, scrap parts. Waste in use mainly associated with repairs (as for manufacture) and disposal of damaged parts (as for end of life). Uncontrolled mechanical destruction as in an aircraft or car crash tends to produce small fine CF splinters which are hazardous; in automotive applications a Kevlar composite skin is sometimes used to contain these. End of life disposal of CFRP is very problematic as there is currently no practical method recovering the valuable element (i.e. long fibres) from CFRP, although it can be ground up to form a stiff filler for lower-grade composites. On the plus side, as CFRP tends to be used for high-performance, high-costs specialised applications (e.g. sports or racing cars, aerospace) waste material will be concentrated in small number of relatively sophisticated customers, so that access for recycling is easy. But the nature of the material especially with thermoset matrix means that recycling gives a low-grade product. Furthermore, while volumes remain small the drive to develop new recycling processes is not great.

(d) Barriers to increased use of CFRP in automotive and aerospace

Automotive: Cost (raw materials and CFRP manufacturing method) still very high compared with sheet metal; obstacle from massive existing investment in conventional pressed/welded steel (and to a much small extent Al alloy) body manufacturing; CFRP production methods not suited to high volume production (but much more suited to low volume, bespoke); recyclability very bad.

Aerospace: major limitation is availability of material which depends on CF industry being willing to invest in new plant, which in turn depends on forecast demand; need for design approval and structural safety assessments for new materials such as CFRP in a safety-critical and generally conservative industry introduces long delays in introduction of new materials

Comment:-

This was a popular and also predominantly very well answered question, with some excellent answers. In the weaker answers, the answers to the last part of the question (concerning barriers to increased use) were rather thin. An aspect missing from almost all answers was an appreciation that, whilst a single CFRP component might be a large and complex-shaped component, it itself is an assembly of a very large number of small "components" (pieces of cloth) into the mould and the "material properties" are directional and vary all over the component, emerging from this orientation and placement of the fibres through this placement process. An appreciation of the complexity of this would have given more understanding to the final part of the question.

2(a) There are several definitions of micromanufacturing. One is ‘manufacture of products whose functional features or at least one dimension are in the order of μm’. Another is ‘the creation of high-precision 3-D products using a variety of materials and possessing features with sizes ranging from tens of micrometers to a few millimeters’.

Two processes which are smaller-scale versions of conventional processes are micro-machining (e.g. micro-milling) and micro-injection moulding.

Micromilling uses very small end-mills e.g. down to 50 μm diameter. To achieve a reasonable cutting speed the rotational speed is up to 200,000 rpm – with a trend to even higher speeds. Some differences from conventional machining are:

- lubrication and cooling
    - we can no longer flood the cutting zone with coolant – need to use mist lubrication and gas cooling
- detection of tool breakage
    - a real problem as you can hardly see it and measurement of tool force is extremely challenging
- depth of cut effects
    - the tool edge radius is comparable with the depth of cut, so it appears ‘blunt’ with consequences for cutting force and surface finish
    - for depths of cut comparable with their grain size, materials are no longer ‘homogeneous’ and ‘isotropic’ with consequences for surface finish and dimensional tolerance

Micro-injection moulding of thermoplastics uses very small moulds and in order to achieve rapid cooling times and reduce scrap (from sprue etc.) tends to use separate stages for melting/plastication and shot injection (with a small diameter piston) in a small-scale machine. This gives a shorter cycle time, allows precise metering of shot size which is important as the part volumes are small, and since only a small amount of polymer is held at high temperature it reduces the effects of thermal degradation on the polymer.

(b) The suggestion appears to be that if the size of the components becomes smaller then the capital investment needed for manufacturing should also become smaller. There may be some effect in this direction, but it may well be counterbalanced by the need for greater precision, possibly high labour costs in part handling, inspection and assembly, possibly clean room environments etc. Automation is difficult for handling very small parts. Micro-injection moulding machines, micromachining centres etc are very specialised and require significant investment. So it is not at all clear than these processes will become ‘cottage industries’ – which tend also to include the implication that the customer is located close to the factory. Actually, transport costs for micro-manufactured parts may well be negligible, so that production location is less of an issue, unless the product is time-critical (e.g. for a bespoke medical or dental component). The production of micro-components is currently highly specialised and some processes are capable of very high production rates, so that a small number of manufacturers may be able to satisfy a large demand – again, in contrast to the implications of a ‘cottage industry’ composed of a large number of small producers.

