MET2
MANUFACTURING ENGINEERING TRIPOS PART IIA

Monday 25 April 2016   9 to 10.30

Paper 2

Module 3P2: OPERATION AND CONTROL OF PRODUCTION MACHINES AND SYSTEMS

*Answer **two** questions, one from each of sections **A** and **B**.*

*Answers to sections **A** and **B** must appear in two separate booklets.*

All questions carry the same number 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 cover sheet.*

STATIONERY REQUIREMENTS
8 page answer booklet x 2
Rough work pad

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper.

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

SECTION A

Answer ***one*** question from this section.

1 (a) Describe the four main categories of chip formation produced in orthogonal cutting. In each case, list the general machining conditions that lead to their production. [20%]

(b) Describe the main classifications of tool wear and discuss their causes. [20%]

(c) Sketch typical wear/time curves for a cutting tool from the initial point of use to the point of failure. Explain how this data can be used to define the characteristic of a particular cutting tool/component material combination. [20%]

(d) A steel ring shown in Fig.1, of outside diameter 600 mm and internal diameter 200 mm, is being face machined on a vertical CNC lathe. The machine is capable of maintaining a constant cutting velocity and the feed rate is set to 0.25 mm/rev. Using Taylor's empirical tool life relationship, determine the number of components that can be machined per tool for a tool life of 50 min. From initial tests, when V = 50 m/min, tool life T = 60 min, and constant n = 0.3. [40%]

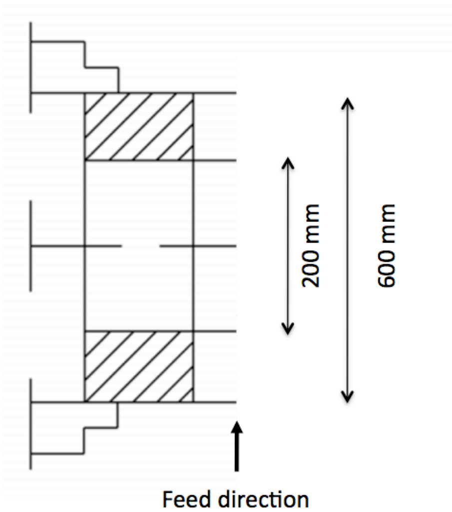
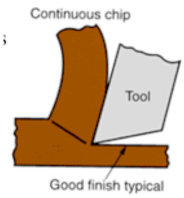


Fig. 1

Question-1 CRIB

a) Four main types:

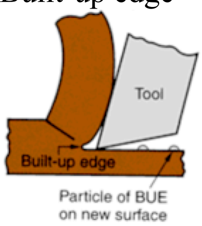
- Continuous



Continuous chips are formed by the continuous plastic deformation of metal without fracture in front of the cutting edge of the tool, with a smooth flow of the chip up the tool face. Formed under the following conditions:

i) Formed with ductile materials
ii) Machined at high cutting speeds
iii) Machined at high rake angles
iv) Machined at small feeds
v) Low tool/chip friction

- Built-up edge

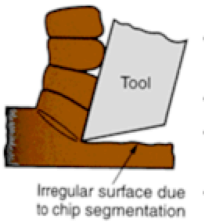


This type of chip is very similar to the continuous chip. With the difference that it has a built up edge adjacent to tool face. Consists of layers of material from the workpiece that are deposited on the tool tip. As it grows larger, the BUE becomes unstable and eventually breaks apart.

Formed under the following conditions:

i) Ductile materials
ii) Low to medium cutting speeds
iii) High tool/chip friction (wrong tool material)
iv) Low levels of cutting fluid

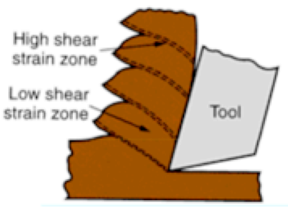
- Serrated or segmented



Serrated/Segmented/Discontinuous chips are formed by a series of ruptures occurring approximately perpendicularly to the tool face. Each chip element passing off along the tool face in the form of small segmented chips that may adhere loosely to each other. Formed under the following conditions:

i) Brittle workpiece materials
ii) Materials with hard inclusions and impurities
iii) Very low or very high cutting speeds
iv) Large depths of cut
v) Low rake angles
vi) Lack of an effective cutting fluid
vii) Low stiffness of the machine tool

- Semi/Discontinuous



Also called segmented or nonhomogeneous chips. They are semicontinuous chips with large zones of low shear strain and small zones of high shear strain (shear localization). Caused by cyclical chip formation. Formed under the following conditions:

i) Associated with difficult to machine metals at high cutting speeds such as titanium alloys, nickel-base super alloys, and austenitic stainless steels.
ii) Phenomenon also found with more common work metals (e.g., steels), when they are cut at high speeds.

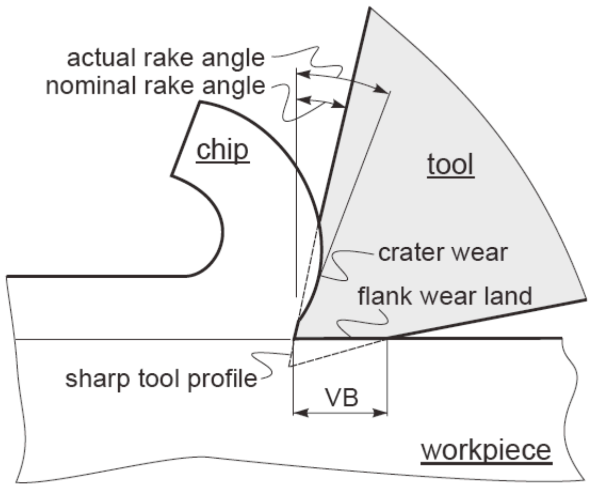
b) Cutting tools are subjected to:

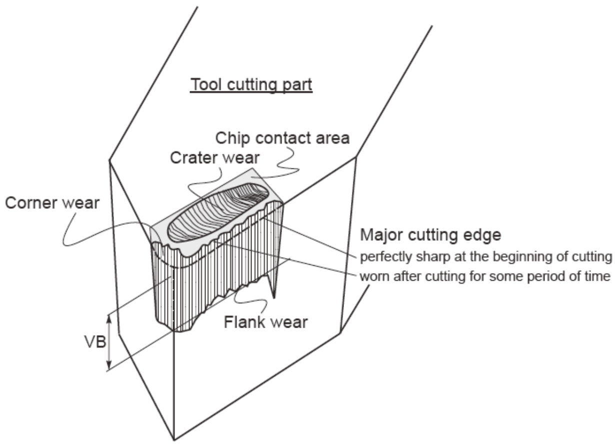
i) High localized stresses at the tip of the tool
ii) High temperatures

iii) Sliding of the chip along the rake face
iv) Sliding of the tool along the newly cut workpiece surface

These all cause tool wear which is a gradual process. The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids and the characteristics of the machine tool.

