Department of Mechanical Engineering

IIT Kanpur

ME361A: Experiment No. 1

Oblique Cutting and Cutting Force Coefficient Identification

Objectives

To measure cutting forces; identify cutting force coefficients; estimate cutting force coefficient from estimated chip thickness ratio; and study influence of cutting speed on cutting forces.

Experimental Setup

- Machine: AceMicromatic make CNC Turning
- Tool: SCLCR2020K12 (SECO make, oblique angle = 5^o, rake angle = 13^o)
- Insert: CCGT120408F-AL, KX (SECO make, Side cutting edge angle ($\psi = 5^o$)
- Work piece: Aluminum 7050 ($\tau_s = 3.03e8\ N/m^2$)
- 3 Axis Piezo- Crystal Dynamometer
- NI DAQ (Data acquisition box)
- Lab View Software for Processing Measurements
- Precision Weighing Balance
- USB Microscope

Schematic of Experimental Setup

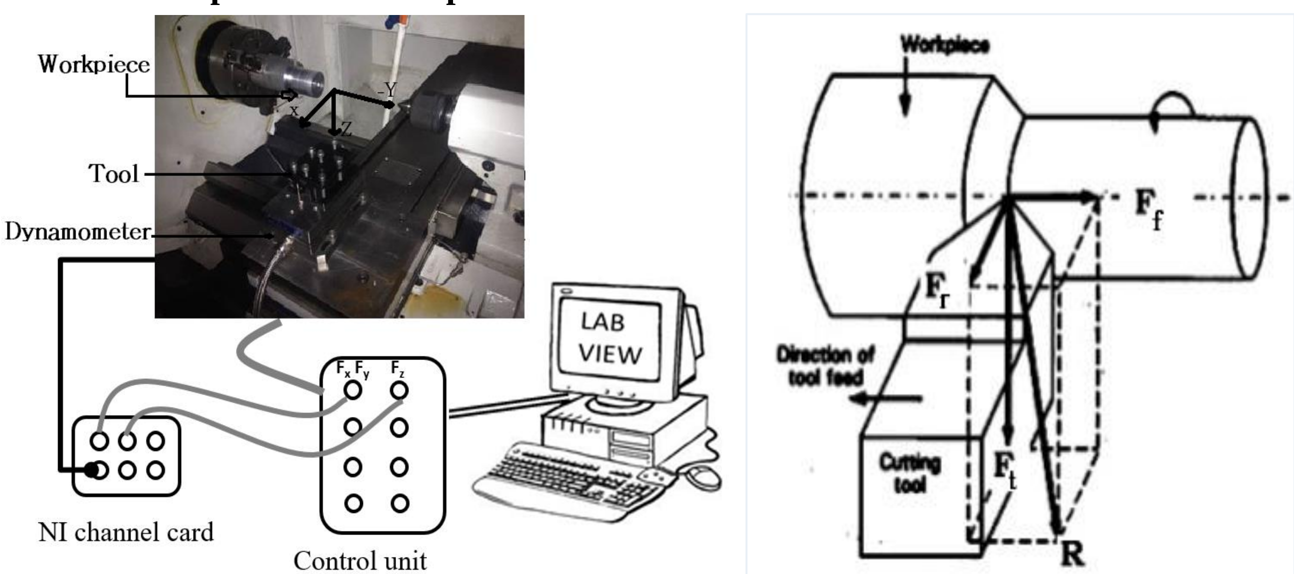


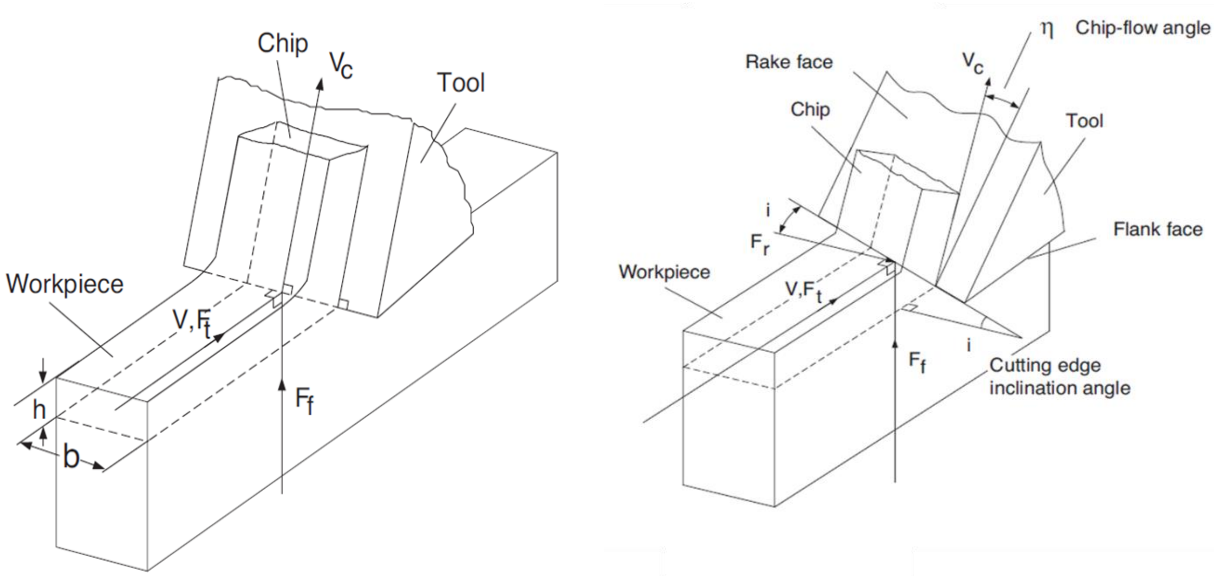
Fig. 1: Schematic diagram of setup of force measurement in oblique cutting

Background

In orthogonal cutting, the cutting edge of the tool is perpendicular to the cutting velocity vector, whereas in oblique it is set at an acute angle i (angle of obliquity) as shown in Fig. 2

Using the following assumptions, the free body diagrams can be drawn (Fig. 3):

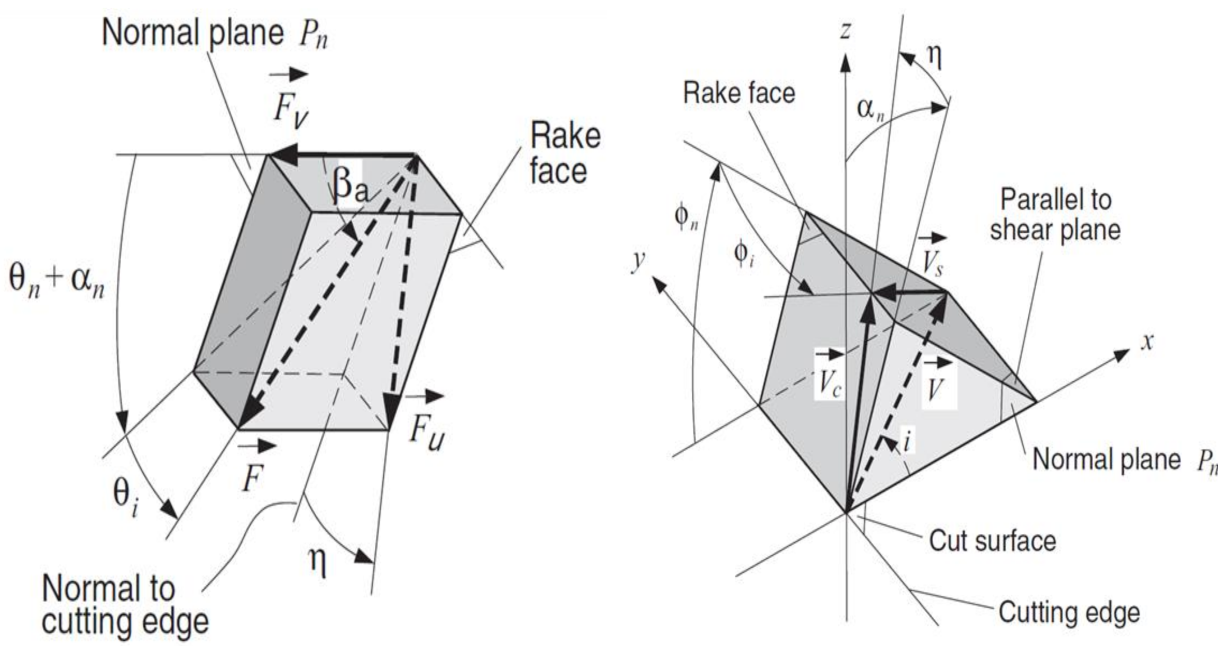
- Tool is sharp and there is no edge rubbing
- Shear occurs across a thin plane called shear plane
- Continuous chip without built up edge (BUE) is formed
- Material behavior is rigid and perfectly plastic



(a) Orthogonal Cutting: Cutting velocity is perpendicular to cutting edge

(b) Oblique Cutting: Cutting velocity is inclined at an acute angle i to the cutting edge

