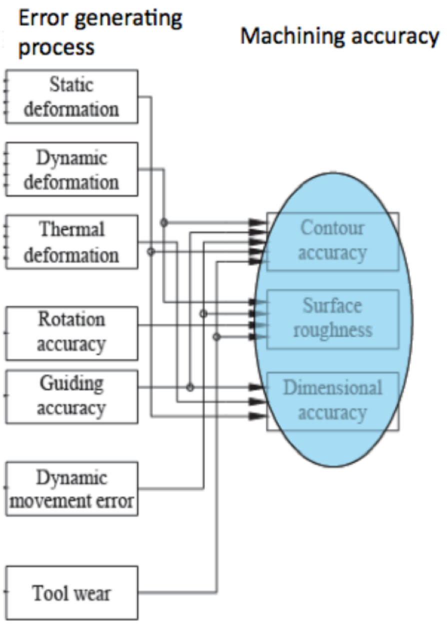
Paper 2 Cribs
SECTION A

1

a)

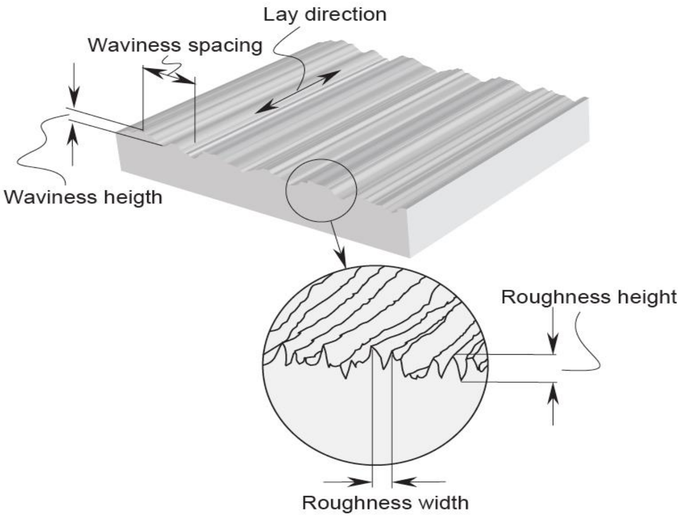
i) The principal error generating processes are shown in the following figure showing their connection with machining accuracy in terms of contour accuracy, surface roughness, and dimensional accuracy.



ii) The machine, cutting tool, and the workpiece form a structural system that has complicated dynamic characteristics. Under certain conditions, vibrations of the structural system can occur which can be divided into three classes

1. Free or transient vibration: resulting from impulses transferred to the structure through its foundation, from rapid motion of heavy masses such as machine tables, or the engagement of the cutting tool. The structure is deflected and oscillates at its natural frequency until the inherent damping causes this vibration to slowly fall away.
2. Forced vibrations: resulting from periodic forces of the system such as imbalanced masses or periodic cutting actions as in multi-tip tools or vibration transmission from nearby machinery. An important consideration when choosing machine tool location in workshops. The machine tool will oscillate at the driving frequency and if this is close to the resonant frequency, the tool will vibrate in natural mode.
3. Self excited vibration: resulting from a dynamic instability: usually resulting from a dynamic instability of the cutting process. This phenomenon is referred to as ‘chatter’ and operates at a natural mode of vibration.

b) (i)



Surface finish is characterised by the following parameters:

Roughness:

Roughness consists of surface irregularities which result from the various machining process. These irregularities combine to form surface texture.

Roughness Height: It is the height of the irregularities with respect to a reference line. It is measured in mm or microns.

Roughness Width: The roughness width is the distance parallel to the nominal surface between successive peaks or ridges which constitute the predominate pattern of the roughness. It is measured in mm.

Lay:

Lay represents the direction of predominant surface pattern produced and it reflects the machining operation used to produce it.

Waviness:

This refers to the irregularities which are outside the roughness width cut off values. Waviness is the widely spaced component of the surface texture. This may be the result of workpiece or tool deflection during machining, vibrations or tool run out.