Examples of processes which have high potential production rates are photochemical machining, photoelectroforming, micro-injection moulding (polymers but also metals and ceramics) and laser machining. Examples with low production rates, used for mould and die manufacture as well as for short production runs, are micro-machining, micro-EDM and LIGA. Any of these would be good examples to include in the answer. All demand quite high investment in precision, specialised equipment (with LIGA needing access to a synchrotron!) as well as highly skilled operatives – not at all compatible with usual concept of a ‘cottage industry’.

(c) (i) We have a short run, very high specification product, probably with cost not as important as performance, and which probably needs good tolerance and presumably also surface finish. Nickel components can be produced by electroforming or LIGA, and photochemical machining and EDM are also possible candidates. If EDM is used then the electrode could be made by LIGA or photochemical milling. Wire EDM would be unlikely to have sufficient accuracy (because minimum size of wire is ~30 μm). Micromilling would not achieve sufficient accuracy. Metal injection moulding would not be appropriate for such a short run. To decide between the options, we need to know what properties of the material are critical (e.g. strength/hardness, toughness, wear behaviour etc) and what manufacturing tolerances are (dimensions, surface finish) and then compare with the values associated with the various processes.

(c)(ii) Here we have a large batch of gears from a thermoplastic polymer – micro-injection moulding is the only feasible method. We need to know what mechanical properties, surface finish and tolerance are required, and select the grade of nylon, and dimensions and surface finish of the mould appropriately. The mould (probably steel) would have multiple cavities and could be made by various processes including micro-EDM, and/or micro-milling. Adjustments may well have to be made for dimensional changes due to shrinkage and/or internal stresses. For a medical application the grade of polymer would be very important and would have to be approved in this highly-regulated area: need to consider both the level of contact with the human body and the length of exposure time. There is a spectrum ranging from drug delivery (short-term, minimally invasive) to long-term implantable devices, and we need to know where this device lies in that spectrum: there is a defined range of classes from I (e.g. inhalers) to IV (long-term implants).

Comment:-

This was a popular question, mostly well answered. The second part of the question, which asked for a discussion of whether this technology would redistribute manufacturing as suggested in the quote, was on the whole not well answered and was the weakest part of the responses. In the third part of the question, suggesting process routes, there were many good and some very good responses but also some weak ones.

3(a) Numerous measures of performance are used to monitor the performance of a manufacturing company, from the highest aggregate level of corporate financial performance, down through many levels of detailed assessment of financial and technical performance at regional, plant, department and process level. Without forms of measurement and assessment a company has no idea how well it is doing what it wants to do.

Measures are no use unless they are meaningful and signal something that people can do something about. Thus they need to be organised and used as tools of management, not simply as processes that generate records that get filed away. So, visibility is an important aspect of performance measures, linked to accountability for the results they show, which in turn must be linked to the ability and authority to act to create good performance.

For measures to work there must be some reference frame that makes bad, average and best practice visible, as a range to assess one's performance against. The term "benchmarking" refers to this aspect of the process. Benchmarking can be carried out at different levels, for instance across different parts of a company, within a region, or world wide, across all the players in that industry, if the data is available (and it usually is). More perceptively, many operational aspects of manufacturing occur in all sectors of manufacturing. So it is possible to look at good practice in each particular aspect of manufacturing, not simply across one's own sector but across manufacturing as a whole. It is this sort of cross-sectoral benchmarking, carried out in detail with many visits and cross-learning, that enable details of best practice to be learnt and to spread. Things like the Baldridge Awards, and the European Quality Awards, are good reference points for this.

(b) The main elements of the benchmarking diagram are shown in figure 1. These show comparisons within a particular corporate group of sites, with the particular value of the site under discussion set as a stand-alone measure.

The framework of the diagram shows the industry-wide average and the industry-wide averages for the top 10% and top 25%, giving a wider comparison.

