



DEPARTMENT OF MECHANICAL ENGINEERING

Haldia, Purba Medinipur, West Bengal
HALDIA INSTITUTE OF TECHNOLOGY

PRACTICAL MANUAL

(Assessment Instrument and Instruction Items)

Course Name	Machine Tools Lab
Course Code	PC-ME 591
Laboratory Name	Workshop 4 & 5
Programme	B. Tech in Mechanical Engineering
Semester / Year	VI th Semester/3 rd Year
Academic Session	2026–27

Faculty-in-Charge & Technical Staff

Faculty-in-Charge	Mr. Pritam Pain
Co-Faculty (if any)	Mr. Sourav Sarkar Dr. Premangshu Mukhopadhyay
Technical Staffs	Mr. Debasis Maity

Vision

To impart quality, industry-relevant teaching-learning that blends knowledge and skill to produce industry-ready mechanical engineering graduates.

Mission Statements

M1: To create qualified and proficient technocrats having contemporary skills through outcome-based and self-learning strategies.

M2: To encourage innovation-oriented and problem-based research capabilities among young engineers through higher studies, in order to nurture the progress of society.

M3: To instill strong ethical values and good professional behaviour, enabling graduates to adopt and absorb emerging changes in the engineering profession.

Program Educational Objective

Graduates of B. Tech. Mechanical Engineering program, four years after graduation will

PEO1: Specify, design, supervise, test, and evaluate engineering skills to design, develop, and implement innovative solutions, systems, and applications in Mechanical Engineering and allied industries.

PEO2: Utilize Mechanical Engineering knowledge to address real-world and societal challenges while pursuing higher studies, research, and professional development.

PEO3: Demonstrate effective individual and collaborative capabilities in multidisciplinary professional environments, with a commitment to lifelong learning and adaptability to evolving technological, industrial, and societal requirements.

Program Specific Outcomes (PSOs)

PSO1: Design, analyze and evaluate mechanical components and systems such as thermal, fluid, manufacturing, design systems and allied engineering solutions.

PSO2: Utilize and evaluate modern engineering tools, software, and techniques to model, analyze, and solve real-world mechanical engineering problems.

PSO3: Demonstrate professional and ethical responsibility, effective communication, and the ability to work in multidisciplinary teams to address societal, industrial, and environmental challenges through sustainable mechanical engineering solutions.

Course Details:

PC-ME 591	Category: Professional Core courses	PCIE Marks	40
Machine Tools Lab	Semester: Fifth	PSEE Marks	60
L-T-P: 0-0-3	Credit: 1.5	Total Marks	100
Pre-Requisites: Manufacturing Processes Lab (PC-ME 492)			
Examination (PSEE): Theory/ Drawing Assignment/ Practical/ Viva-voce/Team work/ others			

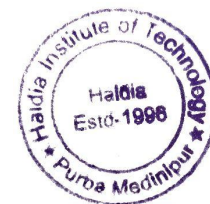
Course Content:

Experiment and instruction items are to be framed based on these units:

Unit	Topics	Hours	CO
UNIT I	Turning operation: computation of Metal Removal Rate (MRR) and machining time; determination of cutting speed, feed, depth of cut and machining parameters; analytical and experimental determination of MRR and machining time.	9	CO1
UNIT II	Drilling: determination of MRR and machining time; drill operations and drilling parameters. Milling: determination of MRR and machining time; up-milling and down-milling; peripheral and face milling; milling cutter and feed-rate parameters.	9	CO2
UNIT III	Shaping operation: determination of MRR and machining time; cutting speed, feed, depth of cut, stroke length and number of strokes; analytical and experimental comparison of machining time and MRR.	6	CO3
UNIT IV	Measurement of cutting forces during turning using a lathe tool dynamometer ; determination of cutting, feed and radial/thrust forces; resultant cutting force; introduction to Merchant's circle diagram; determination of friction force, normal force, shear force and friction angle.	6	CO4
UNIT V	Mechanics of chip formation; uncut chip thickness, chip thickness and chip width; chip reduction coefficient/cutting ratio; shear plane angle, shear area, chip velocity and cutting strain. Taylor's tool-life equation: experimental verification by varying cutting speed and determination of tool-life characteristics.	6	CO5
UNIT VI	Determination and measurement of surface finish/roughness after machining; surface roughness, waviness, lay, sampling length, roughness height and width; measurement using profilograph, Tomlinson surface meter and Taylor-Hobson Talysurf; determination of R_a , R_q , R_z , R_t , R_{sk} and R_{ku} .	6	CO6
Total		42	

Suggested Reference Books

1. Machining and Machine Tools, A.B. Chattopadhyay, Wiley India (P) Ltd., New Delhi
2. Manufacturing Science by A.Ghosh and A.K.Mallik, Wiley Eastern.
3. Principles of Metal Cutting/Principles of Machine Tools by G.C.Sen and A.Bhattacharya, New Central Book Agency, Kolkata.
4. Fundamentals of Metal Cutting Machine Tools by G.Boothroyd, TMH.
5. Production Technology, HMT Publication, TMH.
6. Production Engineering Sciences by P.C.Pandey and C.K.Singh, Standard Publishers Ltd.
7. A. Bhattacharyya, Metal Cutting Theory and Practice, New Central Book Agency, Kolkata