Tool wear and the changes in tool geometry are characterised as:





i) Flank wear

Occurs on the relief (flank) face of the tool

It is due to (a) rubbing of the tool along the machined surface and (b) high temperatures

ii) Crater wear

Crater wear occurs on the rake face of the tool.

Factors influencing crater wear are:

- The temperature at the tool–chip interface

- The chemical affinity between the tool and workpiece materials
- Diffusion rate increases with increasing temperature, crater wear increases as temperature increases
- Location of the max depth of crater wear, KT, coincides with the location of the max temperature at the tool–chip interface

iii) Corner (nose) wear

Corner wear is the rounding of a sharp tool due to mechanical and thermal effects. It dulls the tool, affects chip formation and causes rubbing of the tool over the workpiece.

iv) Notching plastic deformation of the tool tip

Tools also may undergo plastic deformation because of temperature rises in the cutting zone.

v) Chipping

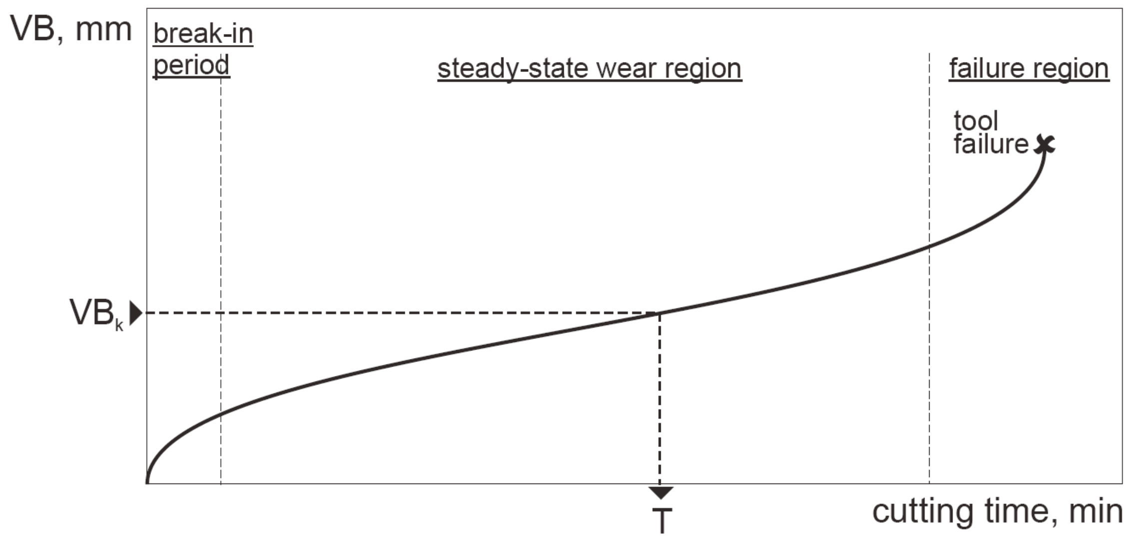
Tools may undergo chipping, where small fragment from the cutting edge of the tool breaks away. Chipping may occur in a region of the tool where a small crack already exists. Two main causes of chipping: Mechanical shock & Thermal fatigue

vi) Gross fracture

Tools may exhibit gross fracture (catastrophic failure) when subject to extreme conditions and excessive wear.

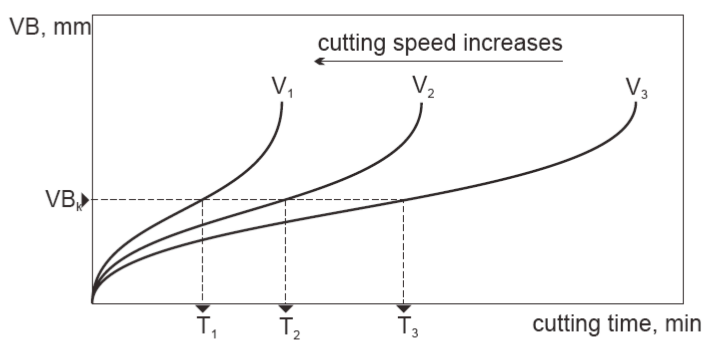
(cont.

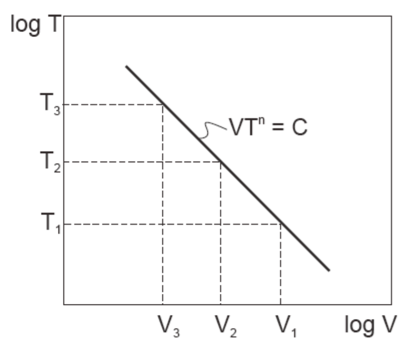
c)



Tool-life curves are plots of experimental data from performed cutting tests on various materials under different cutting conditions. Flank wear land VB is plotted as a function of time. The general relationship of VB versus cutting time is shown here (so-called *wear curve).* Although the wear curve shown is for flank wear, a similar relationship occurs for other wear types. The figure shows also how to define the design tool life T for a given wear criterion VB_k

Better answers will further explain the development of the data to show the effect of different cutting speeds. Where a log-log plot of the speed/life relationship is a straight line of slope 1/n, in which n becomes a defining characteristic of a particular cutting tool/component material combination. Where $VT^n=C$ is Taylor's tool life equation.