Fig. 2: (a) Orthogonal Cutting; (b) Oblique Cutting



(a) Force Diagram

(b) Velocity Diagram

Fig. 3 (a) Force and (b) Velocity diagram in oblique cutting

F_t = Thrust force
F_f = Feed force
F_r = Radial Force
V_c = Chip velocity
η = Chip flow angle
i = Inclination angle

ϕ_n = Normal shear angle
ϕ_i = Oblique shear angle
α_n = Normal rake angle (= 45^o, tool geometry)
F_u = Friction force on rake face
F_v = Normal force on rake face
β_a = Friction angle

The following relations can be derived from Fig. 3:

$$\sin\theta_i = \sin\beta_a \sin\eta$$
$$\tan(\theta_n + \alpha_n) = \tan\beta_a \cos\eta \tag{1}$$
$$\tan\eta = \frac{\tan i \cos(\phi_n - \alpha_n) - \cos\alpha_n \tan\phi_i}{\sin\phi_n}$$

There are five unknown oblique cutting parameters that define the direction of resultant force (θ_i, θ_n), shear velocity (ϕ_i, ϕ_n), and chip flow (η). Component forces (F_t, F_f, F_r) can be obtained as follows:

$$F_t = \frac{\tau_s bh(\cos\theta_n + \tan\theta_i \tan i)}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n}$$
$$F_f = \frac{\tau_s bh \sin\theta_n}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n} \tag{2}$$
$$F_r = \frac{\tau_s bh(\tan\theta_i - \cos\theta_n \tan i)}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n}$$

These can be re-written as:

$$F_t = K_t bh;$$
$$F_f = K_f bh; \tag{3}$$
$$F_r = K_r bh;$$

Wherein the cutting force coefficient K_f, K_t, K_r are:

$$K_t = \frac{\tau_s(\cos\theta_n + \tan\theta_i \tan i)}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n}$$
$$K_f = \frac{\tau_s \sin\theta_n}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n} \tag{4}$$
$$K_r = \frac{\tau_s bh(\tan\theta_i - \cos\theta_n \tan i)}{[\cos(\theta_n + \phi_n)\cos\phi_i + \tan\theta_i \sin\phi_i]\sin\phi_n}$$

Cutting force coefficients can either be measured or modeled. If forces are given (or measured), cutting coefficients can be found by recording eq.(3) as:

$$K_t = \frac{F_{tc}}{bh}; \;\; K_f = \frac{F_{fc}}{bh}; \;\; K_r = \frac{F_{rc}}{bh}; \tag{5}$$

If coefficients need to be modeled, and since eq. (1) has 3 relations & 5 unknowns, Armarego's assumptions and Stabler's rule $(\eta = i)$ are applied to give cutting force coefficients with the following assumptions:

- The shear velocity is collinear with shear force.
- The chip length ratio in oblique cutting is the same as that in orthogonal cutting.

$$K_t = \left[\frac{\tau_s}{\sin\phi_n}\frac{\cos(\beta_n - \alpha_n) + \tan i \tan\eta \sin\beta_n}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta sin^2\beta_n}}\right]$$

$$K_f = \left[\frac{\tau_s}{\sin\phi_n \cos i}\frac{\sin(\beta_n - \alpha_n)}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta sin^2\beta_n}}\right]$$

$$K_r = \left[\frac{\tau_s}{\sin\phi_n}\frac{\cos(\beta_n - \alpha_n)\tan i - \tan\eta \sin\beta_n}{\sqrt{cos^2(\phi_n + \beta_n - \alpha_n) + tan^2\eta sin^2\beta_n}}\right] \tag{6}$$

$$\tan(\phi_n + \beta_n) = \frac{\cos\alpha_n \tan i}{\tan\eta - \sin\alpha_n \tan i}$$

$$\phi_n = \tan^{-1}\left(\frac{r_c(\cos\eta\,/\cos i)\cos\alpha_n}{1 - r_c(\cos\eta\,/\cos i)\sin\alpha_n}\right) \tag{7}$$

Where, r_c is chip thickness ratio:

$$r_c = \frac{h\ (uncut\ chip\ thickness)}{h_c\ (deformed\ chip\ thickness)}$$

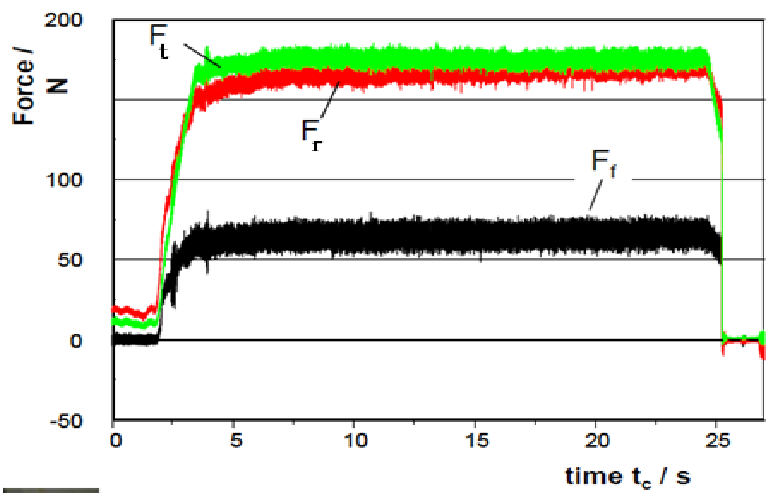
and, $$h_c = \frac{m}{\rho l_c b} \qquad h = f\cos(\psi) \tag{8}$$

Where, m = Chip mass; ρ = work piece material density; b = chip width; l_c = chip length; f = feed rate.

In eq. (6), shear yield stress (τ_s, a material property) and inclination angle (i, process parameter) are known beforehand. Unknown parameters $\beta_n, \phi_n, \alpha_n$ can be obtained through cutting force identification and Stabler's rule ($\eta = i$). Cutting force coefficients can also be identified through numerical solutions of eq. (7) & (8)

Procedure

1. Set-up the experiment and let the instruments warm up for 15 minutes.
2. Measure cutting forces for different values of feed rate (f, mm/rev) and cutting speed (V). See Table1 & 2 for parameters.
3. Calculate the average measured forces in x, y and z over a few seconds. Force profile should look as shown in Fig (4)



$$F_{rc} = F_x$$
$$F_{fc} = F_y$$
$$F_{tc} = F_z$$

Fig. 4: Example plot of force measured forces along x, y and z axes

4. Collect chips during experiments and measure their lengths using a thread and obtain their weights on a semi-micro balance.
5. Fit measured averaged force data in x, y and z with a linear regression model. Example of fitting is shown in Fig. 5
6. Identify cutting force coefficients using Eq. (5).
7. Record the values in Table 1.

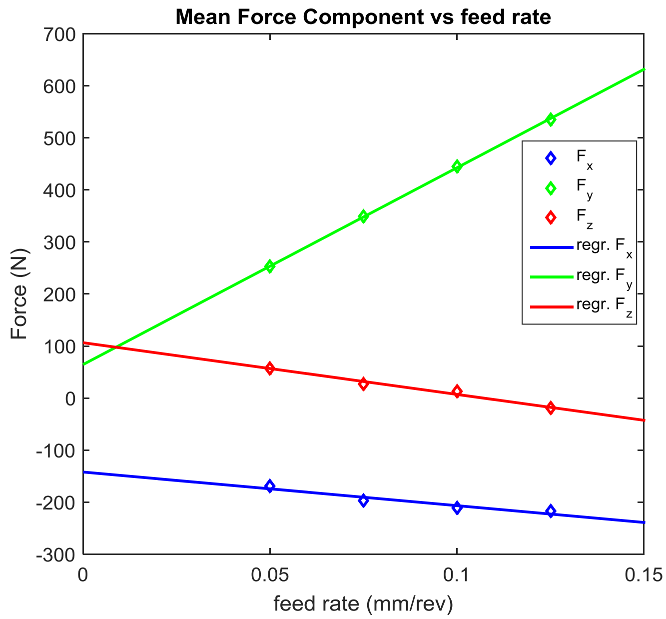


Fig 5: Averaged force data in x, y and z with a linear regression model

Results

Work piece Material: Aluminium (Shear Strength: 3.03e8 N/m^2)

Outside diameter (D): ……………………

Depth of Cut: ……………………..

Table 1: Cutting Parameters

Run	Feed rate (mm/rev)	Cutting Speed (V, m/min)	Spindle speed (RPM = $\frac{V}{\pi D}$)	Avg. F_x		Avg. F_y		Avg. F_z	
				Expt.	Theo	Expt.	Theo	Expt.	Theo
1									
2									
3									
4									

Table 2: Cutting Parameters

Run	Feed rate	Cutting Speed	Spindle Speed	Avg. F_x	Avg. F_y	Avg. F_z
1						
2						
3						
4						

Questions to be addressed in your report to be submitted

1. Plot measured cutting forces in all directions in one figure as shown in Fig.4 (total of 3 figures)
2. Plot the averaged force data (averaged over the stable cutting regime) fit using linear regression modelling (eg. Plot shown in Fig 5) and show the value of R^2
3. Experimentally identify the cutting force coefficients (eq. 5) through given force data and report the values.
4. Calculate chip thickness ratio (eq. 8) using the measured chip length and weight. Identify β_n, ϕ_n using Armarego's assumptions (eq. 7), Stabler's rule ($\eta = i$). Use these identified values to find cutting force coefficients (eq. 6)
5. Compare the experimentally identified and estimated cutting force coefficients. Comment on the difference, if any.
6. Plot the average cutting forces with respect to cutting speed and comment on the trend.