Course Outcomes:

Upon successful completion of the course, students will be able to:			
CO CODES	CO Statement	Knowledge Categories	Cognitive Level
PC-ME 591.1	Determine MRR and machining time in turning by performing lathe experiments, with correct analytical and experimental values.	C, P	Ap
PC-ME 591.2	Determine MRR and machining time in drilling and milling by	C, P	Ap

	performing the operations, with correct selection of process parameters.		
PC-ME 591.3	Analyze shaping performance by comparing analytical and experimental machining time and MRR, with deviations justified.	C, P	An
PC-ME 591.4	Determine cutting forces in turning using a lathe tool dynamometer, with correct force components from Merchant's circle.	C, P	Ap
PC-ME 591.5	Analyze chip formation and tool life by varying cutting speed in turning, with Taylor's equation verified from plotted curves.	C, P	An
PC-ME 591.6	Measure surface roughness using profilograph, Tomlinson meter and Talysurf, with Ra, Rq, Rz, Rt, Rsk and Rku determined correctly.	P	Ap

ALIGNING OF COS IN [CL × KC] METRIC

Knowledge Categories (KC)								
Cognitive Levels (CL)	Factual	Conceptual	Procedural	Meta-cognitive	Fundamental Design Principles	Criteria & Specifications	Practical Constraints	Design instrumentalities
Remember (R)								
Understand (U)								
Apply (Ap)		CO1, CO2, CO4,	CO1, CO2 CO4, CO6					
Analyze (An)		CO3, CO5	CO3, CO5					
Evaluate (E)								
Create (C)								

Assessment Pattern and Assessment Instruments for PCIE & PSEE

Marks allotted	PCIE								PSEE (60)	
	PCAI (40)				PCAII (40)				40	20
	10	10	10	10	10	10	10	10		
CO	EX1	EX 2	EX 3	VIVA I	EX 4	EX 5	EX 6	VIVA II	GR-A	GR-B (Viva)
CO1	10			10/3					40/6	20/6
CO2		10		10/3					40/6	20/6
CO3			10	10/3					40/6	20/6
CO4					10			10/3	40/6	20/6
CO5						10		10/3	40/6	20/6
CO6							10	10/3	40/6	20/6

CO-PO & CO-PSO Articulation Matrix

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3
PC-ME 591.1	3	2	–	3	2	–	–	1	2	1	–	1	3	2	1
PC-ME 591.2	3	2	2	2	2	–	1	1	2	1	–	1	3	2	1
PC-ME 591.3	2	3	–	3	1	–	–	1	2	2	–	1	3	2	2
PC-ME 591.4	3	3	1	3	3	–	–	1	2	1	–	1	3	3	1
PC-ME 591.5	3	3	2	3	2	1	2	1	2	1	1	2	3	2	2
PC-ME 591.6	2	2	1	3	3	–	–	1	2	2	–	2	2	3	1
Average	2.67	2.50	1.50	2.83	2.17	1.00	1.50	1.00	2.00	1.33	1.00	1.33	2.83	2.33	1.33



MACHINE TOOLS LABORATORY (PC-ME 591)**LIST OF ASSESSMENT ITEMS, INSTRUCTION ITEMS**

Experiment No.	Name of the experiment	Instruction Item (II)	CO Congruence
EX1-I	Computation of Metal Removal Rate and Machining Time during Turning Process	II1	CO1
EX1-II	Computation of Metal Removal Rate and Machining Time during Shaping Process		
EX2-I	Computation of Metal Removal Rate and Machining Time during Drilling Process	II2	CO2
EX2-II	Computation of Metal Removal Rate and Machining Time during Milling Process		
EX3	Determination of Cutting Force during the Machining Process	II3	CO3
EX4	Computation of Cutting Parameters along with Shear Plane Angle, Chip Reduction Coefficient and Shear Strain	II4	CO4
EX5	Verification of Taylor's Tool Life Equation for a Given Tool–Work piece Combination by Variation of Cutting Velocity	II5	CO5
EX6	Determination of Surface Finish during Machining Process	II6	CO6

INSTRUCTION ITEM-1(II 1)		
Experiment No.	Name of the experiment	CO Congruence
EX 1 I	Computation of Metal Removal Rate and Machining Time during Turning Process	[CO1]

Theory: Metal Removal Rate (MRR) applies to different types of machining operations where metal is chipped off from a given raw stock job to create a product of desired specification. MRR depends on the type of operation, job geometry, surface finish desired, and job-tool material combination. It is calculated on the basis of volume of material machined out (V) from a given stock within a time (t). The major parameters pertaining to metal turning operations are Cutting speed (V_c), Feed (s) and Depth of cut (t).

Cutting Speed (V): It is the tangential velocity of the job at the periphery owing to its rotation. This is the most important parameter that affects machinability and tool life.

$$\text{Cutting speed (V)} = \pi D N / 1000 \text{ m/min}$$

where D is the diameter of turning (mm) and N is the rpm.