d) Given V = 50 [m/min]; T = 60 [min] and n = 0.3 and using Taylor's relationship $V.T^n = C$, we can calculate

$C = 50.\ 60^{(0.3)} = lg50 + 0.3\ lg60 = lgC$ or

$lg\ C = 1.69 + 0.3\ .\ 1.778 = 2.23$

C = 170.77

From figure.1 we calculate

$$\frac{\phi 600 - \phi 200}{2} = \left(\frac{D-d}{2}\right) = 200mm = S$$

At a feed rate of t = 0.25 mm/rev we will need:

$$n_1 = \frac{S}{t}$$

revolutions of the spindle (workpiece) to be able to machine the face of the ring, giving

$$n_1 = \frac{S}{t} = \frac{200}{0.25} = 800[rev]$$

Since according to the initial assignment, the cutting speed is constant V_c= const, then from Taylor's equation

$V.T^n = C$ and for T = 50 [min] we have

$V.50^{\ 0.3} = 170.77148$

V= 52.81 m/min

The tool path length between ϕ 600 mm and ϕ 200 mm is

$$S_1 = \pi(D-d)n_1$$

$$3.14(600-200).800 = 1004.8[m]$$

Note to examiner: there are of course other methods to calculate the same length: i.e finite sum; polar equation, or area method, where

$$S_1 t = \left(\frac{\pi}{4}\right)\left(D^2 - d^2\right)$$

$$S_1 = 3.412(360{,}000 - 40{,}000) = 1005.44[m]$$

The time T_1 required for a single workpiece to be machined by the tool is

$$T_1 = \frac{S_1}{V} = \frac{1004.8}{52.81} = 19.0266\,\text{min}$$

The number of components that can be machined is

$$N = \frac{T}{T_1} = \frac{50}{19.02}$$

N = 2.62 components

Examiners Comments

The most popular question, answered very well by some, reasonably well by others. Good understanding of chip formation was shown in addition to the machining conditions that lead to the various forms. High scoring candidates were able to give comprehensive lists of the machining conditions for each chip type. Tool wear classifications were well understood by the majority of candidates, with good answers supported by clear diagrams. Taylor's tool life curves were discussed comprehensively by high scoring answers, where cursory descriptions without diagrams scored poorly. A good proportion of the class successfully developed the tool life analysis, although some answers failed to correctly calculate the correct length of the face-cut in order to determine the number of components that could be machined for the given tool life. There was low level of detail in many answers in parts a), and b): candidates could often identify the categories, but failed to understand the key causes of chip formation or tool wear. The question was particularly difficult for those candidates that did not have a broad knowledge of machining.

2 (a) In studying the mechanics of orthogonal metal cutting, Merchant proposed a thin shear-plane cutting model. What assumptions did he base his model on? [10%]

(b) Using Merchant's circle, derive the force equations for friction force F, normal force to the rake face N, shear force on shear plane F_s and normal force to the shear plane F_n as functions of cutting force F_c and thrust Force F_t. [30%]

(c) Orthogonal cutting of steel is carried out with a rake angle of 10 degrees. The cutting speed is 200 mm/min and the chip thickness ratio is 0.31. The thrust force F_t and the cutting force F_c are measured as 1200 N and 650 N respectively. Using this data,

(i) Determine the validity of the shear-angle relationship suggested by Merchant, which is given as

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

where ϕ is the shear angle, β is the friction angle, and α is the rake angle. [30%]

(ii) What is the proportion of shear work to the total work done? [15%]

(iii) What is the proportion of friction work to the total work done? [15%]

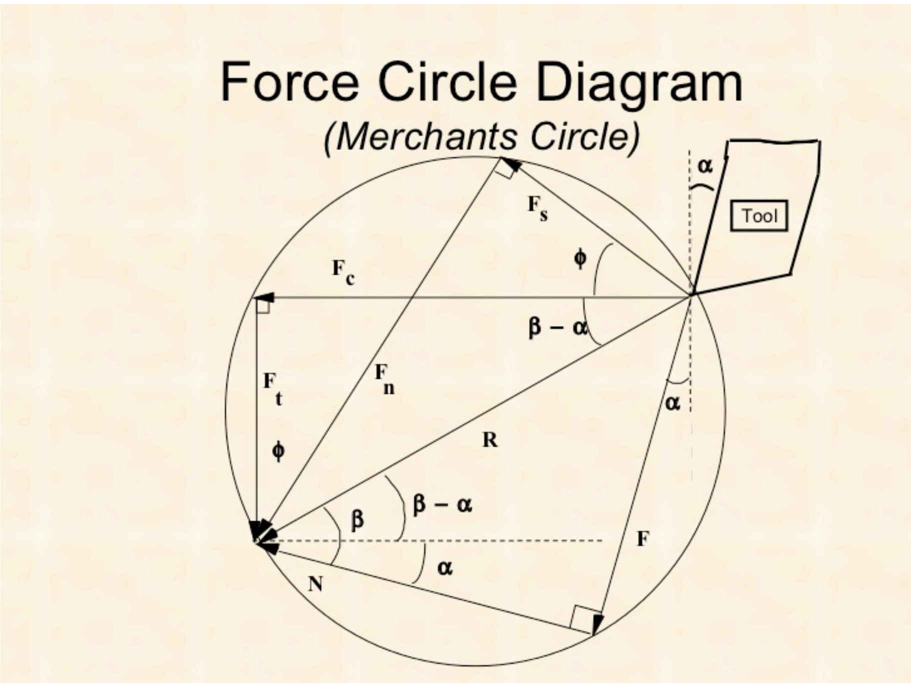
Question 2 Crib

a)

Merchant's assumptions were

1 The tool is perfectly sharp and has no contact along the clearance face
2 The surface of shear is occurring in a plane
3 The cutting edge is a straight line extending perpendicular to the direction of motion and generates a plan surface as the work moves past it
4 The chip does not flow to either side
5 Uncut chip thickness is constant
6 Width of the tool is greater than the width of the work
7 A continuous chip is produced without BUE
8 Work moves in a uniform velocity
9 The stresses on the shear plane are uniformly distributed
from
10 Shear angle φ adjusts itself to minimise work

b)



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From the force circle one can show through trigonometric relations that

$F = F_c \sin \alpha + F_t \cos \alpha$

$N = F_c \cos \alpha - F_t \sin \alpha$

$F_s = F_c \cos \phi - F_t \sin \phi$

$F_n = F_c \sin \phi + F_t \cos \phi$

To verify Merchant's shear angle relationship, which predicts the shear angle from the friction angle and rake angle, we must calculate the shear angle from known values, and compare it with his predictions. To do this we must also calculate the friction angle.