The different columns along the bottom are:-

Manufacturing value added
Delivery on time in full
Adherence to schedule
Customer complaints
Production rate

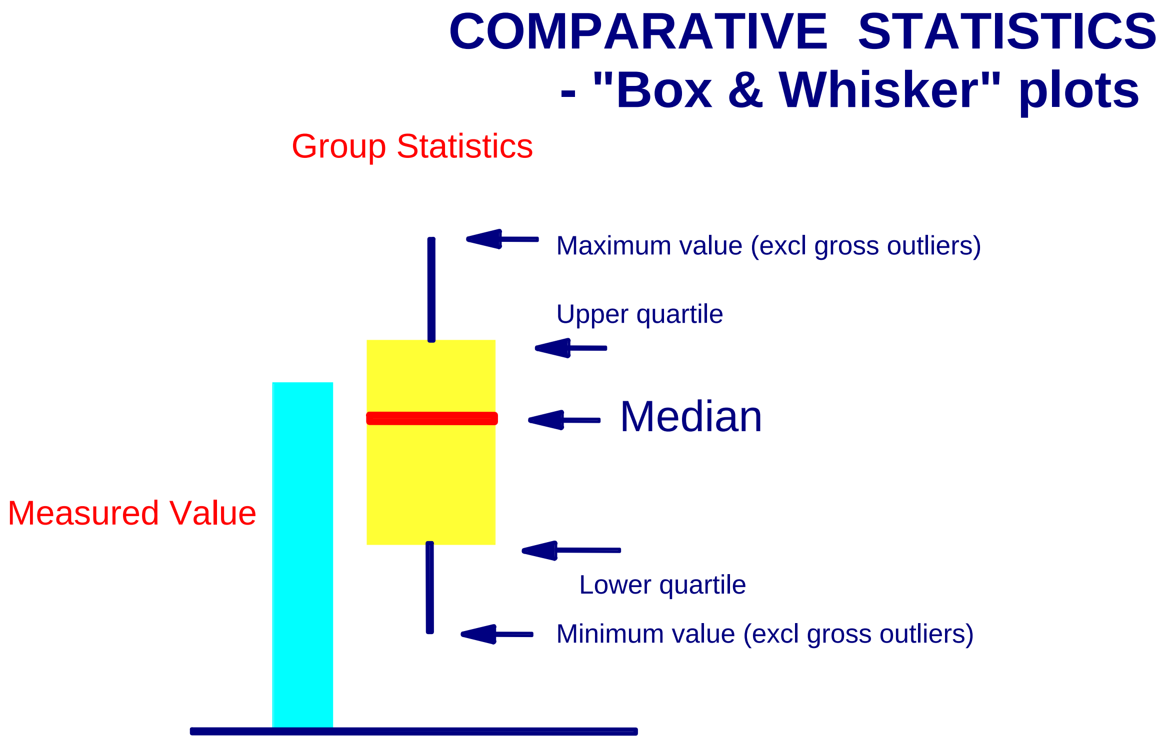

Figure 1

(c) The whiskers in figure 1 refer to maximum and minimum values excluding gross outliers, but the performance shown by the site in the question, in terms of adherence to schedule, is a gross outlier of bad performance, both by industry norms and company norms. It is also low in company terms on “on time in full” delivery – which is to be expected if there is very poor adherence to schedule. And also manufacturing value added is low. One might expect that there is a lot of unscheduled and expensive corrective work going on and at the root of that, seriously poor performance, perhaps due to poor organisation, or poor maintenance of equipment, so that nothing is produced as and when intended, but is produced late, after a scramble of fire-fighting work (which recurs and recurs and is a way of life.) The fire-fighting has to continue or nothing will get made at all, but effort needs to be put in over and above this to find and remove the causes of poor performance and unreliability.

Comment:-

Only 6 answered this question, with two very good answers and three of moderate quality, getting the general understanding but providing less detailed discussion of the different aspects of the question. One candidate had essentially failed to understand the structure of the diagram and thus provided a weak answer, containing misguided responses to the second and third part of the question.

4 (a) (i) All degradation of plant involves steady, and reasonably predictable, slow degradation and sudden, unpredicted failures. Programmed 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.

There is no way of knowing how “oversafe” this is, i.e. how much work is being done unnecessarily. So it is expensive. It does nothing to avoid the sudden, unpredicted failures, and there is no planned and structured response to these. Because the fire-fighting responses are unplanned they are disorganised and very inefficient, both in terms of lost production time and in terms of cost. The overall result is that both the “programmed” and the “fire-fighting” maintenance are expensive.

(a)(ii) 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.

Firstly there is a substantial amount of analysis done to identify different kinds of failure and the necessary equipment needed to respond to that failure, and fully prepared kits of tools, spares and so on are established and maintained so that whenever any failure occurs, the relevant kit if tools etc. is already prepared and available. There are also instructions as to how to do the necessary repairs. Thus, an important element of “response” maintenance is in fact very detailed and thorough planning. But in particular, the response to a failure first includes assessment and planning, and the response aims to repair the failure at an already allowed-for time ahead, so the work is not rushed.