Waviness Width: Waviness height is the peak to valley distance of the surface profile, measured in mm.

Candidates should briefly describe the basic operation of a surface stylus, and an interferometric microscope.

(ii)

Surface finish is primarily influenced by the stability of the machine tool and the processing parameters. Assuming a stable machine, the most important parameters are:

Feed per rev (turning): lower feed per rev gives a better surface finish since it reduces the frequency of surface undulations (spiral marks). As feed increases and tool nose radius reduces, tool marks become greater.

Cutting tool radius (machining): a larger radius can lead to a -ve rake angle for small depths of cut, leading to burnishing of the surface, surface damage such as tearing and cracking
Built-up edge (BUE): BUE refers to metal particulates which adhere to the edge of a tool during machining of some metals. BUE formation causes increased friction and alters the geometry of the machine tool. This, in turn, affects workpiece quality, often resulting in a poor surface finish (scuffing) and inconsistencies in workpiece size.

c (i) The problem is set up as follows

rake angle: $\alpha = +5^0$

μ: = 0.3

width of cut *w*: = 2.5mm

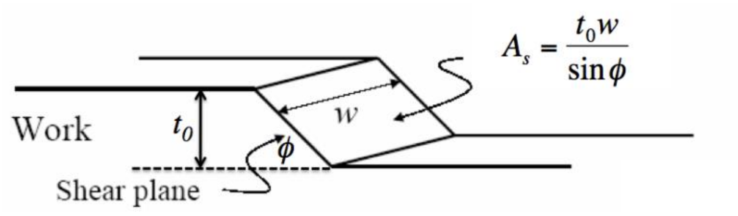
depth of cut t_0: 0.3mm

cutting speed V = 12.95 m/s

Since we have an orthogonal cutting operation

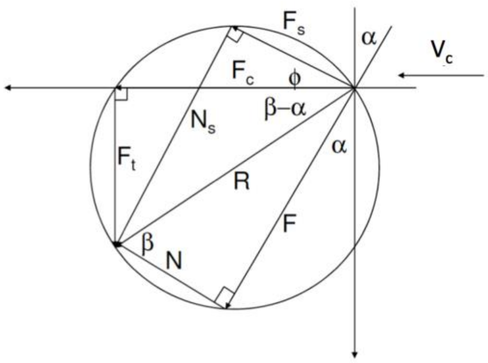
Cutting power P_c (without fluid) $= F_c V$
=> $F_c = P_c/V$
$= (3730/12.95)$
F_c = 288 N

By considering the shear plane stresses



the average shear plane stress is given as

$$t = \frac{F_s}{A_s} = \frac{F_s \sin f}{t_0 w}$$



from the force circle

$$F_s = R\cos(f + b - a)$$
$$F_c = R\cos(b - a)$$

giving

$$F_c = \frac{\tau w t_0 \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

and $$\tau = \frac{F_c \sin\phi \cos(\phi + \beta - \alpha)}{w t_0 \cos(\beta - \alpha)}$$

Friction angle β = arctan (0.3) = 16.69^0

Using Merchant's shear angle relationship

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

we have ϕ = 39.16^0

$$\tau = \frac{(288)(0.631)(0.631)}{(2.5)(0.3 \times 10^{-6})(0.979)}$$

τ = 156 MPa

The thrust force depends on the magnitudes of β and α since from the force circle

$$F_t = R\sin(\beta - \alpha)$$

When β > α, the sign of F_t is +ve (downward), when β< α, it is –ve (upwards). When the thrust force is zero, β = α.