References

1. Manufacturing Automation: Metal cutting mechanics, machine tool vibrations, and CNC design Yusuf Altintas. 2nd edition.

Department of Mechanical Engineering

I.I.T. Kanpur

ME361: EXPERIMENT N0. 2

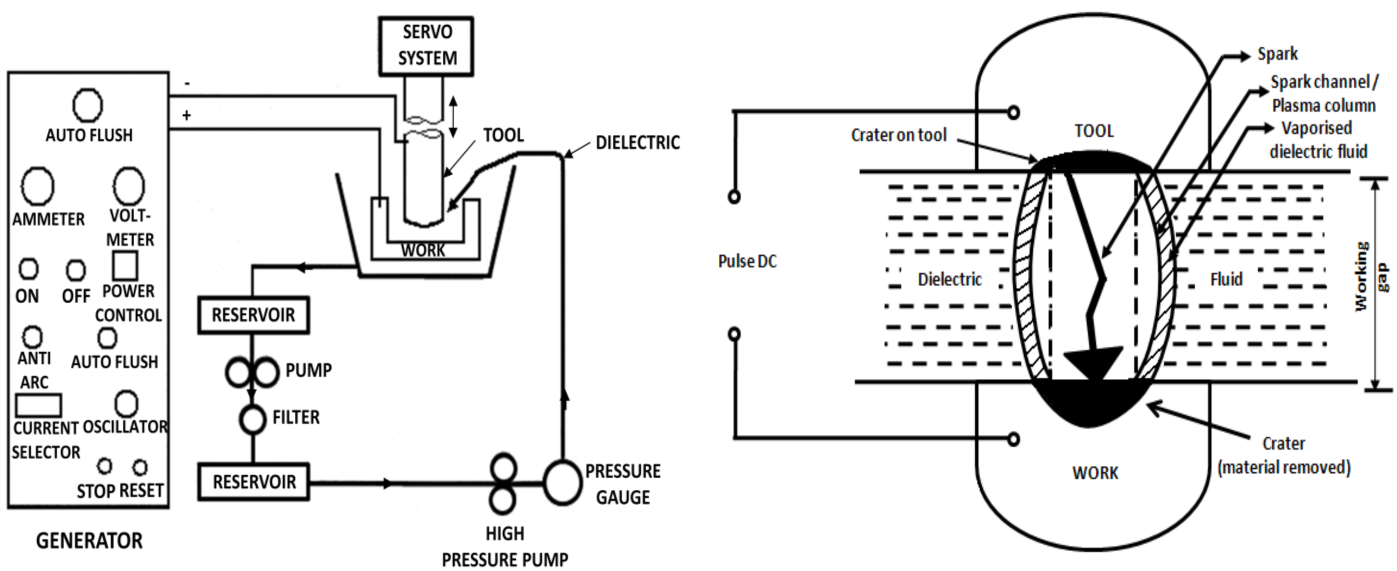
Electric Discharge Machining (EDM)

OBJECTIVE

1. To study the EDM machine and the relevant measuring systems.
2. To determine material removal rate (MRR) and tool wear rate (TWR) during machining of EN8 steel.
3. To measure the initial and final out of roundness of the copper tool.

THEORY

A high energy beam of electrons/ ions in the form of spark between the conductive work material and a shaped electrode (tool) erodes the material from the workpiece and the tool both. The energy to the sparks is provided by a pulse generator of the EDM machine. The schematic diagram of the EDM set-up is shown in Fig. 1(a), Fig. 1(b) shows an enlarged view of the sparking zone.



(a) (b)

Fig 1: Scheme of EDM Process

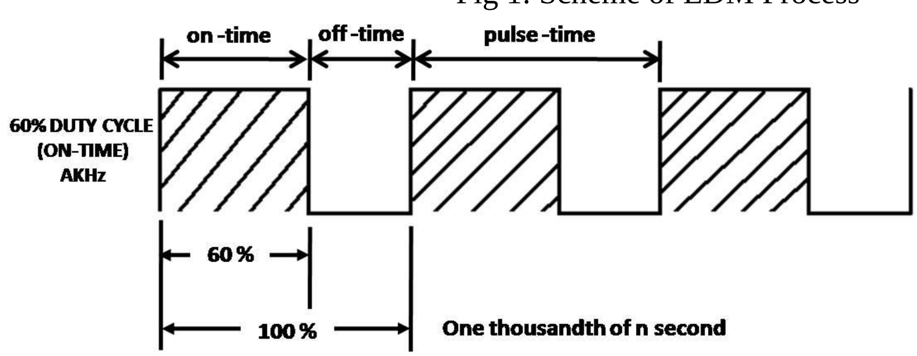


Fig 2: An illustration of pulse frequency and duty cycle.

Since material removal (MR) in each spark is proportional to the energy E of the pulse supplied (Eq. (1)), and the material removal rate (MRR) takes the general from as

$$MR = k\,E^n \quad \ldots\ldots\ (1)$$

$$MRR = k\,E^n f \quad \ldots\ldots\ (2)$$

Where, K and n depend on work and tool material combination, and f is the frequency at which the sparking takes place. The energy is equal to the product of voltage V, current I and pulse width. So

$$MRR = k\,(V.I.\tau_p)^n f \quad \ldots\ldots\ (3)$$

$$MRR = K'\,I^n f \quad \ldots\ldots\ (4)$$

If V and I are kept constant. Specific energy requirement is defined as the ratio of energy input to stock removal.

EQUIPMENTS

1. Electric discharge machine: Electro R50 ZNC machine – make electronica, Pune. Model 5535 ZNC with electronica pulse generator.
2. Round test RA – 116 machine – make mitutoyo.

INSTRUMENTS REQUIRED

1. Stop watch.
2. Precision Weighing Balance (Afcoset).

MATERIALS

1. Work Material - EN8 carbon steel.
2. Tool Material - Cu tool (electrolytic grade).

PROCEDURE

1. Study the machine and sketch a schematic diagram of the experimental set-up.
2. Take the weight of the job and the tool before conducting the experiment.
3. Mount the tool in the quill and clamp the job in the production vice mounted in the machine.
4. Switch on the power supply of the generator and the control unit.
5. Switch on the pump till the operating level is achieved. Position the flushing nozzles properly near the job.
6. Set pulse On-time (1-2000) and pulse Off time (1-10). Find out the actual value from the chart corresponding to the set number.
7. Set the proper gap setting and desired polarity on the machine.
8. Set appropriate current setting for the experiment. (Variable between 1-50 A).
9. Put the feed switch in AUTO position and put the spark On to switch on the generator. Start the stop watch as soon as the spark occurs.
10. Allow machining to occur for a predetermined depth / predetermined time.

11. NOTE DOWN ALL THE VARIABLES DURING MACHINING OPERATION.
12. Note the gap voltage and current on the screen display.
13. Stop the machine and the "stop watch" as soon as the intended machining is over.
14. Drain out the oil and lift the quill.
15. Unmount the job and tool and clean them.
16. Take the changed weights of the job and tool to find the material removal rate (MRR) and tool wear rate (TWR).
17. Repeat the procedure (2-15) with a new job and a tool for different current setting and polarity.

S. No.	**Initial Job Wt.**	**Initial Tool Wt.**	**Gap Voltage**	**Pulse On Time**	**Pulse Off Time**	**Current Setting**	**Machining Time**	**Final Job Wt.**	**Final Tool Wt.**	**MRR**	**TWR**	**Initial Round-ness of Tool**	**Final Round-ness of Tool**

Questions to be addressed in your report to be submitted:

1. Explain the basic mechanism of the EDM process. Also, give the MRR vs Current and TWR vs Current curves, for the set of experiments conducted.
2. Enumerate the merits, demerits and applications of the EDM process.
3. Discuss and comment on the obtained results.

Note: The report should contain the data sheet of the observed values of MRR, TWR and roundness verified by the course TA.

REFERENCES

1. Advanced Machining Processes by V. K. Jain.

OPERATING MODES

A typical program step has the following structure.