First let us calculate the shear angle that is given as

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} = \frac{0.31\cos 10}{1 - 0.31\sin 10}$$

Shear angle, $\phi = \tan^{-1}(0.32266) = 17.88^0$

The coefficient of friction μ at the chip tool interface is given by

$\mu = \dfrac{F}{N}$ and the friction angle b is given by $\beta = \tan^{-1}\mu$

Therefore we must calculate F and N

Where $F = F_c \sin \alpha + F_t \cos \alpha = 650 \sin 10 + 1200 \cos 10 = 1294.64$ N

And $N = F_c \cos \alpha - F_t \sin \alpha = 650 \cos 10 - 1200 \sin 10 = 431.75$ N

The friction angle β is then given by

$$\beta = \tan^{-1}\mu = \tan^{-1}\frac{1294.64}{431.75} = 71.56^0$$

Applying this value to Merchant's shear angle relationship gives

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) = \frac{\pi}{4} - \frac{1}{2}(71.56 - 10) = 14.22^0$$

This differs from the calculated value of 17.88, making the Merchant relationship some 20.5% in error.

Better answers will discuss the causes of violation of the model, i.e

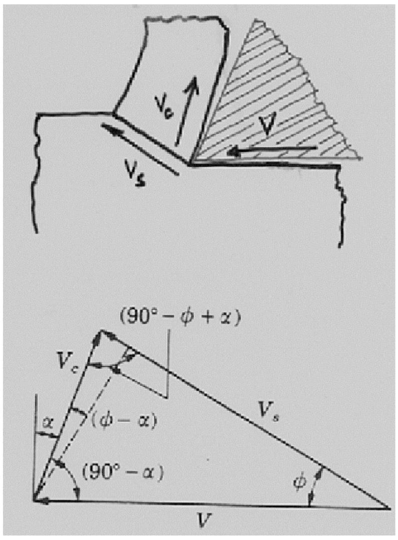
- Geometry and form violations (non zero angles of inclination, non-sharp tools, radius ends)
- Shear takes place over a volume not a plane
- Cutting is never continuous
- Cracks in the material which is not homogenous
- Size effect (larger stresses are required to produce deformation when the chip is small)

iii) Shear work done is

$$W_s = F_s V_s$$

We must therefore calculate V_s and F_s

From Velocity diagram, we can obtain equations from trigonometric relationships



$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos \alpha} = \frac{V_c}{\sin \phi}$$

In which case gives

$$V_s = \frac{V\cos\alpha}{Cos(\phi - \alpha)} = \frac{3.3 \times 10^{-3}\cos 10}{\cos(17.88 - 10)} = 3.31 \times 10^{-3} m/s$$

and

$F_s = F_c \cos\phi - F_t \sin\phi = 650 \cos 17.88 - 1200 \sin 17.88 = 250.2$ N

Which gives

$W_s = F_sV_s = 250.2 \times 3.31 \times 10^{-3} = 0.83$ Nm/s

The total work done is

$W = F_cV = 650 \times 3.33 \times 10^{-3} = 2.165$ Nm/s

Therefore the proportion of shear work to the total work done is

$$\frac{0.83}{2.165} = 0.3833$$ (38.34%)

iii) The proportion of friction work done to the total work is simply the remainder, i.e. 61.66%, since Power input $F_c.V$ = Shearing + friction.

Examiners Comments

A well-answered question, with relatively few takers. Those that chose this question were confident in their knowledge and were not put off by its analytical nature. Few candidates were able to offer comprehensive discussion of the model assumptions. The force equations were developed with the use of the force circle, with come candidates choosing the graphical approach. The numerical analysis was attempted well. The validity of the shear angle was tested numerically by most, with few candidates choosing to expand on the reasons for its violation. Some candidates used their value of ϕ from the Merchant's expression rather than the calculated value. Most marks were lost due to developing incorrect force terms, or lack of accuracy in the calculations.

SECTION B

Answer ***one*** question from this section.

3 (a) Industrial robots have been developed over many years to meet the needs of industrial applications. These developments have been in many areas including robot arm configurations, motion drive systems and on-board software systems.

(i) Discuss and compare the different approaches used for programming robots. [10%]

(ii) For three robot types with different degrees of freedom, discuss the influence that the robot's degrees of freedom will have on potential applications. [20%]

(iii) Why are more flexible, 'human-like' robots becoming more popular in industrial robot developments? [20%]

(b) A consumer electronics company is looking to purchase a robot to carry out packaging at the end of a washing machine production line. The robot is required to lift a 50 kg washing machine off the assembly line and place it into an open cardboard box on the pallet line. This will require a robot to have a reach of three meters and an axis speed of one meter per second. Fig. 2 gives a chart showing the characteristics of different types of robots. Examine the information given in Fig. 2 and determine the best type of robot for this task. Describe why you have chosen this type of robot, listing both the benefits and limitations that you have considered. What other information might you request to assist you in making your decision? [50%]