Feed (s): Feed is the tool movement along the axis of the work per revolution of the work. It is expressed in mm per revolution. Feed rate (S_m) is the total tool movement per minute. This is the motion responsible for the progress of the job.

$$\text{Feed rate (S}_m\text{)} = f \times N \text{ mm/min}$$

Depth of cut (t): It is the distance between the work and machined surfaces, measured in a direction perpendicular to the workpiece axis.

$$\text{Depth of cut (t)} = (D - d) / 2 \text{ mm}$$

where D and d are the diameters of the unfinished and finished surface respectively.

(a) Computation of Metal Removal Rate (MRR)

Metal Removal Rate (MRR) can be computed by the following expression:

$$MRR = 1000 \times V_c \times s \times t \text{ mm}^3/\text{min}$$

(b) Computation of Total Machining Time ($T_{m/c}$)

$$T_{m/c} = (L \times n_p) / (s \times N)$$

where n_p = number of passes = $(D_o - D_f) / 2t$, and L = length to be turned.

Also,

$$T_{m/c} = [\pi D L / (1000 \times S_m \times t)] \times [(D_o - D_f) / 2] \text{ minutes} = k / MRR$$

where 'k' is a constant known as the work-dimension parameter.

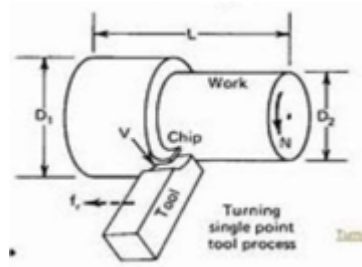


Fig.: Turning with a single-point tool

Experimentation

MRR is determined by turning the given MS work-piece where:

- Cutting tool used: _____
- RPM applied: _____

The workpiece is fixed into the chuck and then centred. The final dimension on the workpiece is achieved by turning through several passes.

Measuring instruments used

- Tachometer
- Vernier Caliper (Mitutoyo make)
- Stop watch

Observation Table

No. of obs.	Initial Dia (mm)	Final Dia (mm)	Turning Length (mm)	Volume of Metal removed (mm ³)	Time taken (sec)	MRR (mm ³ /sec)
1.						
2.						

Analysis

Initially the machining time and metal removal rate are experimentally determined; then they are analytically estimated.

Responses	Experimental value	Analytical value
Machining Time		
MRR		

Precautions

- Ensure that the workpiece is properly fixed and securely tightened in the chuck before starting the turning operation.
- Check that the cutting tool is properly clamped and accurately aligned with the workpiece centre.
- Set the required spindle speed, feed and depth of cut before starting the machining operation.
- Do not touch the rotating workpiece, cutting tool or chips during machining.
- Stop the machine before taking dimensional measurements or making any adjustments.
- Use a suitable measuring instrument such as a vernier caliper carefully to measure the initial and final dimensions of the workpiece.
- Remove chips using a suitable brush or chip hook; never remove them by hand.
- Record the machining time accurately using a stopwatch for determination of experimental MRR and machining time.

INSTRUCTION ITEM-1(II 1)		
Experiment No.	Name of the experiment	CO Congruence
EX1-II	Computation of Metal Removal Rate and Machining Time during Shaping Process	[CO1]

Theory: In shaping, a single-point cutting tool reciprocates linearly with respect to the work part.

Cutting Speed: It is defined as the average linear speed of the tool during the cutting stroke in m/min, which depends on the number of ram strokes (or ram cycles) per minute and the length of the stroke.

$$V = N L (1 + m) / 1000 \text{ m/min}$$

where,

N = number of double strokes or cycles of the ram per minute (one double stroke comprises one cutting and one return stroke)

m = return stroke time / cutting stroke time

L = length of the ram stroke, mm = $L_f + 2C$

L_f = workpiece length

C = clearance

Feed: Feed (f) is the relative motion of the workpiece in a direction perpendicular to the axis of reciprocation of the ram. In a shaper, feed is normally given to the workpiece and can be automatic or manual. It is expressed in mm/double stroke, or simply mm/stroke, because no cutting is done in the return stroke.

Depth of Cut: Depth of cut (d) is the thickness of the material removed in one cut, in mm.

Machining time: Using the cutting speed (v), the machining time for one double stroke is given by

$$t = L (1 + m) / (1000 v) \text{ min}$$

where L = length of stroke in mm and m = return-to-cutting time ratio (2:3).

With a feed (f) mm/double stroke, the number of double strokes required to machine a surface of width 'w' will be

$$N_s = w / f$$

Therefore, the total time required for machining the surface will be

$$T = L w (1 + m) / (1000 v f) \text{ min}$$

Metal Removal Rate

$$MRR = f d N L (1 + m) \text{ mm}^3/\text{min}$$

where d = depth of cut in mm, f = feed in mm/double stroke, N = strokes/min.

Experimentation

MRR is determined by shaping the given MS work-piece where:

- Workpiece size: _____
- Cutting tool used: _____
- Feed applied: _____

The workpiece is fixed in the machine vice and then aligned. The final dimension on the workpiece is achieved by the shaping operation through several passes.

Measuring instruments used

- Spirit level
- Stop watch
- Vernier Caliper (Mitutoyo make)

Observation Table

No. of obs.	Initial Volume (mm ³)	Final Volume (mm ³)	Volume of metal removed (mm ³)	Time taken (sec)	MRR (mm ³ /sec)
1.					
2.					

Analysis

Initially the machining time and metal removal rate are experimentally determined; then they are analytically estimated.