Therefore from Merchant's relationship

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

$$\phi = \frac{\pi}{4}$$

then

$$F_c = \frac{\tau w t_0 \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)} = \frac{\tau w t_0}{\sin\left(\frac{\pi}{4}\right)\cos\left(\frac{\pi}{4}\right)} = \frac{(156 \times 10^6)(0.3)(2.5 \times 10^{-6})}{0.5}$$

F_c = 234 N

(ii) Comment: it is clear that cutting fluid can reduce the power loading on a machine which would reduce any potential dynamic instabilities. In addition, cutting fluid removes heat by carrying it away from the cutting tool/workpiece interface. This prevents tools from exceeding their thermal operating range beyond which the tool softens and wears rapidly. Fluids also lubricate the cutting tool/workpiece interface, minimizing the amount of heat generated by friction. A fluid’s cooling and lubrication properties are critical in decreasing tool wear, extending tool life, and maintaining part quality by achieving the desired size. finish and shape of the workpiece. A secondary function of metalworking fluid is to remove chips and metal fines from the tool/workpiece interface. To prevent a finished surface from becoming marred, chips generated during machining operations must be continually flushed away from the cutting zone.

2 Crib

a) (i) Temperature has a large effect on the life of a cutting tool because:-

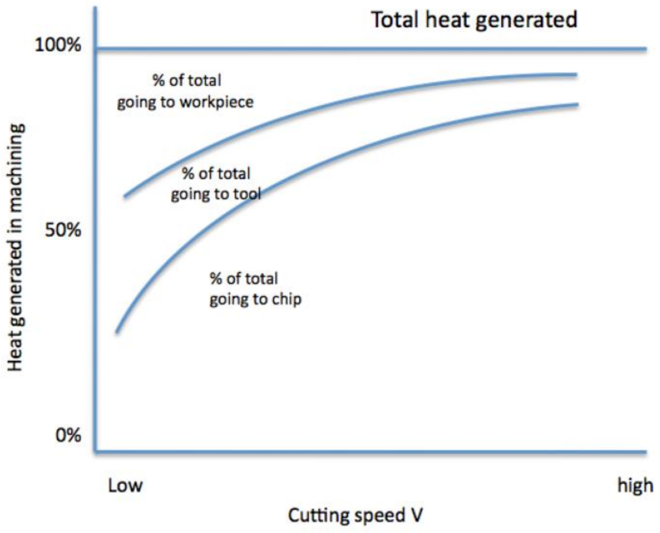
- Materials become weaker and softer as they become hotter, hence their wear resistance is reduced.
- Chemical reactivity generally increases with increasing temperature, thus increasing the wear rate.
- The effectiveness of cutting fluids can be compromised at excessive temperatures.
- Because of thermal expansion, workpiece tolerances will be adversely affected.

(ii)There are three main sources of heat. Listed in order of their heat-generating capacity,

1) The shear front itself, where plastic deformation results in the major heat source. Most of this heat stays in the chip.
2) The tool/chip interface contact region, where additional plastic deformation takes place in the chip, and considerable heat is generated due to sliding friction.
3) The flank of the tool, where the freshly produced workpiece surface rubs against the tool.

(iii)

Sketch showing the distribution of heat generated in machining as a function of speed.



(iv) The maximum temperature in orthogonal cutting is located at about the middle of the tool-chip interface. The chip reaches high temperatures in the primary shear zone; the temperature would decrease from then on as the chip climbs up the rake face of the tool. If no frictional heat was involved, we would thus expect the highest temperature to occur at the shear plane. However, friction at the tool-chip interface also increases the temperature. After the chip is formed it slides up the rake face and temperature begins to build up. Consequently, the temperature due only to frictional heating would be highest at the end of the tool-chip contact. These two opposing effects are additive, and as a result the temperature is highest somewhere in between the tip of the tool and the end of contact zone.