PARAMETERS	DESCRIPTION	RANGE
z	z Depth	-999.00 to 9999.99
I_P	Sparking Current	0 to 50 A for Normal machining 0 to 2 A for Super finish machining
Ton	Pulse On Time	1 to 2000 micro second for Normal machining 0.5 to 2 micro second for Super finish machining
t	% Duty Cycle	1 to 12 for Normal machining 1 to 4 for Super finish machining
V_g	Gap Voltage	20 to 100 V
SEN	Sensitivity (Quill Up Speed)	1 to 10
ASEN	Antiarc Sensitivity	1 to 10
TW	Work Time	0.3 to 30 sec
T Up	Lift Time	0.1 to 5 sec
Ib	Prepulse Sparking Current	0 to 3 A
X	X Displacement	-999.00 to 9999.99
Y	Y Displacement	-999.00 to 9999.99
Pol	Polarity +ve / -ve	+ve, i.e. E+, W- (Normal) -ve, i.e. E-, W+(Reverse)

	DUTYCYCLE POSITION	0 & 1	2	3	4	5	6	7	8	9	10	11	12.5
		DUTY CYCLE											
		0.08	**0.16**	**0.24**	**0.32**	**0.4**	**0.48**	**0.56**	**0.64**	**0.72**	**0.8**	**0.88**	**0.96**
T – ON POSITION	**T – ON (µ SEC)**	**T – OFF (µ SEC)**											
0 & 1	**5.00**	**57.50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
2	**10.00**	**115.00**	**52.50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
3	**20.00**	**230.00**	**105.00**	**63.33**	**42.50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
4	**50.00**	**575.00**	**262.50**	**158.33**	**106.25**	**75.00**	**54.17**	**39.29**	**28.13**	**19.44**	**12.50**	**6.82**	**2.08**
5	**100.00**	**1150.00**	**525.00**	**316.67**	**212.50**	**150.00**	**108.33**	**78.57**	**56.25**	**38.89**	**25.00**	**13.64**	**4.17**
6	**150.00**	**1725.00**	**787.50**	**475.00**	**318.75**	**225.00**	**162.50**	**117.86**	**84.38**	**58.33**	**37.50**	**20.45**	**6.25**
7	**250.00**	**2875.00**	**1312.50**	**791.67**	**531.25**	**375.00**	**270.83**	**196.43**	**140.63**	**97.22**	**62.50**	**34.09**	**10.42**
8	**500.00**	**5750.00**	**2625.00**	**1583.33**	**1062.50**	**750.00**	**541.67**	**392.83**	**281.25**	**194.44**	**125.00**	**68.18**	**20.83**
9	**750.00**	**8625.00**	**3937.50**	**2375.00**	**1593.75**	**1125.00**	**812.50**	**589.29**	**421.88**	**291.67**	**187.50**	**102.27**	**31.25**
10	**1000.00**	**11500.00**	**5250.00**	**3166.67**	**2125.00**	**1500.00**	**1083.33**	**785.71**	**562.50**	**388.89**	**250.00**	**136.36**	**41.67**
11	**1500.00**	**17250.00**	**7875.00**	**4750.00**	**3187.50**	**2250.00**	**1625.00**	**1178.57**	**843.75**	**583.33**	**375.00**	**204.55**	**62.50**
12.5	**2000.00**	**23000.00**	**10500.00**	**6333.33**	**4250.00**	**3000.00**	**2166.67**	**1571.43**	**1125.00**	**777.78**	**500.00**	**272.73**	**83.33**

VALUES IN COLOUR ARE LIMITED TO 50 MICRO SECOND DUE TO LIMITATION OF MAXIMUM FREQUANCY T-ON & T-OFF VALUES SHOWN IN TABLE ARE IN MICRO SECONDS.

Department of Mechanical Engineering

I.I.T. Kanpur

ME361: EXPERIMENT NO.3

Deep Drawing through Hydraulic Press

OBJECTIVE

To draw a cup by cup drawing process and measure the drawing force.

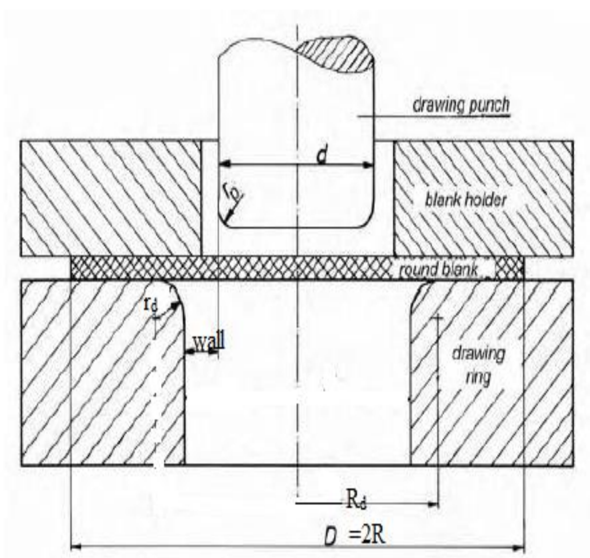
EXPERIMENT

To correlate the initial and final dimension of the job and to estimate the drawing forces on draw a cup.

Drawing forces are measured using an IPA Load cell FC-074HO, capacity 70K kg; gauge 350 OHMS, for the measurement of drawing forces. Die steel tool (Die & punch) and cold rolled steel work piece (1.0, 0.8, 0.6 mm) are used for the experiments.

BACKGROUND

In deep drawing, a cup shaped product is obtained from sheet metal with the help of a punch and a die. The sheet metal is held over the die by means of a blank holder to avoid defects in the product.



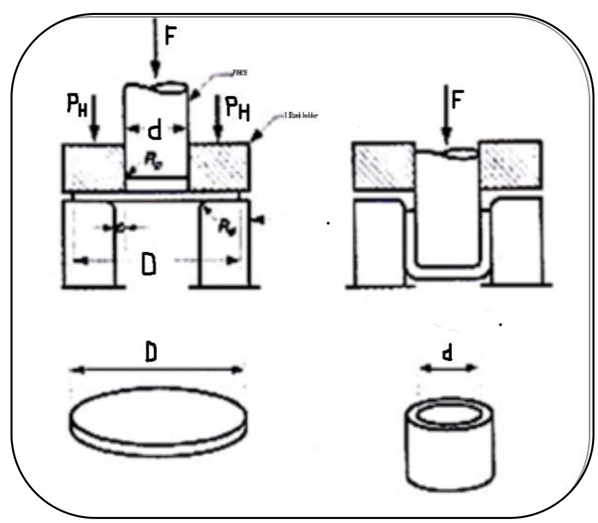


Fig (1): **Deep Drawing**

In this process various types of forces operates simultaneously. The annular portion of the sheet metal work piece between the blank holder and the die is subjected to a pure radial drawing, whereas the portion of the workpiece around the corners of the punch and die are subjected to a bending operation. Further the portion of the job between the punch and the die walls undergoes a longitudinal drawing.

The major objective of our analysis is

(i) to correlate the initial and final dimension of the job and

(ii) to estimate the drawing force F.

And compare these results with the experimental result.

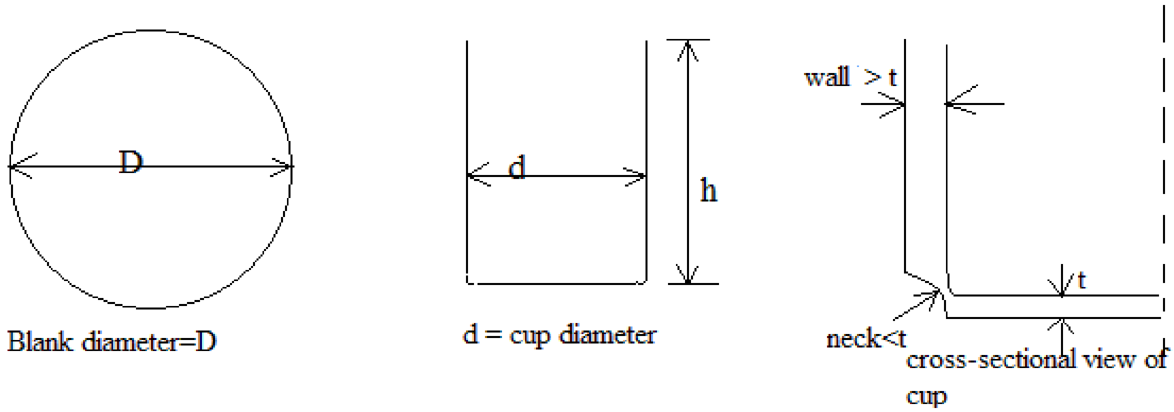


Fig (2): Deep Drawing operation

$$\frac{D}{d} = \text{Draw Ratio}$$

$$\frac{\pi}{4} D^2 = \frac{\pi}{4} d^2 + \pi dh$$

$$D = \sqrt{d^2 + 4dh}$$

Limiting draw ratio= $\dfrac{D_{\max}}{d}$

Die corner radius (r_d) = 10t

Punch corner radius (r_{cp}) = 6t

Clearance = (1.2 to 1.4) t

Blank holding pressure = 2% of yield strength.