Responses	Experimental value	Analytical value
Machining time		
MRR		

Precaution

- Ensure that the workpiece is firmly clamped and properly aligned in the shaper vice before starting the operation.
- Select a suitable cutting tool and ensure that it is properly sharpened and securely fixed in the tool post.
- Set the appropriate cutting speed, feed, and depth of cut according to the workpiece and cutting-tool material.
- Ensure adequate clearance between the ram, tool, workpiece, and vice to avoid collision during the reciprocating motion.
- Do not touch the workpiece, cutting tool, or moving parts while the machine is running.
- Measure the dimensions of the workpiece only after completely stopping the machine.
- Use a properly calibrated vernier caliper for measuring the initial and final dimensions of the workpiece.
- Record the machining time accurately using a stopwatch, starting and stopping it consistently for each observation.
- Remove chips using a brush or suitable chip-removal tool; never remove chips by hand.
- Wear appropriate safety goggles, safety shoes, and suitable workshop PPE throughout the experiment.
- Ensure that the machine is switched off before making any adjustment to the tool, workpiece, or machine settings.
- Take multiple observations and use consistent measurement procedures to obtain reliable experimental MRR values.

INSTRUCTION ITEM-1(II 2)		
Experiment No.	Name of the experiment	CO Congruence
EX2-I	Computation of Metal Removal Rate and Machining Time during Drilling Process	[CO2]

Theory: Drilling is a cutting operation that uses a drill bit to cut or enlarge a hole of circular cross-section in solid materials. The drill bit is a rotary cutting tool, often multipoint. The drill bit, commonly known as a twist drill, is pressed against the workpiece and rotated at rates from hundreds to thousands of revolutions per minute. This forces the cutting edge against the workpiece, cutting off chips (swarf) from the hole as it is drilled. Drilling is used extensively to originate or enlarge through or blind holes in a workpiece. It is considered a roughing operation, and accuracy and surface finish are generally not of much concern.

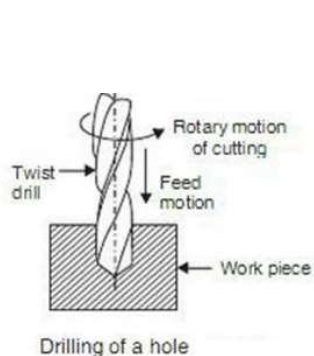


Fig. : Drilling of a hole

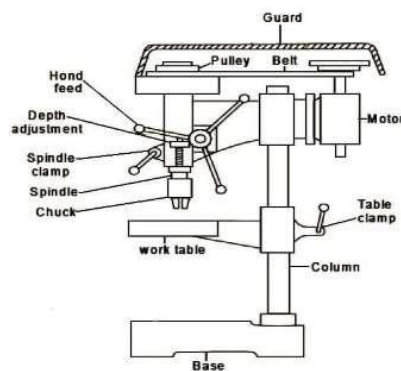


Fig.: Drilling machine

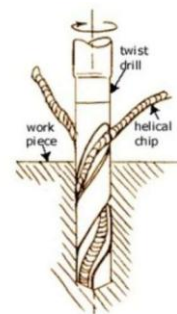


Fig.: Twist drill cutting action

A Twist Drill: It comprises a cutting point at the tip of a cylindrical shaft with helical flutes.

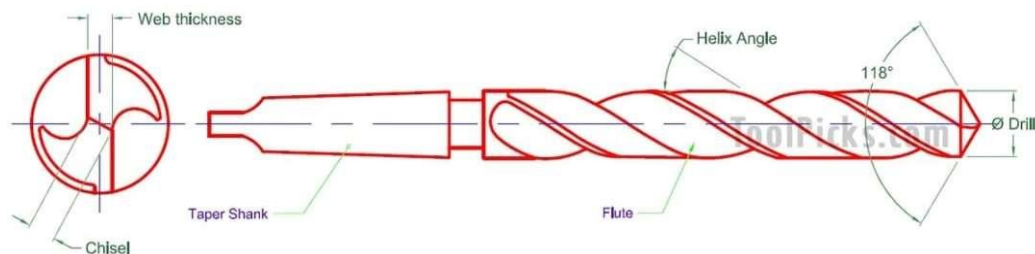


Fig.: Twist drill nomenclature

The angle between the flute and the axis of the drill that forms the cutting edge is known as the rake angle. Generally the rake angle is between 18° and 45° , with 30° being the most common.

Straight shank drills are used on most portable drilling machines – for example, the electric drill.

Geared Drill Chuck: Drills with straight shanks are held in geared drill chucks, which have three adjustable jaws to clamp onto the drill.

Tapered shank drills can be quickly and accurately inserted into the spindle of a machine without using screws or clamps.

Drill Sleeve and Socket: A drill too small for the machine spindle may be fitted into a socket or sleeve, which has a taper hole of the proper size to hold the drill and a taper shank of the proper size to fit the drill spindle.

Drill Operations: Drilling machines may be used to perform other operations. They can perform reaming, boring, counterboring, countersinking, tapping, etc.

Reaming: The process of enlarging a hole is called reaming. A typical reamer consists of a set of parallel straight or helical cutting edges along the length of a cylindrical body. It is a finishing operation giving high precision to a previously drilled hole.