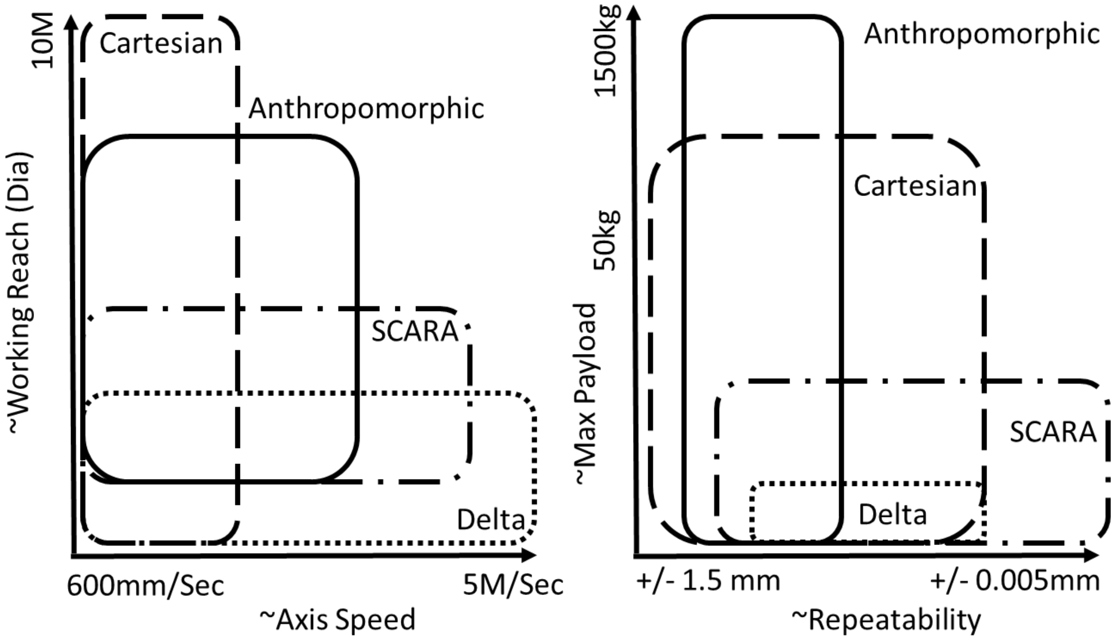

10M
~Working Reach (Dia)
Cartesian
Anthropomorphic
SCARA
Delta
600mm/Sec
5M/Sec
~Axis Speed
1500kg
50kg
~Max Payload
Anthropomorphic
Cartesian
SCARA
Delta
+/- 1.5 mm
+/- 0.005mm
~Repeatability

Fig.2

(Cont.

Q3 Crib

Answer

3ai) See table below

Techniques	Pros	Cons	Usage
Teach Mode	• Simple wide used technique. • No additional infrastructure required during programming.	• Time consuming and repetitive. • Limited automated testing and verification.	80% Most Popular (Assembly) (Welding) (Packaging)
Lead Through	• Mimics complex trajectories used by skilled operators (Paint Sprayer).	• Difficult to deal with Large Robots. • Inaccuracies in programmes can't be edited.	Small % Mainly Historic (Paint Spraying)
Off-Line	• Reduced down time during in programming. • Assists cell design and allows process optimisation.	• Requirement for accurate CAD models of instillation. • Accuracy of robot is critical when using off-line programming techniques.	20% Growing Usage Used to verify takt time. (All Areas)

(TURN OVER

3aii) Different robot styles have different degrees of freedom. A robots degrees of freedom relates to joint configuration. The number of degrees of freedom relates to the number of joint motions within the robot arm. (These motions can be both linear and Rotational). The greater the number of joints, the greater the degrees of freedom and the more dextrous (flexible) the robot is.

Applications:

Robot Type	Degrees of freedom	Application Features
Cartesian	3	Used for X,Y,Z motions of products and tools. No capability for rotating for skewing the product. Often used in basic packaging or material loading. (Heavy Payloads & large working volume)
Scara	4	Used for the X,Y,Z motions and rotation B of products and tools. No capability for skewing the product. Often used in electronic assemble operations. (Medium Payloads)
Anthropomorphic	6	Used for the X,Y,Z, motions and rotation A,B,C of product and tools. Often used in complex assembly and welding applications requiring high levels of dexterity. (Wide range of payloads & complex working volume)

3 aiii) Human like (Anthropomorphic) robots are becoming more popular in industrial robot applications because:

a) This type of robot is the most dextrous allowing it to carry out a wide variety of tasks. (Packaging, Assembly, Welding..)

b) Production systems and incorporated robots have to be as flexible possible to handle product change and customisation requirements.

c) They can have a longer operational life as they can be repurposed to a wide range of activities.

(Cont.

3 bi) Characteristics:

Robot Reach 3M, Payload 50Kg, Axis Speed 1M/s for these characteristics two robot types would be suitable for this task, Cartesian or Anthropomorphic. From the information provided I would chose a Cartesian robot.

Robot Style	Benefits	Limitations
Cartesian	• *Can handle heavy payloads*	• *May have limited rotary axis for rotating or skewing the product.*
	• *Has a big working volume*	• *Can require high ceilings to cater for Z Axis in the up position.*
	• *Good configuration for straddling equipment in the factory.*	• *Limited flexibility depending on wrist configuration.*
	• *Typically is a lower cost robot*	
	• *Less complicated to programme*	

Other information that would be required to verify this decision.

a) Will the washing machine need to be rotated or skewed during the packing operation?

b) What space is available for the robot installation / Operation?

c) What repeatability will be required in the packing operation?

c) Will the robot be required to carry out any other tasks?

<u>Examiners comments</u>

The question was answered well with a good spread of marks across each section of the question. The question tested candidate's knowledge of the 3P2 material. It could be seen from 3ai (Robot programming techniques) that candidates had the least clarity about Off-Line programming. 3aii (General Robot Types DoF & Applications) was answered well although candidates discussions on applications was limited. 3aiii. (The use of "Human" like robots) again was answered well with a good number of candidates adding additional knowledge of Collaborative robotics. 3b the majority of the candidates identified that either a Cartesian or Anthropomorphic robot could be used for the task specified. Extra credit was awarded for selecting a Cartesian robots due to its lower cost and simplicity.

The largest differentiator in candidate's answers was in discussions of benefits, limitations and additional information required for further system specification.