(b) Part of the planning is a categorisation of failures into those needing an imperative response, because of the high financial loss of downtime, and those where some delay can be afforded to enable a well organised repair to be carried out.

In a 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.

An 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.

(c) The hurdle rate is the threshold cost that different failures will cause per day due to lost production, which is used to determine which failures are responded to as imperative. If a graph is plotted of total cost of “lost production costs plus maintenance costs of all failures” taken together, with the hurdle between standard and imperative responses set at different lost production cost levels, this will show as a graph of total cost set against the hurdle rate, assuming 5 days of delay in a standard response. The hurdle rate is set to give the minimum total cost.

Comment:-

Though there were some very good answers, this question was not well answered overall. Many had a poor understanding of “programmed” and “response” maintenance and hardly any understood Fawley’s development of the hurdle rate as a plant-wide measure used for dividing the whole site’s approach to maintenance to all incidents into pre-defined categories requiring “standard” or “imperative” responses.

5(a) (i)

The main transformation in components over this period has been the shift from thermionic valves as the active components to silicon based semi-conducting components, in the form of transistors and integrated circuits (ICs). The associated reduction in physical size and operating voltage has also resulted in the many other passive components, (resistors, capacitors, inductors, etc) also being reduced in size.

The greater integration of components, ie the increasing number of transistors and other components within a given physical space, has enabled many new forms of IC packaging. These include flip chips, chip-on-die, ball grid arrays (BGAs) and many others.

The passive components, and in some cases the ICs, have changed from being connected to the circuit by wire leads, to being surface mounted on the underlying circuit board.

(a)(ii)

The changes in component size and structure have partly caused, and partly enabled, many changes in circuit board construction (as opposed to point-to-point wiring, the so-called ‘rat’s nest’). The main one being the introduction of printed circuit boards (pcbs), which may have many layers of circuitry embedded within them.

Components are now assembled onto the board with automated placement machines, in place of the earlier hand fitting and hand soldering. Components with wire leads (either axial or radial in orientation) can be inserted into the circuit board automatically. Surface mount devices may be assembled at high speed (up to 100k components per hour) by vision-guided pick and place robots.

Soldering processes have also evolved in line with the changes in components. Wave soldering is used for components where the leads show through the board (the board rides over the wave of solder) and reflow soldering is used for surface mounted components. In this case solder past is applied to the location points of the components, the components are placed on the paste spots usually automatically, and the paste ‘reflows’ fixing the component to the board when passed through a hot oven.

Other process technologies that could be mentioned include component dispensing and testing, and circuit testing techniques.

(b)

The main material developments have been in the field of semi-conducting materials to make transistors. Originally germanium based, but now primarily silicon based, the performance of integrated circuits has increased exponentially in recent decades. Based on CMOS technology (complementary metal oxide semiconductor), this has been achieved by greater purity of the materials, decreasing line width in the circuits and better process control.

The increasing integration is described and predicted by Moore’s law, which says that the density of transistors in an integrated circuit doubles every two years.

Semi-conductors are also damaged by heat, and progress has been made in making components more heat tolerant. This is important with the introduction of lead-free solders (typically tin/copper/silver) for environmental reasons, which melt around 218 degrees C rather than around 188 degrees C for traditional tin/lead solders.

In the future Moore’s law will cease to apply as physical size can longer be reduced due to quantum effects and interference between adjacent circuit tracks or junctions cannot be managed effectively.

A further development is the introduction of polymer (or organic) based semiconductors. These have the advantage of low temperature manufacture, using processes that would not require the very large investment of the modern silicon fab.

(c)

Embedding software in an electronics product can greatly enhance its functionality, but may not be within the scope of expertise of many manufacturing businesses.

The key factors a company should consider are:

- is it in their business interest to outsource the software development (risk of loss of core knowledge)
- is the development task suitable for another company to carry out (can it be adequately specified)
- is the potential supplier capable of the job
- can a good collaboration agreement, ie contract, be set up

More details on these factors and the associated questions are contained in the software sourcing checklist given to the class.

Comment:-

A popular question with many good answers, some very good indeed, but also many of the answers having s poor sense of the technical developments that have enabled the miniaturisation of electronics and the automated production over time. There were much stronger answers to the part of the question related to the development of embedded software as an “element”, although it was not clear that there was good understanding about the development of the software itself. The general “feel” of the answers suggested a poor sense of what is involved in electronic hardware manufacturing.