Boring: It is the process of enlarging a hole that has already been drilled, by means of a single-point cutting tool. Boring is used to achieve greater accuracy of the diameter of a non-standard hole.

Counterboring: A counterbore is a cylindrical flat-bottomed hole that enlarges another coaxial hole. It is typically used when a fastener, such as a socket head cap screw, is required to sit flush with or below the level of a workpiece's surface. Whereas a counterbore is a flat-bottomed enlargement of a smaller coaxial hole, a countersink is a conical enlargement of such a hole.

Countersinking: A countersink is a conical hole cut into a manufactured object, or the cutter used to cut such a hole. A common use is to allow the head of a countersunk bolt or screw, when placed in the hole, to sit flush with or below the surface of the surrounding material.

Tapping: The process of cutting or forming internal threads in a hole using a tap is called tapping. Three types of tap are used in a set: bottoming tap, intermediate tap and taper tap.

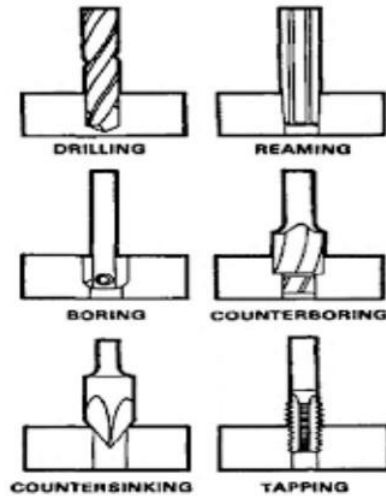


Fig.: Drilling machine operations

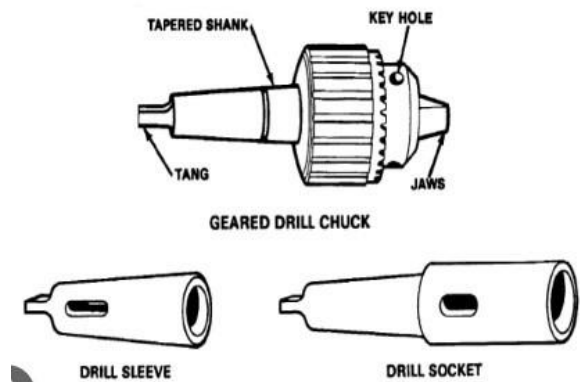


Fig.: Geared drill chuck, drill sleeve and drill socket

Machining Time

The machining time, T_c , is estimated from:

$$T_c = L_c / (N \times S_o) = \pi D (L_w + A + O + C) / (1000 \times V_c \times S_o)$$

where $L_c = L_w + A + O + C$

A and O are the approach and over-travel, and $C = (D/2) \cot p$

D = diameter of the drilled hole

p = half the drill point angle (60°)

Metal Removal Rate

It is the volume of material removed by the drill per unit time.

$$MRR = (\pi/4 \times D^2) \times S_m$$

where D = diameter of the drilled hole and S_m = feed rate.

Experimentation

Observation Table

No. of obs.	Drill dia. D (mm)	Depth of hole L_w (mm)	Spindle speed N (rpm)	Feed S_o (mm/rev)	Feed rate $S_m = S_o \times N$ (mm/min)	Time taken (sec)	Volume of metal removed (mm ³)	MRR (mm ³ /sec)
1.								
2.								

Volume of metal removed = $(\pi/4) \times D^2 \times L_w$; Experimental MRR = Volume / Time taken.

Analysis

Initially the machining time and metal removal rate are experimentally determined; then they are analytically estimated.

Responses	Experimental value	Analytical value
Machining Time		
MRR		

Precaution

- Clamp the workpiece firmly in a machine vice or on the table before starting; never hold it by hand while drilling.
- Fix the drill bit tightly and centrally in the chuck, and remove the chuck key before switching on the machine.
- Wear safety goggles; avoid loose clothing, gloves, ties and jewellery, and tie back long hair.
- Select the correct spindle speed and feed for the drill diameter and workpiece material, and apply the feed steadily. Reduce the feed as the drill breaks through a through hole.
- Remove chips only with a brush or hook after the spindle has stopped completely, never with bare hands.
- Switch off the machine before measuring the hole, changing the drill or adjusting the setup.

INSTRUCTION ITEM-1(II 2)		
Experiment No.	Name of the experiment	CO Congruence
EX2-II	Computation of Metal Removal Rate and Machining Time during Milling Process	[CO2]

Theory: A milling machine is a machine tool that removes metal as the workpiece is fed against a rotating multipoint cutter. As the workpiece is moved against the cutting edges of the milling cutter, metal is removed in the form of chips. The milling cutter rotates at a very high speed and removes metal at a very fast rate with the help of multiple cutting edges.