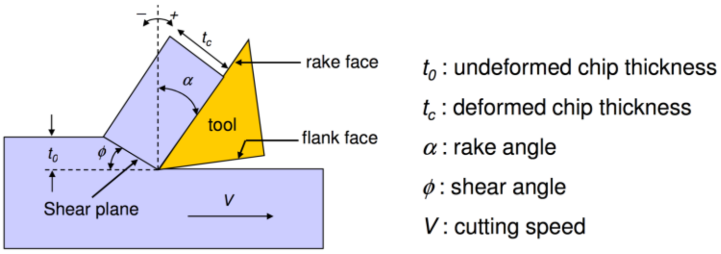
b)
(i)

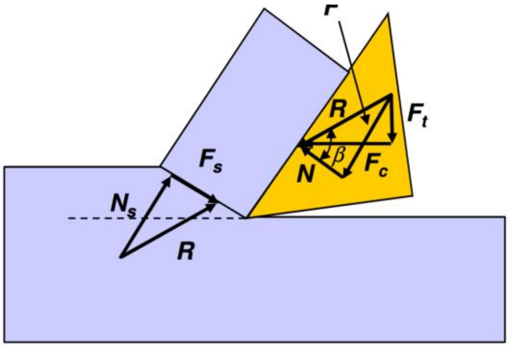
Solution:
Total cutting power = power in shear zone + power in friction zone

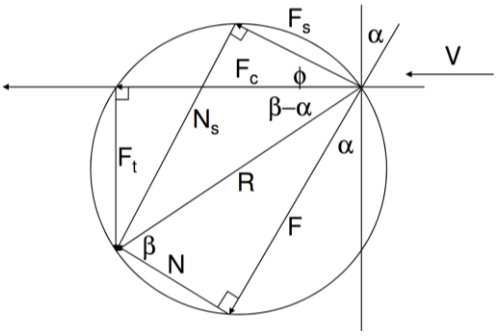
$P_c = P_s + P_f$

$P_c = F_cV$, where F_c is cutting force and V is the cutting velocity (m/s)
$P_s = F_sV_s$, where F_s is the shear force and Vs is the shear velocity (m/s)

From the force diagram in orthogonal cutting operations







$P_c = F_cV = (890)(2) = 1780$ W

$P_s = F_sV_s = R\cos(\phi+\beta-\alpha)V_s$

$$R = \sqrt{F_c^2 + F_t^2} = 1112.2N$$

Using the cutting ratio to find ϕ

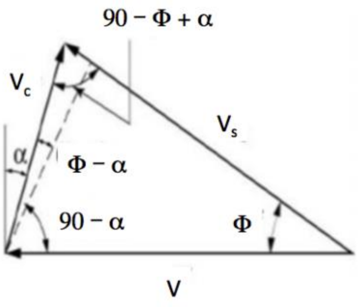
$$r = \frac{t_0}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)}$$

$$r(\cos\phi\cos\alpha+\sin\phi\sin\alpha)=\sin\phi$$
$$r(\cos\alpha+\tan\phi\sin\alpha)=\tan\phi$$
$$r\cos\alpha=\tan\phi\left(1-r\sin\phi\right)$$
$$\tan\phi=\frac{r\cos\alpha}{1-r\sin\alpha}$$

$$\tan\phi=\frac{r\cos\alpha}{1-r\sin\alpha}=\frac{(0.25/0.83)(\cos(10))}{1-(0.25/0.83)(\sin(10))}\Rightarrow\ \phi=17.3\deg$$

$$\beta=\tan^{-1}\left(\frac{F_t+F_c\tan\alpha}{F_c-F_t\tan\alpha}\right)=46.85\deg$$

from the velocity diagram and using the sine rule to determine V_s in terms of V, ϕ and α.



$$V_s=\frac{V\cos\alpha}{\cos(\phi-\alpha)}=1.986m/s$$

$P_s = F_sV_s = 1293$ W

Therefore % of total power dissipated in the shear zone = $\frac{P_s}{P_c}\times 100=72.6\%$

(ii)
Given the assumptions, we can determine the power dissipated in the chip and subtract this value from the power dissipated in the shear zone since we can ignore losses due to flank-tool workpiece contact as this is the lowest source of heat. The remainder will be the power lost to the workpiece through conduction.