4 An aircraft manufacturing plant has a semi-automated riveting machine. The machine clamps two aluminium components A and B into position and then rivets the components together. The machine is fitted with a simple robot loader for loading the components. The loading sequence for Components A and B can be specified by an operator. The unload operation is carried out manually after the riveting operation is complete. The control system for the machine is being updated with a Programmable Logic Controller (PLC). The Petri Net for the machine control is given in Fig. 3.

(a) (i) Describe the function of the Petri Net state designated Robot Loader (S2). [20%]

(ii) Show how the Petri Net could be enhanced to ensure that Component A is loaded and clamped in place before Component B is loaded. Clearly describe the changes you are proposing. [20%]

(iii) The Robot Loader is also to be used to unload the riveted part once completed. Show how you would amend the Petri Net in Fig. 3 to allow for this. [10%]

(b) (i) Discuss the factors that need to be considered when converting a Petri Net to Ladder Logic for use in an automated manufacturing operation. [15%]

(ii) Convert the section of the Petri Net shown in Area A into Ladder Logic. [35%]

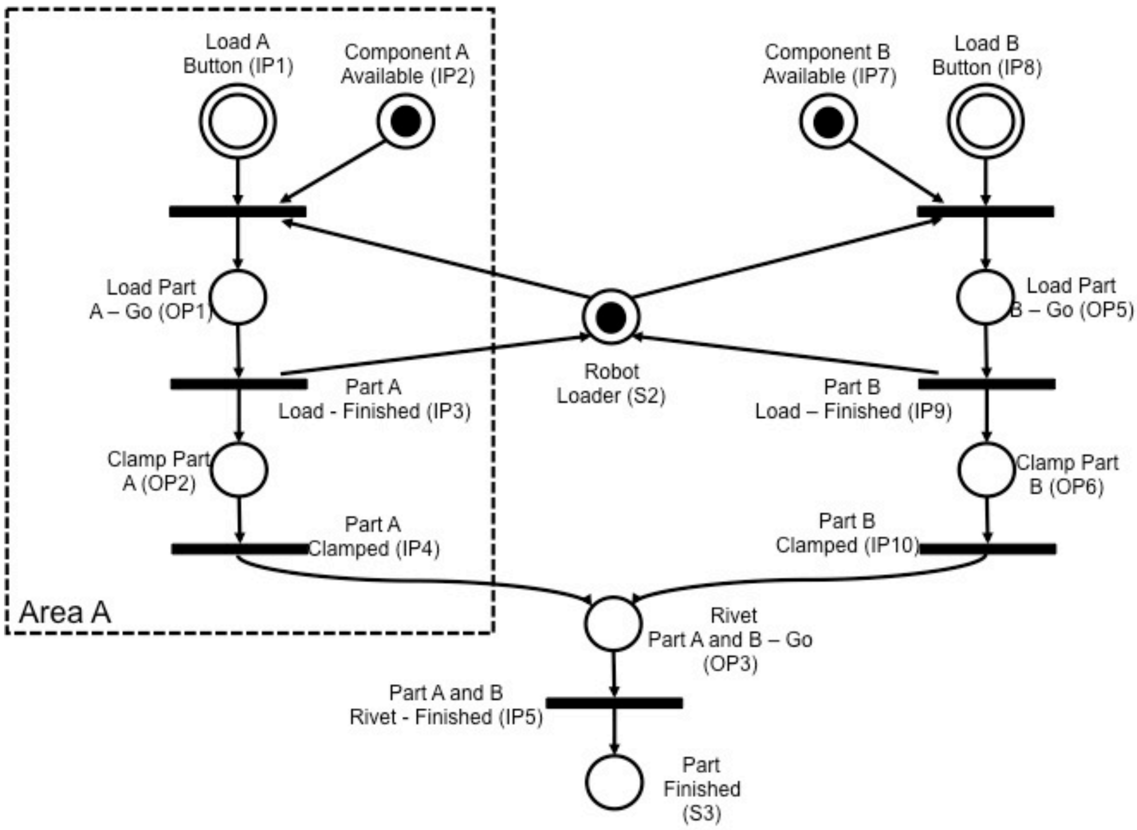


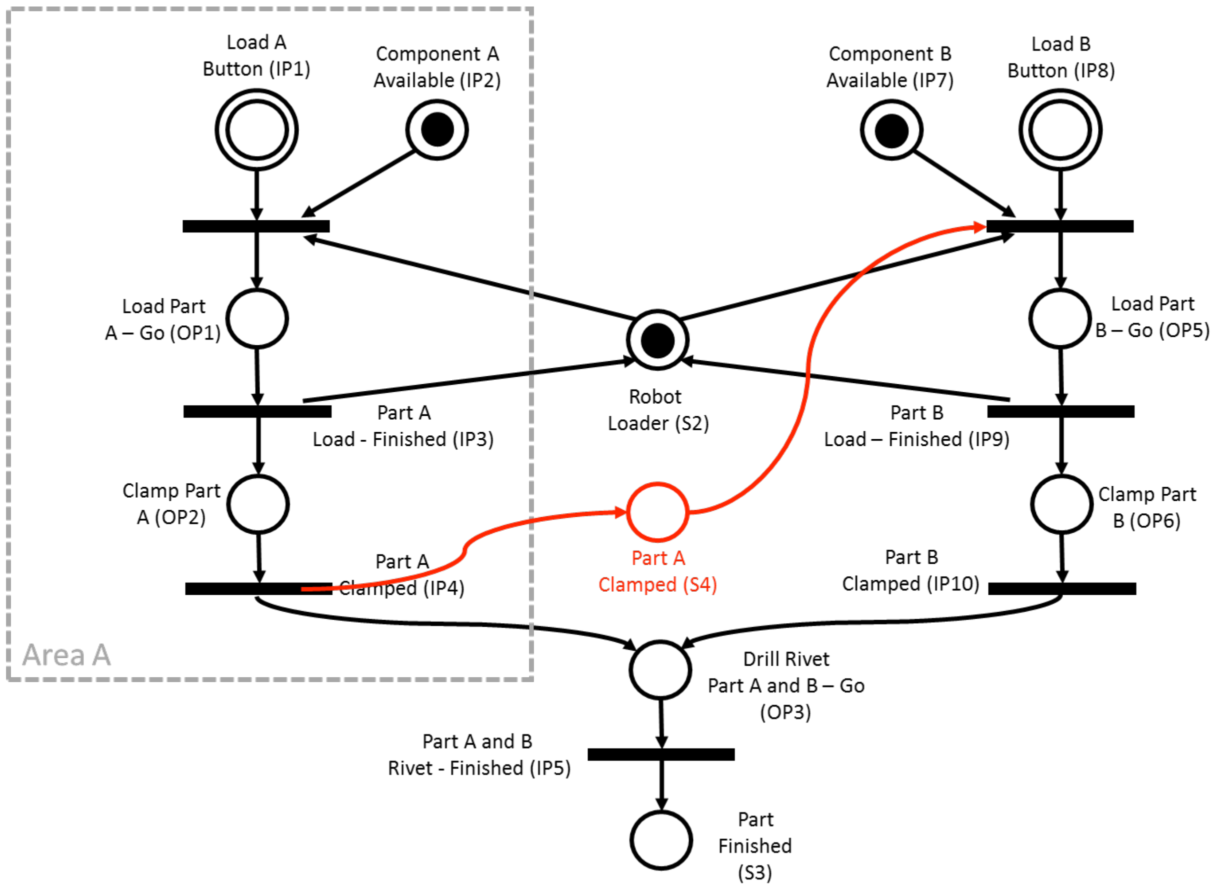
Fig. 3

END OF PAPER

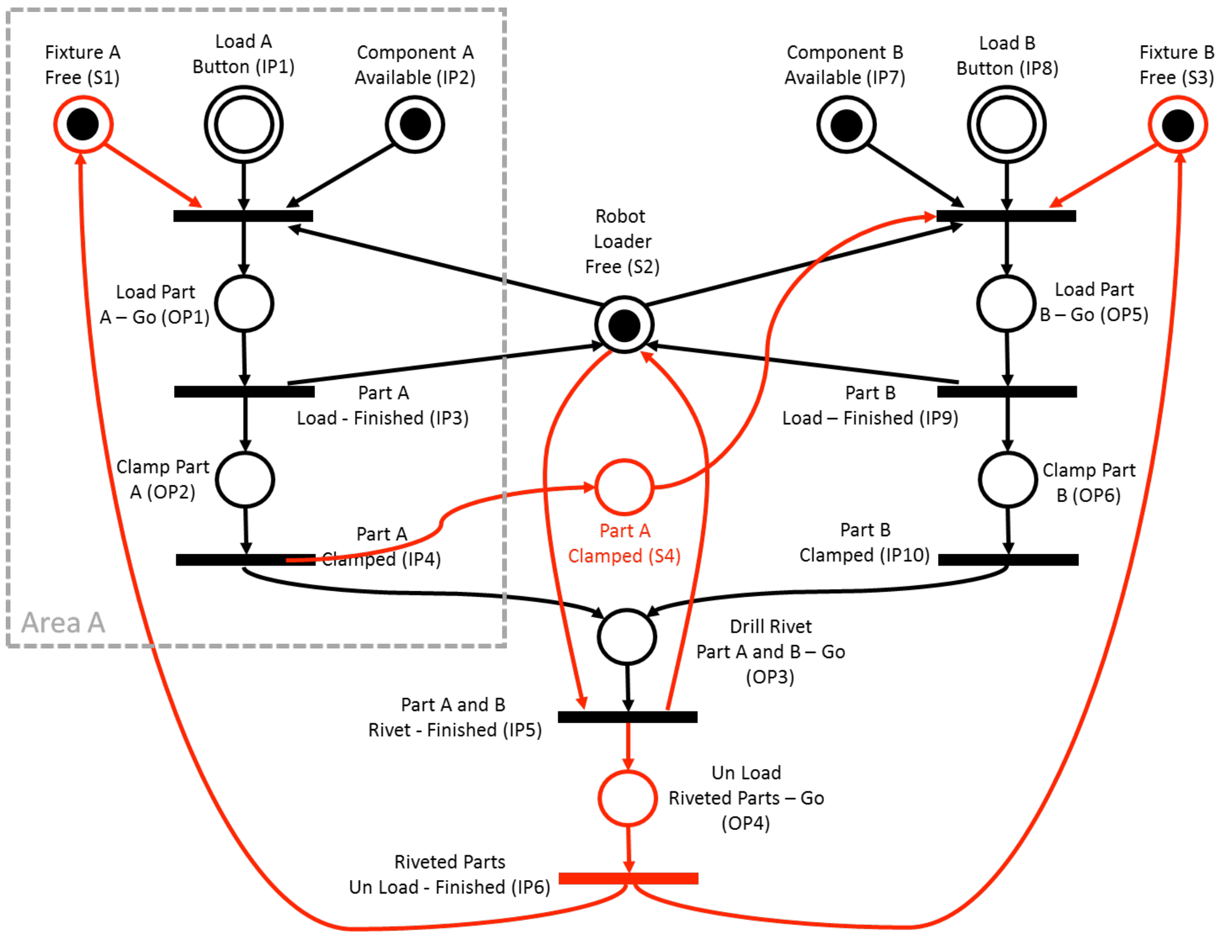
Q4 Crib

4 ai) The state (Robot Loader) has two functions, firstly it indicates that the robot loader is free to undertake a task and secondly it ensures that both load cycles cannot be run simultaneously.

4 aii) The petri net could be modified as shown below. Effectively adding an additional condition (Part A being Clamped) prior to (load part B) being carried out.



4 aiii) The petri net could be modified as shown below. Effectively adding additional place to perform the unload operation as well as linking back to the initial places for load operations. The Robot Loader place has also been linking into the unload operation to eliminate resource contention between load and unload operations.