Types of Milling Cutter

Milling cutters are usually made of high-speed steel and are available in a great variety of shapes and sizes for various purposes. They are classified based on various factors:

1. Based on constructional features of the tooth of milling cutter:
 - a. Solid teeth milling cutter
 - b. Inserted teeth milling cutter
 - c. Tipped teeth milling cutter
2. According to the relief characteristics:
 - a. Profile relieved milling cutter
 - b. Form relieved milling cutter
3. Based on methods used for mounting:
 - a. Arbor type
 - b. Facing type
 - c. Shank type
4. According to the direction of rotation of cutter:
 - a. Right hand rotational milling cutter
 - b. Left hand rotational milling cutter
5. According to the direction of helix:
 - a. Parallel or straight teeth milling cutter
 - b. Right hand helical milling cutter
 - c. Left hand helical milling cutter
 - d. Alternate helical milling cutter
6. According to purpose or use of cutter:
 - a. Standard milling cutter
 - b. Special milling cutter

Methods of Milling

Milling is the process of cutting away material by feeding a workpiece past a rotating multiple-tooth cutter. The cutting action of the many teeth around the milling cutter provides a fast method of machining. The machined surface may be flat, angular or curved. The surface may also be milled to any combination of shapes.

1. Up-milling or Conventional Milling: In up-milling, metal is removed in the form of chips by the cutter rotating against the direction of travel of the workpiece.

2. Down-milling or Climb Milling: In down-milling, metal is removed in the form of chips by the cutter rotating in the same direction as the feed of the workpiece.

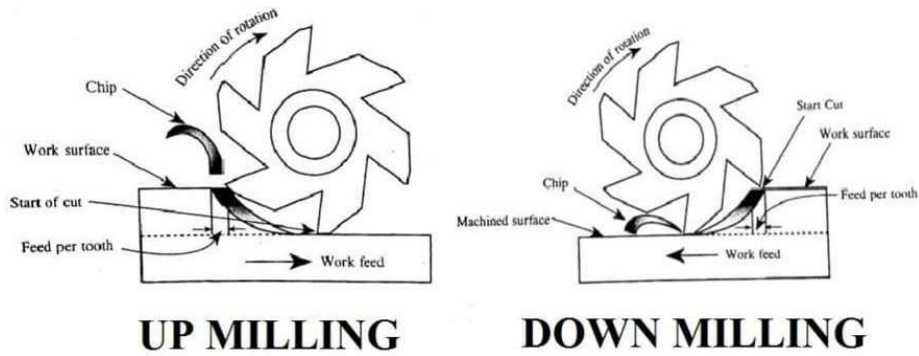


Fig. Up milling and down milling

Milling Equations

Rotational speed (rpm)

$$N = v / (\pi D)$$

N = rotational speed (rpm)

v = cutting speed (SFPM)

D = cutter diameter

Feed rate, f_r (distance/min)

$$f_r = N \times n_t \times f$$

f_r = feed rate (distance/min)

N = rotational speed

n_t = number of teeth on cutter

f = feed (in/tooth)

Machining time: Peripheral milling

$$T_m = (L + A) / f_r$$

T_m = machining time (min)

L = length of cut

A = approach distance

f_r = feed rate (distance/min)

Machining time: Face milling

$$T_m = (L + A + O) / f_r$$

T_m = machining time (min)

L = length of cut

A = approach distance

O = cutter run-out distance

f_r = feed rate (distance/min)

Metal removal rate (cu. in./min)

$$MRR = w \times d \times f_r$$

MRR = material removal rate (cu. in./min)

w = width of cut

d = depth of cut

f_r = feed rate (distance/min)

Experimentation

MRR is determined by milling the given MS work-piece where:

- Type of milling (peripheral / face; up / down): _____
- Milling cutter used: _____
- Cutter diameter, D (mm): _____
- Number of teeth on cutter, n_t : _____
- Spindle speed, N (rpm): _____
- Feed per tooth, f (mm/tooth): _____

The workpiece is fixed in the machine vice on the table and aligned. The cutter is mounted on the arbor, the required speed and feed are set, and the depth of cut is adjusted using the vertical feed. The table is fed against the rotating cutter and the time taken to complete the cut over the length of cut is noted with a stop watch. The width and depth of cut are measured with a vernier caliper.

Measuring instruments used

- Tachometer
- Vernier Caliper (Mitutoyo make)
- Stop watch

Observation Table

No. of obs.	Length of cut L (mm)	Width of cut w (mm)	Depth of cut d (mm)	Volume of metal removed (mm ³)	Time taken (sec)	MRR (mm ³ /sec)
1.						
2.						

Volume of metal removed = $L \times w \times d$; Experimental MRR = Volume / Time taken.

Analysis

Initially the machining time and metal removal rate are experimentally determined; then they are analytically estimated using $f_r = N \times n_t \times f$, $T_m = (L + A)/f_r$ (peripheral milling) or $(L + A + O)/f_r$ (face milling), and $MRR = w \times d \times f_r$.

Responses	Experimental value	Analytical value
Machining Time		

Responses	Experimental value	Analytical value
MRR		

Precautions

- Do not make contact with the revolving cutter.
- Place a wooden pad or suitable cover over the table surface to protect it from possible damage.
- Use the buddy system when moving heavy attachments.
- Do not attempt to tighten arbor nuts using machine power.
- When installing or removing milling cutters, always hold them with a rag to prevent cutting your hands.
- While setting up work, install the cutter last to avoid being cut.
- Never adjust the workpiece or work-mounting devices when the machine is operating.
- Chips should be removed from the workpiece with an appropriate rake and a brush.
- Shut the machine off before making any adjustments or measurements.
- When using cutting oil, prevent splashing by using appropriate splash guards.
- Cutting oil on the floor can cause a slippery condition that could result in operator injury.