The power dissipated in the chip can be determined as a function of the material properties, the mass removal rate in chip production, and temperature rise of the chip $P_{chip} = C_pM\Delta T$

Where Cp is the specific heat capacity (J/kgK), M is the mass removal rate (kg/s), and ΔT is the temperature rise of the chip

The volume removal rate is given as (2)(2.5 x10^{-4})(2.54x10^{-3}) = 1.27 x10^{-6} m^3/s.
The mass removal rate is given as (1.27 x10^{-6}) (8050) = 0.0102 kg/s

P_{chip} = (490)(0.0102)(350) = 1749 W

Given that P_c = (2)(890) = 1780 W

The power dissipated into the workpiece is (1780) – (1749) = 31 W

Comment: In terms of power dissipated in the shear zone, this represents a percentage of 31/1293 = 2.4%, which is appropriate given the high cutting speed and low cut depth.

SECTION B

3 Crib

3 (a) State Machines are used to clarify the different allowable states of the operation in a graphical manner and these states in turn can be used as "internal states" of the ladder logic code.

A typical approach to integrating state machines discussed in lectures is as follows:

1. *Determine key processing steps*
2. *Determine resources/equipment required*
3. *For each resource specify:*
   - *Triggers [control inputs]*
   - *Operations*
   - *Pre requisites*
   - *Constraints*
4. *Identify allowable states for each resource*
5. *Using key processing steps (1) and allowable state (5)*
   - *Identify single or joint states required for the process*
   - *develop state model for required operations*
6. *For each process state identify:*
   - *Required inputs from equipment*
   - *Required output signals to equipment*
   - *Any latching, counting, timer requirements*
7. *Generate equivalent ladder code to represent each state*

Limitations of state machines are the lack of analysis tools available and also it is not always 100% straightforward to map state machines into ladder logic or similar control systems codes.

(b)

(i) One approach (of many) is to designate the allowable states of Robot 1 (Anthropomorphic Robot) and Robot 2 (Cartesian Robot) as:

- *Robot 1: X1 – Idle, X2 - Collect Part A, X3 - Collect Part B, X4 - Remove Finished Box*
- *Robot 2 : Y1 - Idle, Y2 – Screwing*

Then, the allowable combined states – noting that both robots cannot be operating at the same time are:

B1: (X1 , Y1)
B2: (X2 , Y1)
B3: (X3 , Y1)
B4: (X1 , Y2)
B5: (X4 , Y1)

(ii) The students will show some working at this point clarifying the constraints and operation logic. E.g.