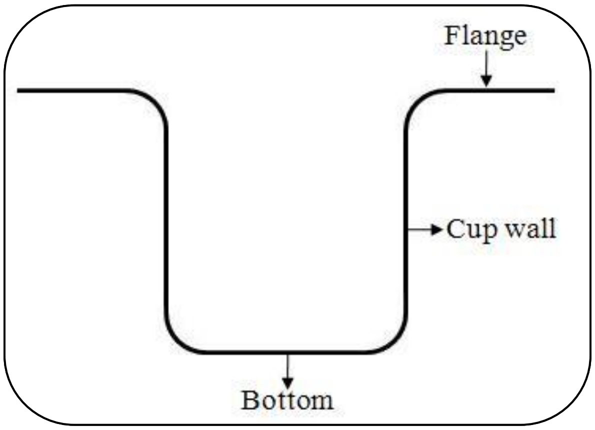
There will be three loads acting during deep drawing operation i.e. the Flange, bending and pulling over die curvature. Total load will be addition of these three loads.

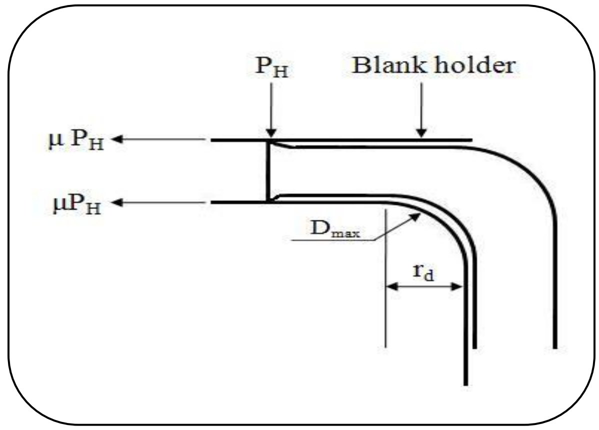
Assuming that σ_r and σ_θ are the principal stresses and σ_θ is compressive so

$$\frac{d\sigma_r}{dr} + \left(\frac{\sigma_r + \sigma_\theta}{r} \right) = 0$$

From Tresca's yield criterion, Mean flow stress (Yield shear strength) = $\frac{\sigma_r + \sigma_\theta}{2} = K$

$$\frac{d\sigma_r}{dr} = -\frac{2K}{r}$$





By integrating

$$\int d\sigma_r = \int \frac{-2K}{r} dr$$

$$\sigma_r = -2K \ln r + c_1 \qquad (1)$$

Boundary condition at r = R,

$$\sigma_r = \frac{\mu P_H}{\pi R t}$$

P_H = Holding pressure force

Substituting boundary condition in equation (1)

$$\sigma_r = 2K ln\left(\frac{R}{r}\right) + \frac{\mu P_H}{\pi R t} \qquad (2)$$

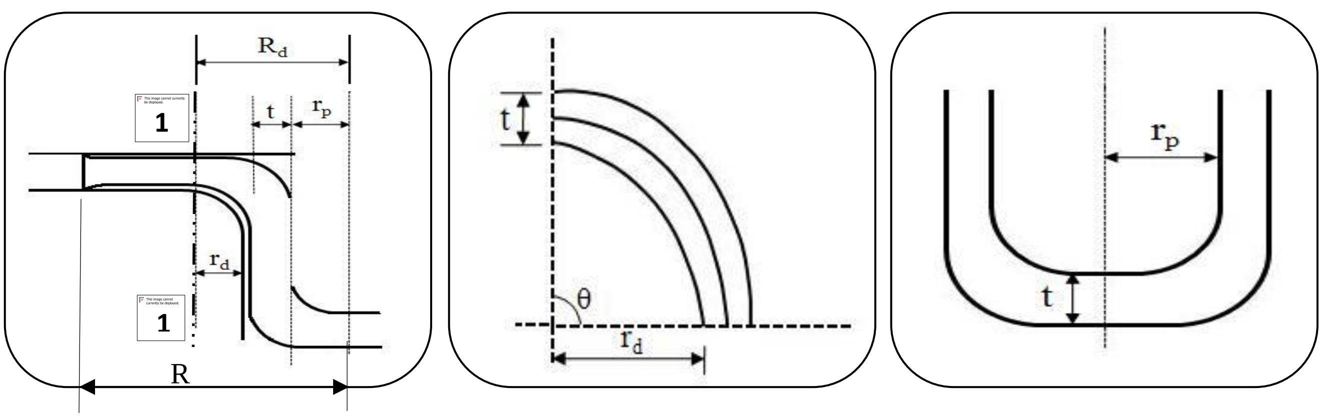


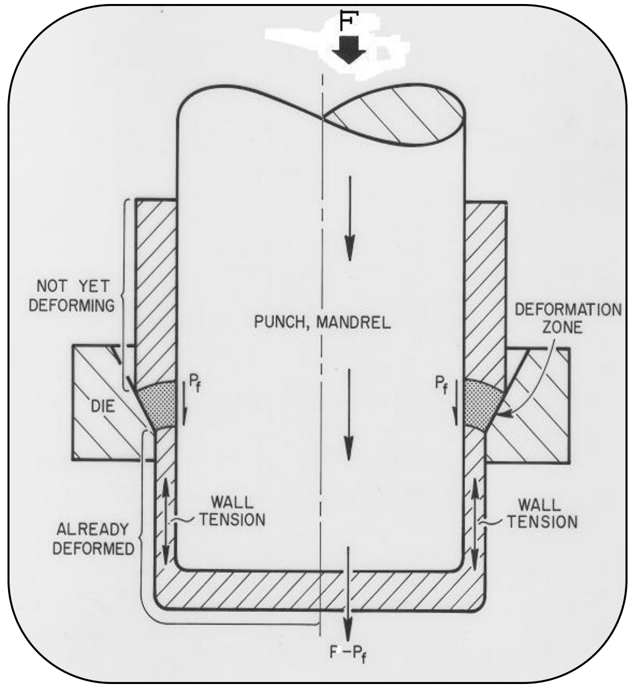
Fig. (4):

Up to section (1-1) as shown in Fig. (4)

$r = \left(r_p + t + r_d\right) = R_d$

Drawing pressure up to section (1-1) flange

$\sigma_r = 2Kln\left(\frac{R}{R_d}\right) + \frac{\mu P_H}{\pi R t}$



Punch Pressure required for bending the sheet:

Maximum strain $= \dfrac{\left(r_d + t\right)\theta - \left(r_d + \dfrac{t}{2}\right)\theta}{\left(r_d + \dfrac{t}{2}\right)\theta}$

$\left(r_d + \dfrac{t}{2}\right) = r_n$ = radius of neutral plane

Maximum strain = $\dfrac{t}{2r_n}$

Average strain $= \dfrac{0 + \dfrac{t}{2r_n}}{2} = \dfrac{t}{4r_n}$

Pressure required for bending = $\dfrac{t}{4r_n} \times \sigma_0$

Total pressure required by the punch up to bending of sheet

$$\sigma_w = 2Kln\left(\frac{R}{R_d}\right) + \frac{\mu P_H}{\pi R t} + \frac{\sigma_0 t}{4r_n} \quad (3)$$

As the sheet blank slides along the die corner, the stress given by equation (3) and sheet metal is pulled over the die curvature in axial direction. So, this increment can be roughly estimated by using belt-pulley analogy. If the angle of contact between sheet blank and die is θ ($\sim\frac{\pi}{2}$), and μ = coefficient of friction between workpiece and die corner (~0.1). Neglecting the friction between workpiece and die wall. Then total pressure required by the punch to draw the cup is:

$$\sigma_z = \left[2Kln\left(\frac{R}{R_d}\right) + \frac{\mu P_H}{\pi R t} + \frac{\sigma_0 t}{4r_n}\right] e^{\mu\theta} \quad (4)$$

Punch Load $\quad F = \sigma_z . 2\pi r_p t \quad (5)$

Where, σ_y = Yield stress

$\sigma_o = \sigma_y$

$2K = \sigma_y$

Where, K = Yield shear strength, P_H = Blank holding pressure, r_p= inner diameter of cup,

PROCEDURE

1. Set-up the experiment and let the instruments warm up for 15 minutes.
2. Measure drawing force on different sheet thickness.
3. Measure blank holding pressure.

RESULTS

1. Evaluate the theoretical and experimental values of the drawing force.
2. Tabulate the results as shown below.

Tool material: EN-31
Work material: Cold Rolled Sheet (0.02 C)
Shear strength: 400 N/mm^2

Blank dia. (D)………………………..
Cup dia. (d): ……………………….
Sheet thickness: (t_1)………………….
Sheet thickness: (t_2)………………….
Sheet thickness: (t_3)………………….

Sr. No.	**Blank holding pressure**	**Drawing Force**		**Measure the thickness ratio**	
		Theo.	**Expt.**	**Initial thickness**	**Final thickness**
1					
2					
3					
4					
5					
6					
7					
8					
9					

Questions to be addressed in your report to be submitted:

1. Present calculations for one set of reading and provide the tabulated results.
2. Plot the variation in experimental and theoretical drawing force.
3. How the calibration of load cell is carried out.
4. Sketch the load cell used and explain its working.

Note: the report should contain Table 1 populated with values used during experiments.