6 (a) Short lead times require that we minimise the manufacturing throughput time. With traditional manufacturing routes, this is generally more a function of queueing and transport than of machining time. Customised components in small batches demands flexible automation.

The state of the art in CNC machine tool technology is embodied in machines which can manufacture a component from raw material to finish machined in one set up. This vastly reduces throughput times by reducing all the queueing, and transport associated with multi machine, multi set-up manufacture. With CNC control labour input is also significantly reduced. With automated loading and ancillary operations being handled by a robot labour can be almost eliminated.

In order to achieve one hit machining – 'done in one', the number of controlled axes has increased dramatically. It is now difficult to classify machine tools as machining centres, or CNC lathes as these two main types are becoming merged. Candidates should discuss in detail the state of the art characteristics of each.

CNC lathe. – will now typically have two driven spindles (C axis) to allow for both ends of a component to be machined. Each spindle will be under full CNC control allowing indexing to typically 0.0001 degree. Typical spindle speed of 5000 rpm allows high speed machining.
The x axis will typically carry a turret carrying 8-10 tools. There may even be a secondary turret which may have driven tooling.
There will be a milling spindle (B axis) capable of say 12,000 rpm . This will be supplied with an automatic tool changer.(20-40 or 80 tools are typical options) The B axis will be capable of rotating through a wide angle (again under full CNC control) This will enable face machining, milling drilling etc. It will likely be equipped with through spindle coolant to allow deep hole drilling. The high speed of the spindle allows the inclusion of grinding operations, and machines can have an optional wheel dressing facility built in.
Real advantage coming from the simultaneous, synchronised driving of multiple axes, this allows operations such as gear hobbing, cam milling etc which, in the past, would have been carried out on dedicated machines.
Advances to chuck design, using hydraulically driven pins to grip, enable almost all shapes to be held without custom designed tooling.
Advances in CNC programming using computer assistance allow for the rapid production of programs. Conversational programming for simpler jobs.
Automatic tool inspection, measuring and compensation on the machine to speed set up; sister tooling to cope with wear, breakage.

CNC Machining centre
Very similar approaches. The main table will likely be provided with a tilting and rotating precision table, providing A and C axis. Full CNC of X,Y,Z,A,C axes.
High speed spindles, large tool changers, 80 ,120 typical. Pallet changers to allow extended periods of unmanned operation.

The state of the art in robotics is primarily in smarter sensing and control systems, the basic mechanical configurations have changed little in the last 20 years. Specific areas of relevance here are to do with flexibility and safe operation.

- 2D and 3D vision can cope with part loading and unloading of varying components.
- Collision detection can prevent damage, important with unmanned operation with variable workpieces

- ‘Soft float’ can aid loading and part transfer, particularly if parts are passed robot to robot
- Force sensing – particularly useful for ancillary ops such as deburring.

(b)

Problem	Potential Solution
Work Holding: Integration of grippers, requirement for handling both raw material and finished product	Software handshaking, use of ‘soft –float’ function on robot, flexible grippers or reversible (multi) end effectors.
Robot dexterity and payload capability at extended positions	Correct choice of robot, ensuring sufficient axes and taking account of loads
Access to Machine	Motorised guards, sensing and interlocking required
Swarf clearance	High pressure air jet; coolant swarf separation, swarf conveyors
Control integration	If robot serves only one m/c tool, can be done through machine tool controller interfacing directly with robot controller. If multiple machines – plc control required.
Ancilliary operation (such as deburring) will probably require some form of sensing	Soft float
Transport to and from cell	Although not explicitly addressed in the question, the means of getting material and parts to and from the cells requires thinking about. In a fully automated system, a conveyor system or AGV will need integrating and this raises the level of complexity.
Errors	A major activity in integrating is to try to anticipate all the potential things that might go wrong, to put sensors in place to detect errors and to provide error handling routines. These may be automatic correction routines or may involve stopping the cell and requiring operator intervention

Comment-

Only three chose this question. There was one very good answer, recognising that an answer to the last part of the question (about inter-machine integration) needed to include both software integration and the development of co-ordinated operational instructions for all the elements of the machine tool and robot combination. One moderate solution drew on their own particular experience of getting machines to do this in the Robot lab. There was one poor response, in effect answering a different question for part of what is a very clearly worded question.

M J Platts 21 May 2010.