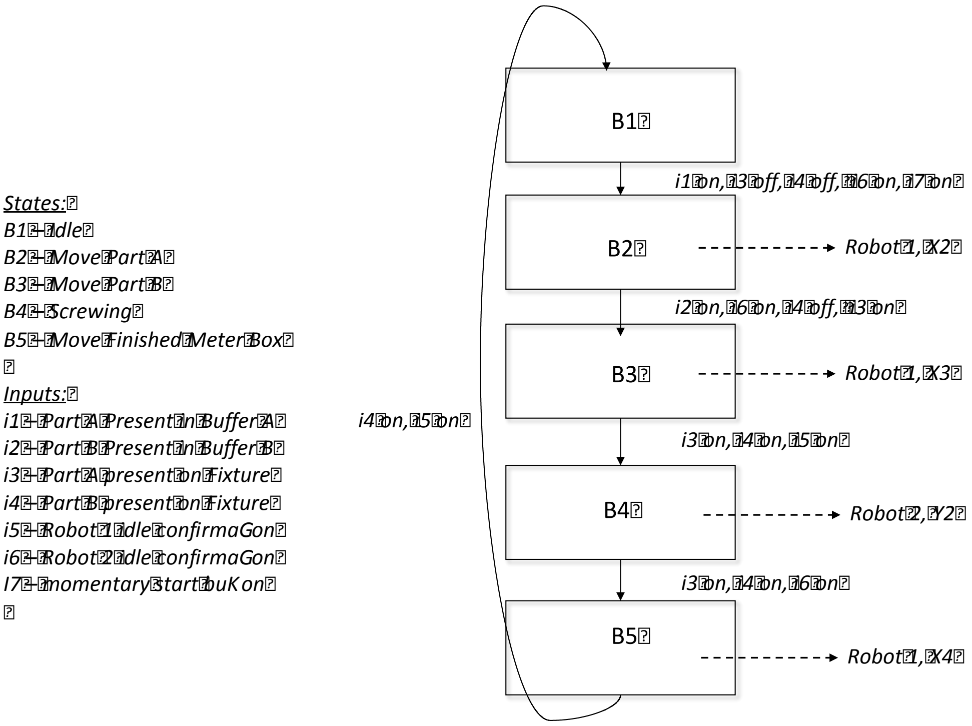
ROBOT 1

- Control/Trigger: Momentary contact to start cycle
- Operations: Collect Part A / Collect Part B / Move Finished Box / *idle*
- Pre Requisites: parts in place in Buffer A or B, fixture free for Part A, Part A in fixture for Part B
- Other Constraints: Must be idle when Robot 2 operating

ROBOT 2

- Control/Trigger: Momentary contact to start cycle
- Operations: drilling function, *idle*
- Pre Requisites: part in place in drilling fixture
- Other Constraints: Must be idle when Robot 1 operating

and they will use this logic to construct a state machine of the form below – although there are numerous variations.



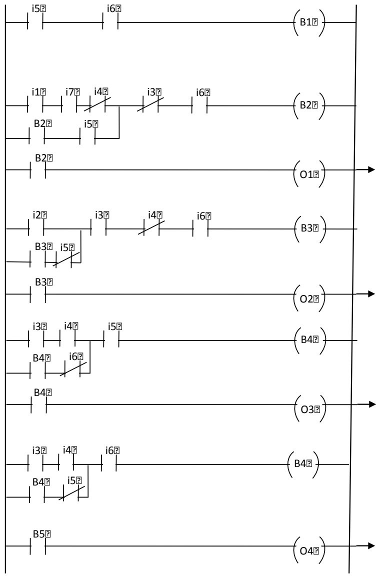
Note that Robot 1 has four potential outputs so cannot be treated as a simple on/off device.

The ladder logic to go with the state machine may take different forms but the general approach is that

- *each state represents one (or more rung outputs)*
- *the input transition signals represent the latching of the state*
- *the output transition signals represent the unlatching of the state*
- *the output signals to the robots as a rung output*

Good students might also ensure that any one state cannot be enabled while a previous state is enabled as this would imply the potential for both robots to operate simultaneously.

Although the students are not asked to produce ladder logic code some may provide examples to illustrate their answer. As an illustration a sample piece of ladder code is provided below although it is stressed that numerous other options exist.



Robot 1, 2 both idle

*Latching with i1 on, i3 off, i4 off, i6 on, i7 on
And unlatching with part A at fixture i3 on and/
or Robot 1 idle i5 on.*

Initiate Robot 1, routine X2

*Latching with i2 on, i6 on, i4 off, i3 on
and unlatching with part B at fixture i4 on and/
or Robot 1 idle i5 on.*

Initiate Robot 1, routine X3

*Latching with i3 on, i4 on, i5 on
and unlatching with Robot 2 idle i6 on.*

Initiate Robot 2, routine Y2

*Latching with i3 on, i4 on, i6 on
and unlatching with Robot 2 idle i6 on when
meter box transfer has been completed.*