REFERENCES

1. Manufacturing Science by A. Ghosh & A.K.Malik
2. Production Engineering by Swadesh Kumar Singh

Department of Mechanical Engineering

I.I.T. Kanpur

ME361: EXPERIMENT No. 4 – **MILLING**

Experiment: Mechanistic identification of cutting force coefficients in milling.

OBJECTIVE

To measure cutting forces and identify the cutting force coefficients.

EXPERIMENTAL SETUP

- **Machine tool:** 5 axes milling center **(EMCO)**
- **Tool material:** Solid Carbide
- **Tool type:** End mill
- **Tool diameter:** 12/16 mm
- **No. of teeth on tool:** 04
- **Milling operation:** Slotting
- **Workpiece:** Aluminum

EXPERIMENTAL CONSIDERATIONS

- Use a small workpiece.
- Ensure dynamometer is clamped rigidly to the table.
- Measure cutting forces at stable depth of cut (DOC) and at low cutting speed.
- Collect cutting forces for a full number of revolutions.
- Conduct set of milling tests at different feeds but constant axial DOC and immersion (preferably slotting).

BACKGROUND

Using orthogonal cutting parameters such as shear angle, shear stress, and friction coefficient to determine oblique milling constants is desired for modeling a variety of milling cutter geometries. However, some cutting tools may have complex cutting edges, and the evaluation of cutting constants by creating a time-consuming orthogonal cutting database may not be possible. In such cases, a quick method of calibrating the milling tools, the mechanistic approach, is used. A set of milling experiments are conducted at different feed rates, but at constant immersion and axial depth of cut. The average forces per tooth period are measured. To avoid the influence of runout on the measurements, the total force per spindle revolution is collected and divided by the number of teeth on the cutter. The experimentally evaluated average cutting forces are equated to analytically derived average milling force expressions, which leads to the identification of cutting constants. Because the total material removed per tooth period is constant with or without helix angle, the average cutting forces are independent of helix angle.

Average milling forces per tooth period over one revolution:

$$\overline{\boldsymbol{F_q}} = \frac{\mathbf{1}}{\boldsymbol{\phi_p}}\int_{\boldsymbol{\phi_{st}}}^{\boldsymbol{\phi_{ex}}} \boldsymbol{F_q}(\boldsymbol{\phi_j})\boldsymbol{d\phi}; \quad \boldsymbol{q = x, y, z} \tag{1}$$

Cutting takes place only when tooth is in cut i.e. $\phi_{st} \le \phi \le \phi_{ex}$.

Where,

ϕ_p = Pitch angle $= \frac{2\pi}{Nt}$,

ϕ_j = Instantaneous immersion angle of tooth j

ϕ_{st} = Entry angle

ϕ_{ex} = Exit angle

Nt = Number or teeth,

Integrating the instantaneous cutting forces leads to:

$$\overline{F_x} = \left\{\frac{N_{ac}}{8\pi}\ [K_{tc}\cos 2\emptyset - K_{rc}[2\emptyset - \sin 2\emptyset]] + \frac{N_a}{2\pi}[-K_{te}\sin\emptyset + K_{re}\cos\emptyset]\right\}_{\emptyset_{et}}^{\emptyset_{ex}}$$

$$\overline{F_y} = \left\{\frac{N_{ac}}{8\pi}\ [K_{tc}(2\emptyset - \sin 2\emptyset) + K_{rc}\cos 2\emptyset] - \frac{N_a}{2\pi}[K_{te}\cos\emptyset\ + K_{re}\sin\emptyset]\right\}_{\emptyset_{et}}^{\emptyset_{ex}} \tag{2}$$

$$\overline{F_z} = \frac{N_a}{2\pi}\ [K_{te}\cos\emptyset\ + K_{re}\sin\emptyset]_{\emptyset_{et}}^{\emptyset_{ex}}$$

Full-immersion (i.e. slotting) milling experiments are most convenient; here, the entry and exit angles are $\phi_{st} = 0; \phi_{ex} = \pi$, respectively. When full-immersion conditions are applied to Eq. (2), the average forces per tooth period are simplified as follows:

$$\overline{F_x} = -\frac{N_t a}{4}K_{rc}c - \frac{N_t a}{\pi}K_{re}$$

$$\overline{F_y} = \frac{N_t a}{4}K_{tc}c + \frac{N_t a}{\pi}K_{te} \tag{3}$$

$$\overline{F_z} = \frac{N_t a}{4}K_{ac}c + \frac{N_t a}{\pi}K_{ae}$$

Where, a = Depth of cut

K_{rc} = Radial cutting coefficient

K_{tc} = Tangential cutting coefficient

K_{ac} = Axial cutting coefficient

K_{re} = Radial edge coefficient

K_{te} = Tangential edge coefficient

K_{ae} = Axial edge coefficient

The average cutting forces can be expressed by a linear function of feed rate (c) and an offset contributed by the edge forces as follows:

$$\overline{F_q} = \overline{F_{qc}}c + \overline{F_{qe}}; \quad q = x, y, z \tag{4}$$

The average forces at each feed rate are measured, and the cutting edge components ($\overline{F_{qc}}$,$\overline{F_{qe}}$) are estimated by a linear regression of the data. Finally, the cutting force coefficients are evaluated from Eq. (3) and (4) as follows:

$$\begin{gathered} K_{tc} = \frac{4\overline{F_{yc}}}{N_t a}, K_{te} = \frac{\pi\overline{F_{ye}}}{N_t a} \\ K_{rc} = -\frac{4\overline{F_{xc}}}{N_t a}, K_{re} = -\frac{\pi\overline{F_{xe}}}{N_t a} \\ K_{ac} = -\frac{\pi\overline{F_{zc}}}{N_t a}, K_{ae} = \frac{2\overline{F_{ze}}}{N_t a} \end{gathered} \tag{5}$$

The procedure is repeated for each cutter geometry; hence, the milling force coefficients cannot be predicted before the testing of newly designed cutters using mechanistic models.

SCHEMATIC DIAGRAM

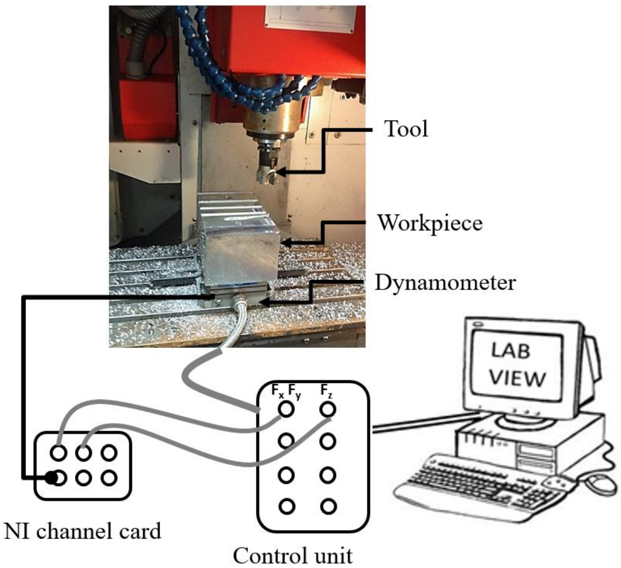


Fig. 1: Schematic diagram of setup of force measurement in milling.

PROCEDURE

1. Calibrate the dynamometer for measuring forces in three directions. Plot the calibration curve. (Calibration values are provided)
2. Set-up the experiment and let the instruments warm up for 15 minutes.
3. Measure cutting forces force different values of feed rate (mm/tooth).
4. Measure forces for at least 10 full revolutions of the cutter.
5. Calculate the average measured forces in x, y and z over two or more revolutions.

Example plot of force measured along x, y and z axes (as shown in Fig. 2):

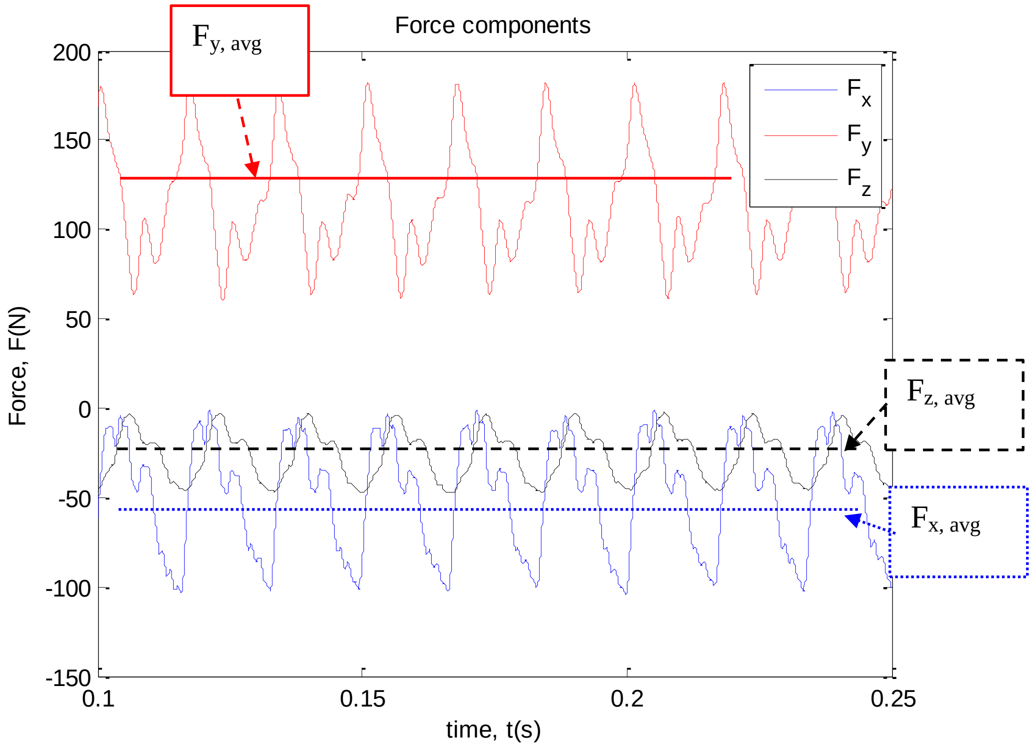


Figure 2: Measured force components in x, y and z. Also shown are averaged forces.