INSTRUCTION ITEM-1(II 3)		
Experiment No.	Name of the experiment	CO Congruence
EX3	Determination of Cutting Force during the Machining Process	[CO3]

Theory: A force can neither be seen nor touched, but it can be felt and measured by its effect(s) and the quantity of those effects (on some material), like elastic deflection, deformation, pressure, strain, etc. These effects, described as signals, normally need proper conditioning for easy, accurate and reliable detection and measurement. The measurement process comprises three stages:

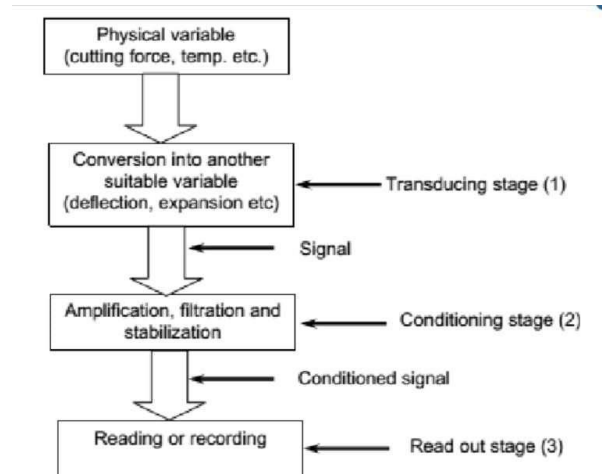


Fig.: Stages of the force measurement process

Measurement of cutting force(s) is based on three basic principles:

- (a) Measurement of elastic deflection of a body subjected to the cutting force
- (b) Measurement of elastic deformation, i.e. strain induced by the force
- (c) Measurement of pressure developed in a medium by the force

(a) Measuring deflection caused by the cutting force(s)

In turning, deflection δ is proportional to the magnitude of the cutting force P_z :

$$\delta = P_z L^3 / (3EI)$$

where L = overhang, E = Young's modulus of elasticity of the beam, I = moment of inertia of the beam section.

The deflection δ can be measured mechanically by a dial gauge and electrically by a potentiometer.

(b) Measurement of elastic deformation (strain) induced by the force

The strain ϵ is proportional to the magnitude of the force P_z :

$$\epsilon = \sigma / E = (M / Z) / E = P_z L / (Z E)$$

where M = bending moment, Z = sectional modulus of the section, I = moment of inertia of the section.

(c) Measurement of pressure developed in a medium by the force

The force causes pressure on a piezoelectric crystal and produces an emf proportional to the force or pressure:

$$Emf = \lambda t F$$

where λ = voltage sensitivity of the crystal, t = thickness of the crystal, F = force.

Turning dynamometers may be of the strain-gauge or piezoelectric type and may be of one, two or three dimensions, capable of monitoring all of P_x , P_y and P_z . In practice, all metal cutting operations are oblique in nature, resulting in a spatial distribution of the cutting force components. The cutting forces generated in metal cutting have a direct influence on heat generation, tool wear or failure, quality of the machined surface and accuracy of the workpiece.

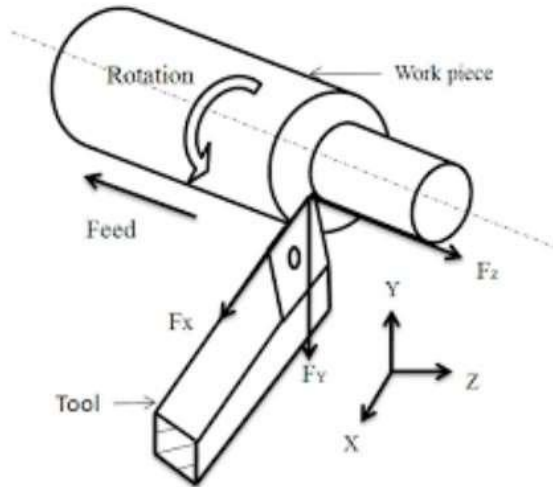


Fig.: Cutting force components in turning

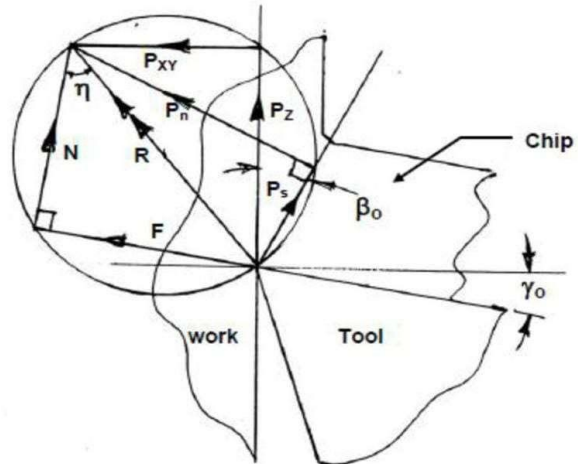


Fig.: Merchant's circle diagram

The components of the cutting force act along three perpendicular directions. The Lathe Tool Dynamometer measures the reaction forces acting in these three directions on the tool during cutting. The cutting force (F_z), thrust force (F_y) and feed force (F_x) values during the turning operation are to be logged. The same operation, with the parameters unchanged, is to be repeated a stipulated number of times. In each case the values of F_x , F_y and F_z are logged from the dynamometer. The value of the actual cutting force is calculated from the components in each case and then averaged.

$$F_R = \sqrt{(F_x^2 + F_y^2 + F_z^2)}$$

Operation: The job is gripped in the headstock chuck and centred. The tool-post of the lathe is removed and replaced by the tool-post supplied with the Lathe Tool Dynamometer. It is then connected to the controller, and the whole system of the Lathe Tool Dynamometer is powered by an electrical connection. Chip is removed from the job by straight turning, selecting a suitable feed rate and depth of cut. During this cutting operation the values of cutting force, thrust force and feed force are taken from the display panel of the controller and logged. The operation is repeated a number of times.