Initiate Robot 1, routine Y4

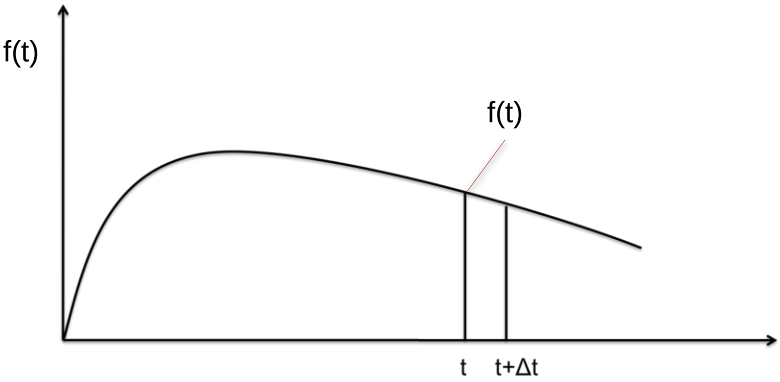
(iii) In order to prepare the cell for the introduction of a finite capacity output buffer the following changes would be needed:

Assembly Operation: additional sensing would be needed to determine the number of items in the output buffer at any given time. An alternative would be a counter. Some consideration to the removal of finished goods from the buffer may also need to be considered.

Automation Logic: the sensor output would then be used as a logical flag for preventing the initiation of transfers to the buffer when it is full but also to preclude assembly operations being started. There is a potential here for a deadlock condition to develop if the logic is not managed carefully. A further option would be to integrate a counter system in which only a finite number of products can be built before an alarm is triggered signalling the need to clear the buffer.

4 Crib

(a)



The failure rate function is the probability per unit time that a failure occurs in the interval [t, t+Δt] given that a failure has not occurred prior to t, the beginning of the interval.

This is given by:

$$\frac{F(t+\Delta t)-F(t)}{R(t)\cdot\Delta t}$$

The failure rate or hazard rate h(t) is defined as the limit of the failure rate function as the interval approaches zero.

$$\therefore h(t)=\lim_{\Delta t\to 0}\frac{F(t+\Delta t)-F(t)}{R(t)\cdot\Delta t}=\frac{f(t)}{R(t)}$$

Consider a test where a large number of identical components are put into operation and the time to failure of each component is noted. An estimate of the hazard rate of a component at any point in time may be thought of as the ratio of a number of items that failed in an interval of time (say, 1 week) to the number of items in the original population that were operational at the start of the interval. Thus, the hazard rate of an item at time t is the probability that the item will fail in the next interval of time given than it is good at the start of the interval; i.e., it is a conditional probability.

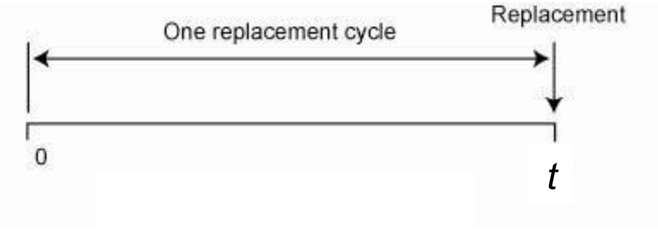
(b) Noting that the machine fails if any of the components fail, we can model the reliability of the machine as the reliability of a system with three components in series. In this case, the hazard rate of the machine is given by the sum of the hazard rates of individual components. Also noting that the hazard rate is found to be constant, the age of the components will not have any implications on their reliability.

Hazard rate of component A, λ_A *= 1/50 = 0.02*
Hazard rate of component B, λ_B *= 1/1000 = 0.001*
Hazard rate of component C, λ_C *= 1/200 = 0.005*

Therefore the hazard rate of the machine, $\lambda_M = \lambda_A + \lambda_B + \lambda_C = 0.026$

Therefore the probability that the machine will survive a five hour operation is given by $R(t) = e^{-\lambda_M t} = e^{-0.026*5} = 0.878$

(c) (i) The objective here is to determine the optimal replacement interval to minimize the total cost of operation and replacement per unit time.