6. Fit measured averaged force data in x, y and z with a linear regression model. Example of fitting as shown in Fig. 3
7. Identify cutting force coefficients using Eq. (5).
8. Record the values in Table 1.

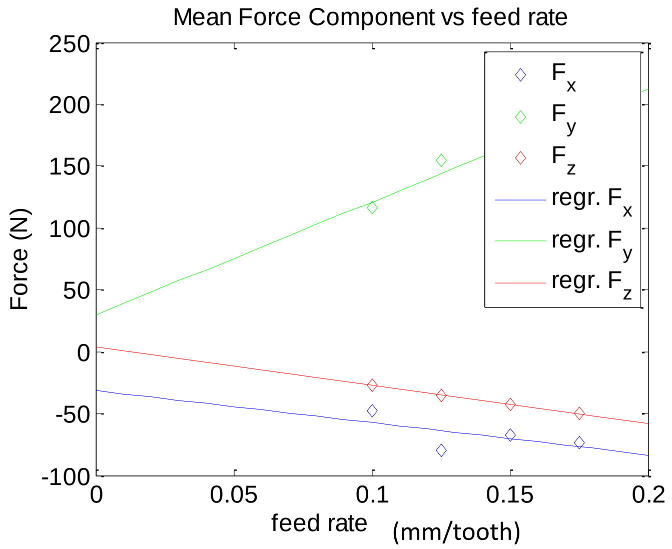


Fig. 3: Averaged force data in x, y and z with a linear regression model.

RESULTS

Table 1: Experimental Input parameters and output responses

Run	Axial DOC [mm]	Radial engagement [% of D]	Feed/tooth [mm/tooth]	Cutting speed [m/min]	Spindle speed [RPM]	Feed [mm/min]	Avg. F_x	Avg. F_y	Avg. F_z
1									
2									
3									
4									

Questions to be addressed in your report to be submitted:

1. Plot measured cutting forces in all directions (x, y and z) over two complete revolutions for each run (total 4 figures).
2. Plot the averaged force data fit using a linear regression modelling (eg. Plot shown in Fig. 3) and show the value of R^2.
3. On the same figure as above (point 3) also plot average.
4. Experimentally identify cutting force coefficient and report the values.

Note: the report should contain Table 1 populated with values used during experiments.

5. REFERENCES

1.Manufacturing Automation: Metal cutting mechanics, machine tool vibrations, and CNC design Yusuf Altintas. /2nd edition.

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ME 361: Experiment No. 5

3D printing + Metrology

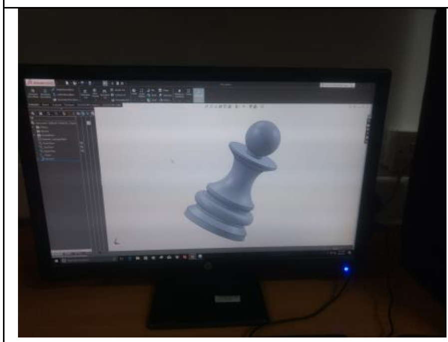
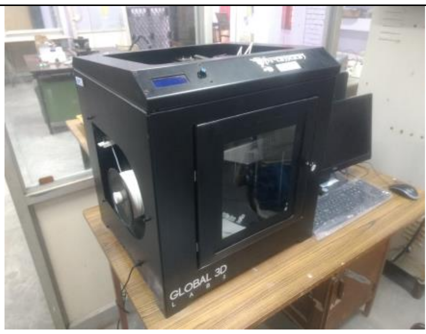
OBJECTIVE

To fabricate a three-dimensional object using the fused deposition additive manufacturing process (part A), and to its measure dimensions using a coordinate measuring machine (part B).

A) 3D printing

EXPERIMENT

FDM (Fused Deposition Modelling) is a rapid prototyping technology commonly used for prototyping and production applications. FDM process involves three steps:

Step 1: Pre Processing	Step 2: Production	Step 3: Post Processing
		
A CAD model is constructed, which is then converted to a STL format to be used by the FDM machine.	FDM machine processes the given information. Layers are created until completion of the model.	The model and any supports are removed by washing or stripping it away. The surface of the model is then finished and cleaned.

In this experiment these three steps will be followed to fabricate a 3D object.

BACKGROUND

Rapid Prototyping (RP) or Additive Manufacturing is the term given to a set of processes that can quickly fabricate any given three-dimensional object directly from a CAD file via the additive deposition of individual cross-sectional layers of the part. The underlying principle in all RP processes is the same that they create 3D objects layer-by-layer. Each layer is stacked upon a previous layer until the model is complete.

How FDM works?

FDM Technology builds parts layer-by-layer by heating thermoplastic material to a semi-liquid state and extruding it according to computer-controlled paths. FDM uses two materials: modelling material and support material. Modelling material constitutes the finished piece, and support material acts as scaffolding. Material filaments are fed from the filament spool to the print head, which moves in X and Y coordinates. The material is being deposited to complete each layer before the platform moves downward in the Z direction and then the next layer begins. Once the 3D object is built, the user breaks the support material away or dissolves it in detergent and water.

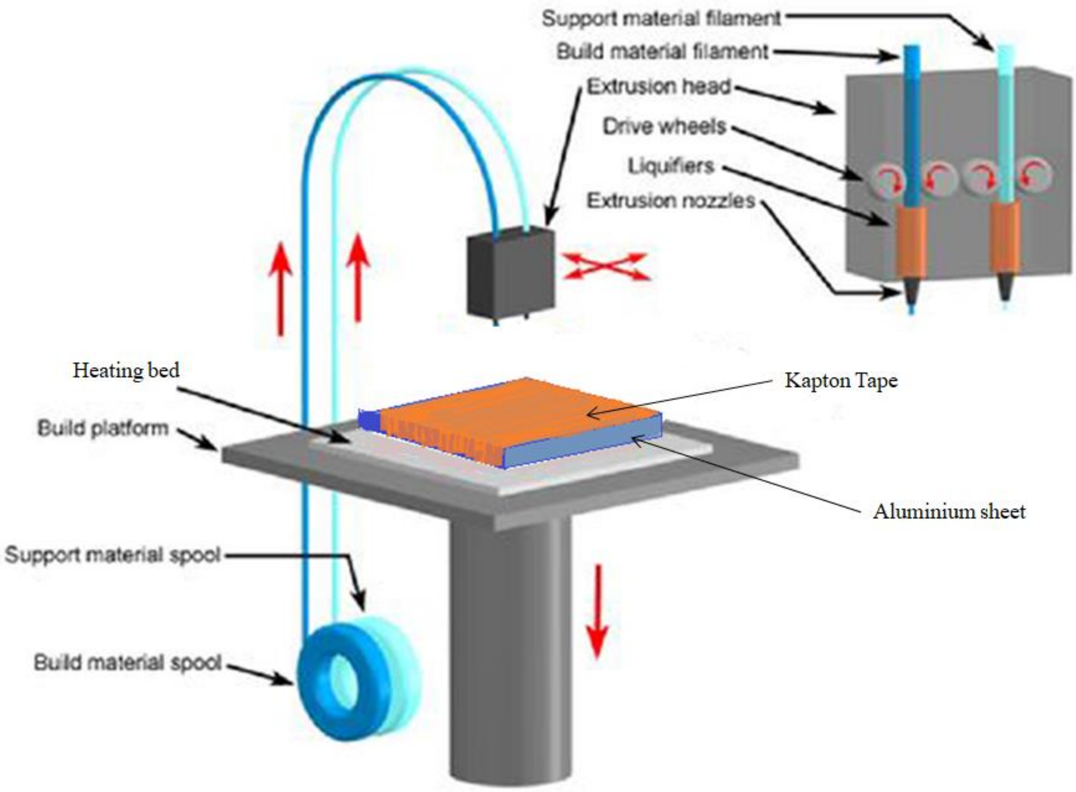


Fig. 1 Schematic of FDM machine (Adapted from [1])

MACHINE DESCRIPTION

- Machine Name: Pramaan V3
- Build Volume: 250 × 250 ×250 mm
- Filament Type: Open Source
- Filament Storage: Inside the Printer
- Filament Diameter: 1.75 mm
- Printable Materials: ABS, PLA, PVA, Nylon. We will use ABS material.
- Printable Temperature: ABS - 235°C, PLA - 210°C, PVA – 220°C, Nylon - 240°C
- Hot end: E3D v6 Full Mattel Hot end
- Nozzle Type: Hardened Steel
- Nozzle Diameter: 0.4/0.3/0.25 mm (our nozzles have 0.4 mm dia.)
- Bed Leveling: Automatic
- Number of Nozzle: 02
- Layer Resolution: Ultra-Fast: 300 microns, Fast: 200 microns, Normal: 100 microns, High: 60 microns, Ultra High: 40 microns. We will use 300 microns (Ultra-Fast) layer resolution while printing.