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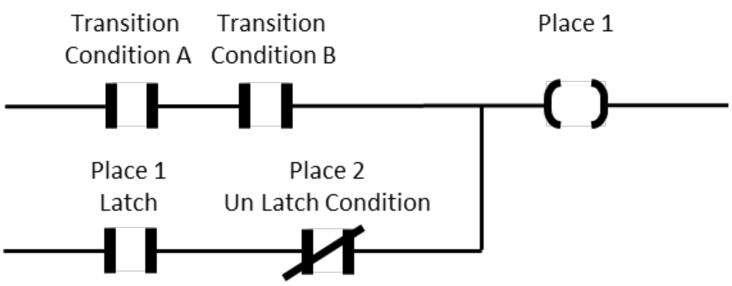
4 bi) The following considerations have to be made in converting a petri nets to ladder logic.

a) Ensure that the logic within the petri net is correct and it provides the correct functionality keeping in mind. (Start Conditions, Deadlocks, Conflicts, Suitability for continues operations).

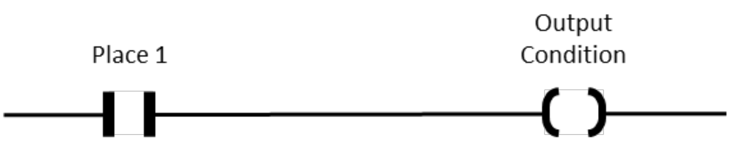
b) For each of the elements within the petri net, identify related variable conditions. Transitions need to be mapped to specific external triggers [I/O Input's and their states]. Places need to be mapped to PLC memory locations [associated variables]. Places also need to be mapped to external actuation signals [I/O Output's and their states].

c) Petri Nets are converted into ladder logic in two phases i) Building latch logic to activate a place when transition conditions are meet. This logic is designed to unlatched when a subsequent place becomes valid. ii) Output logic is then built to check for place conditions becoming true and then firing relevant outputs. By handling input and output conditions in this way we eliminate race conditions associated to PLC scan cycles. (Examples of this logic can be seen below)

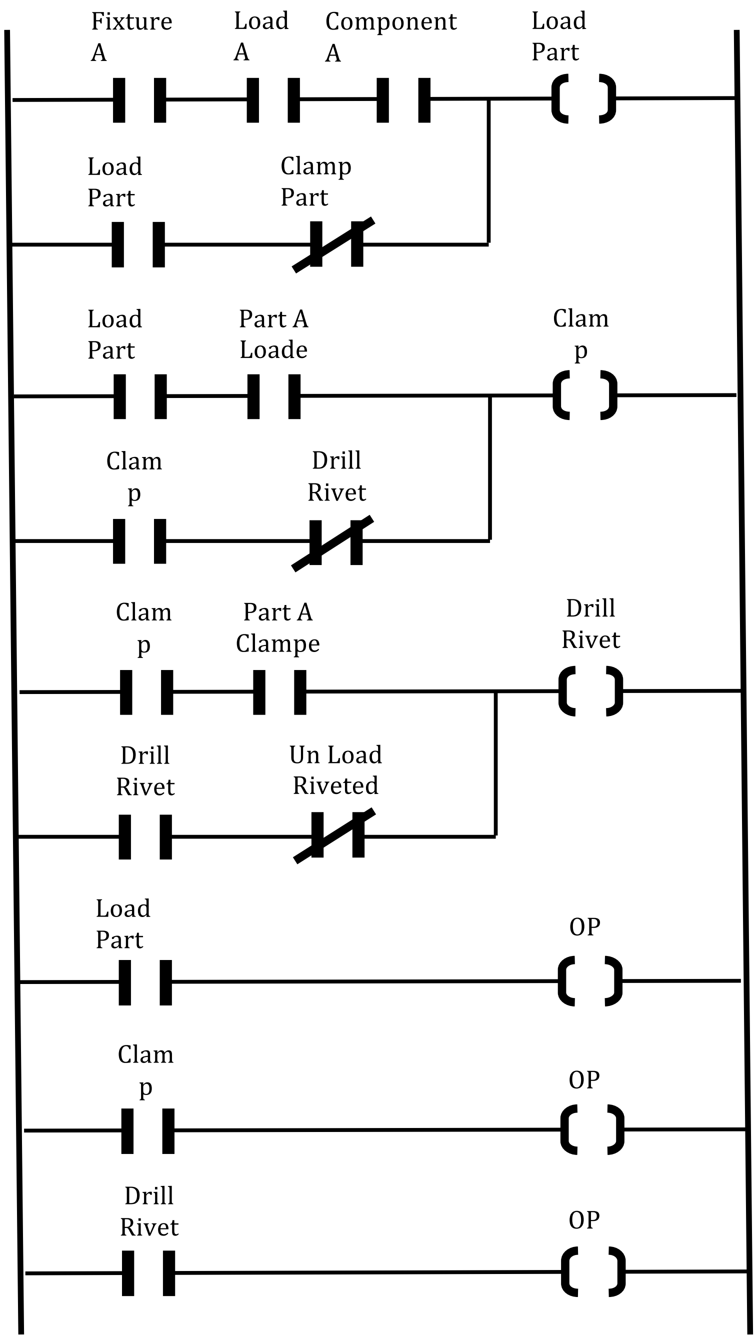
Ladder Code for activate a place (State).



Ladder Code for triggering outputs once a place (State) is active.



4 bii) Petri Net in Area A converts to the following Ladder Logic.



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Examiners Comments

The question was answered with a good spread of marks across each section of the

question. 4ai (Describe the function of the petri net state (S2) designated Robot Loader) all candidates could understand a petri net diagram and that state S2 was used for conflict control. In question 4aii and 4aiii (modify the petri net to ensure Component A is loaded and clamped in place before Component B) and (modify the petri net so that the Robot Loader is also used to unload the finished riveted part) a very mixed response was provided by candidates. The modification of a petri net to allow for new logic was challenging. 4bi (Discuss factors that need to be considered when converting a Petri Net to Ladder Logic) had a good response from candidates with varying levels of discussion. 4bii (Converting a petri net shown into ladder logic) again had a very mixed responses from candidates.

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