The total cost per unit time for replacement at time t_r *is given by:*

$$C(t_r) = \frac{total\ cost\ in\ interval\ (0, t_r)}{length\ of\ interval}$$

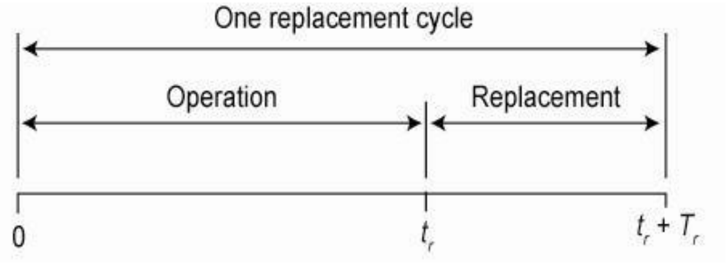
Total cost in interval = cost of operating + cost of replacement = $\int_0^{t_r} c(t)dt + C_r$*, where* C_r *is the cost of replacement*

$$\therefore C(t_r) = \frac{1}{t_r}\left[\int_0^{t_r} c(t)dt + C_r\right] = \frac{1}{t_r}\left[\int_0^{t_r} (5000 + 1600t)dt + 500000\right]$$

Now the optimal replacement interval can be found by differentiating the above expression and equating it to zero.

$$t_r^* = \sqrt{\frac{2 * 500000}{1600}} = 25 years$$

(ii) In order to consider the effect of a replacement time, we need to include the replacement time in the length of the replacement cycle.



If we denote the replacement time by T_r *the total cost equation becomes*

$$C(t_r) = \frac{1}{t_r + T_r}\left[\int_0^{t_r} c(t)dt + C_r\right]$$

Hence if Tr is relatively small is will have negligible effect on this equation

However, in a situation where the replacement time is non-negligible – i.e. involving a substantial installation period - we will also need to consider the opportunity cost of lost production during the time taken for replacement if no other machine is available to take over the load. Hence the above equation can be re-written as:

$$C(t_r) = \frac{1}{t_r + T_r}\left[\int_0^{t_r} c(t)dt + C_r + C_o\right]$$

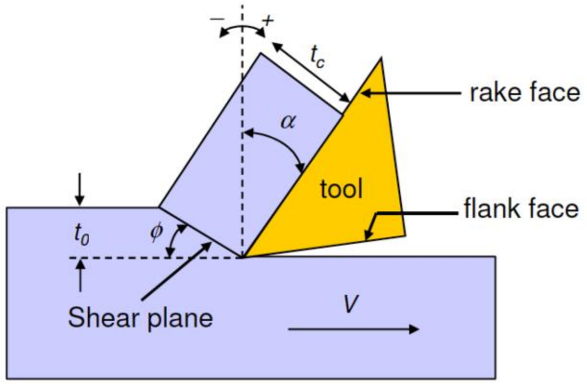
where C_o *is the opportunity cost of lost production.*

Normally this would be high increasing the replacement cost effectively and as a result will result in an increase in the replacement interval.

Section A

Data Sheet

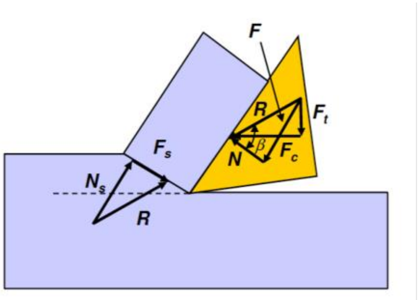
Major variables in orthogonal cutting



t_0: undeformed chip thickness
t_c: deformed chip thickness
□: rake angle
F: shear angle
V: cutting speed
□: friction angle

Forces in Orthogonal Cutting

R: resultant force
F_t: thrust force
F_c: cutting force
F: friction force
N: normal force
F_s: shear force
N_s: normal force on shear plane



Forces on the shear plane

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

Forces on the tool-chip interface

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

Merchant’s Shear Angle Relationship

$$f = \frac{p}{4} - \frac{1}{2}(b - a)$$

Cutting ratio

$$r = \frac{t_0}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$