ELECTRICAL SPECIFICATION

- Power Source: SMPS/ATX 450 Watt Power Supply
- Input Voltage: 220 V AC 50 Hz

SOFTWARE

- Open source: Cura software for slicing the object and Pronterface software to control the FDM machine.
- File Type: STL, OBJ, DAE/AMF. (STL format files will be used).
- OS: Windows.

SPEED and PRECISION

- Print speed: 30-300 mm/s (we will use 300 mm/s printing speed)
- Travel speed: 30-300 mm/s (we will use 300 mm/s traveling speed)
- Precision: 12.5/12.5/5 microns (these are the machine capabilities in X/Y/Z axis)

SAMPLE MODELS TO BE FABIRCATED

Fig. 2 (a)

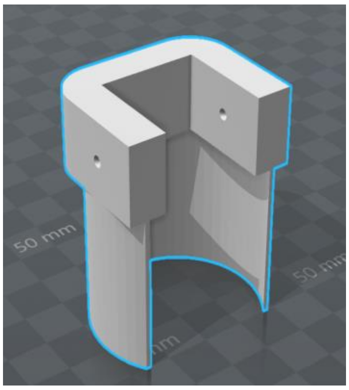


Fig. 2 (b)

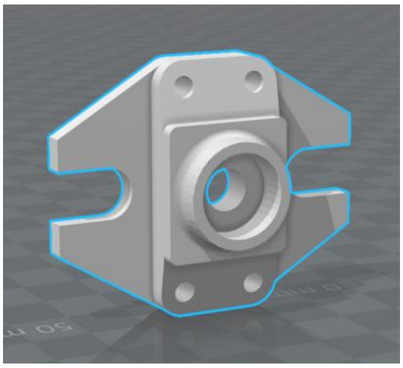


Fig. 2 (c)

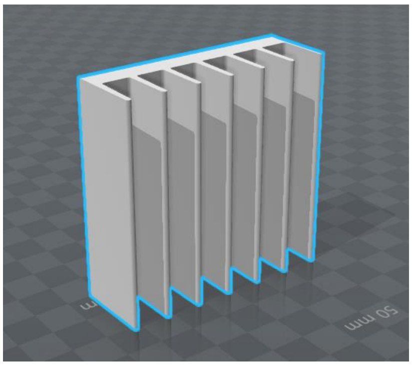


Fig. 2 (d)

PROCEDURE

1. We will provide you a .STL file of any one of the above given objects (Fig. 2). For our FDM machine we generally prefer Solidworks to make our .STL file because it gives more pixel density as compare to other packages (like Catia, Autocad etc.), so the finally product will be more dense.
2. We will open this .STL file using CURA software.
3. In CURA software we will properly orient our model and save the cross-sectional information of each layer in G code format file using options given in CURA software.
4. Prepare the machine bed by spreading acetone and ABS mixture solution over it, this solution is used so that a proper grip between the created object and bed can be obtained.
5. Now load the Pronterface software and connect FDM machine to it using CONNECT PRINTER option.
6. Open the G code format file in Pronterface software.
7. We will set nozzle temperature and bed temperature at 235 ˚C (for ABS) and 120 ˚C, respectively and wait till the temperature rises to the specified value.
8. Now click the START option to start the machine.
9. When the object is created, machine will automatically stop and wait till temperature drops to the normal value. Now we will remove the object from the machine.
10. After that we will remove all the supporting material and finish the product if needed.
11. On average, fabricating objects shown in Fig. 2 is expected to take up to 55-60 min.

REPORT

A – 3D printing

- What are the differences between 3D printing and CNC milling? Discuss briefly.
- Describe the delamination defect in 3D printed object.
- What role does the support material play? Describe briefly.

REFERENCES

1. Rapid prototyping technology - Study of fused deposition modeling technique, O. Dandgaval, P. Bichkar, International Journal of Mechanical And Production Engineering, ISSN: 2320-2092, Volume- 4, 2016.

2. Fused Deposition Modeling – A rapid prototyping technique for product cycle time reduction cost effectively in aerospace applications, Deepa Yagnik, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320-334X PP 62-68.

3. 3D Printing with FDM: How it Works, J. Hiemenz, Stratasys Inc.

B) <u>Metrology</u>

Objective

To measure features and part dimensions of the part fabricated additively, and to demonstrate measuring of other complex parts using a coordinate measuring machine (CMM).

Description

CMM is a machine capable of providing accurate dimensional information and feature characteristics of the part being inspected. CMM systems are designed to move a measuring probe to determine the coordinates of points on the work piece surface. CMMs are comprised of five main components: the machine itself, air bearing, linear scale, the measuring probe, the Renishaw control or computing system and the measuring software (Tangram). Machines are available in wide ranges of sizes and designs with variety of different probe technologies.

Equipment

1. Accurate 5.6.4 3D Co-ordinate Measuring Machine
2. Refrigeration Dryer – make Kaeser

Machine Specifications

Scale Regulation: 0.5 µm Machine accuracy: (± 2.5 + L/250) µm; (L: Standard length in mm) Angular accuracy: 1” (One second) Granite flatness: 2 micron per meter square Granite grade: zero grade Probing system: MS2DI M/c version: CNC version M/c working volume: X 500 mm; Y 600 mm; Z 400 mm Controller name: Renishaw UCC (Universal CMM Controller) lite-2 (U.K.) Model: Spectra 5.6.4. CNC	

Start-up procedure

<u>Step 1</u>: Switch **“ON”** the dryer, and then turn on the compressor and ensure the air pressure is 5.5 to 6 bar.

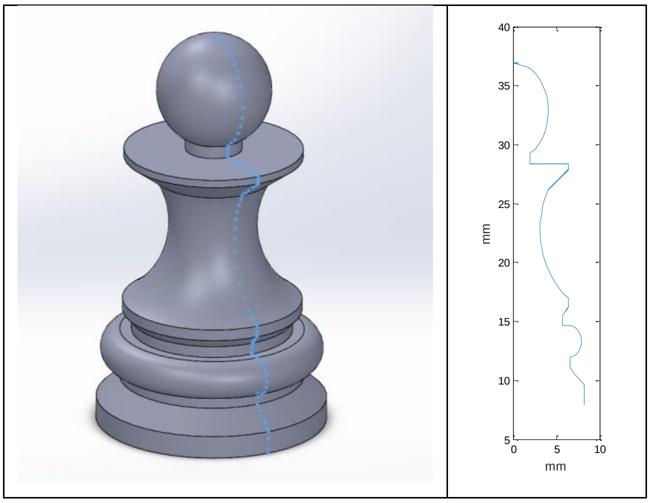
<u>Step 2</u>: Turn “**ON**” the computer and the controller and load the ‘Tangram’ software.

<u>Step 3</u>: Clean the machine and guide ways properly with a clean tissue paper. Do not use any chemicals.

Operating procedure

First understand the working principle of the machine with regards to the role of the air bearings, the probing principle, etc. Then, once the 'Tangram' software is loaded, do the following:

1. Connect to the CMM and implement the homing procedure. (The machine will move to its home position)
2. Configure/set the required tool (stylus).
3. Decide if you want to operate in the CNC mode or the manual mode. Depending on the mode of operation, follow the software prompts for executing measurements, and/or ask the TA/Lab technician. Note that if you select the CNC mode, you may need to first calibrate the machine. Again, the software will prompt instructions to calibrate, or ask the TA/Lab technician, as necessary.
4. Regardless of which mode of operation you choose, measure as many data points as necessary to capture features of the object being measured. Record all measurements. Measure along one plane as shown in the figure below, such that you obtain the profile of the part under investigation (also shown below). Since you will be asked to compare measured profile(s) with the designed profile(s) (design profile will be provided to you), it is recommended to obtain high-fidelity measurements.



5. In addition to measuring the part that you have fabricated (printed), demonstrations to measure complex components will also be made by the TA/Lab technician.

REPORT

B – Metrology

- Overlay (plot) the measured profile over the design profile, both of which will be provided to you in terms of their coordinates. If the profiles deviate from each other, comment on the potential sources of these deviations. Provide reasoned analysis.