Experimentation

For metal removal by turning of the given MS work-piece:

- Cutting tool used: _____
- RPM applied: _____
- Principal cutting edge angle (ϕ): _____
- Rake angle (γ_o): _____

Measuring instruments used

- Vernier Caliper (Mitutoyo make)
- Tachometer
- Stop watch

Observation Table

Turning length (L) = _____

Feed rate (S_o) = _____

Depth of cut (t) = _____

No. of obs.	Feed force F_x (N)	Radial force F_y (N)	Cutting force F_z (N)	$F_{xy} = \sqrt{(F_x^2 + F_y^2)}$
1				
2				
3				
N =	$\Sigma F_x^2 / N$	$\Sigma F_y^2 / N$	$\Sigma F_z^2 / N$	$\Sigma \sqrt{(F_x^2 + F_y^2)} / N$

Procedure for drawing Merchant's Circle Diagram

1. Determine P_{xy} from P_z .
1. Choose a suitable scale for presenting P_z and P_{xy} in cm.
2. Draw P_z and P_{xy} along and normal to V_o .
3. Draw the cutting force R as the resultant of P_z and P_{xy} .
4. Draw the circle (Merchant's circle) taking R as diameter.
5. Get F and N as intercepts in the circle by extending the tool rake surface and joining the tips of F and R.
6. Divide the intercepts of F and N by the scale and get the values of F and N.
7. Determine P_s and P_n from the value of the shear angle β_o .
8. Draw the shear plane with the value of β_o , and then P_s and P_n as intercepts.
9. Get the values of P_s and P_n by dividing their corresponding lengths by the scale.
10. Get the value of the apparent coefficient of friction, μ , at the chip-tool interface.
11. Get the friction angle, η .

Precautions

- Ensure that the workpiece is firmly gripped and properly centred in the lathe chuck before starting the operation.
- Check that the Lathe Tool Dynamometer is properly mounted and securely connected to the controller.
- Ensure that the dynamometer is correctly calibrated and set to zero before taking measurements.
- Fix the cutting tool rigidly at the correct height and maintain the specified tool geometry, including rake angle and principal cutting-edge angle.
- Set the required RPM, feed rate, and depth of cut accurately and keep these parameters constant during repeated observations.
- Ensure that the dynamometer cables and electrical connections are properly secured and kept away from moving parts.
- Do not touch the rotating workpiece, cutting tool, chuck, or any moving component during machining.
- Record the values of F_x , F_y , and F_z only after the cutting conditions have become steady.
- Take readings consistently for each trial and avoid recording transient force fluctuations during tool entry or exit.
- Use a suitable cutting tool and ensure that it is sharp and free from damage to obtain reliable force measurements.
- Remove chips only after stopping the machine, using a suitable brush or chip-removal tool; never remove chips by hand.
- Verify all measured force components and calculations before determining the resultant cutting force and drawing the Merchant's circle diagram.

- Switch off the lathe and dynamometer system before making any adjustment to the tool, workpiece, or measuring equipment.

INSTRUCTION ITEM-1(II 4)		
Experiment No.	Name of the experiment	CO Congruence
EX4	Computation of Cutting Parameters along with Shear Plane Angle, Chip Reduction Coefficient and Shear Strain	[CO4]

Theory: Machining is a process of gradual removal of excess material from preformed blanks in the form of chips. The form of machined chips depends mainly upon:

- Work material
- Material and geometry of the cutting tool
- Levels of cutting velocity and feed, and also to some extent on depth of cut
- Temperature and friction at the chip-tool and work-tool interfaces
- Cutting fluid – flow, type, velocity

Chip reduction coefficient or cutting ratio

In the formation of continuous chips, the chip thickness (a_2) usually becomes larger than the uncut chip thickness (a_1). The reason can be attributed to:

- Compression of the chip ahead of the tool
- Frictional resistance to chip flow
- Lamellar sliding according to Piispanen

Cutting parameters during chip formation

t = depth of cut (mm): perpendicular penetration of the cutting tool tip into the work surface

S_o = feed (mm/rev): axial travel of the tool per revolution of the job

b_1 = width (mm) of chip before cut

b_2 = width (mm) of chip after cut

a_1 = thickness (mm) of uncut layer (or chip before cut)

a_2 = chip thickness (mm), i.e. thickness of chip after cut

A_1 = cross-section (area, mm²) of chip before cut

The degree of thickening of the chip is expressed by the chip reduction coefficient (ξ) = $a_2/a_1 > 1.0$, since $a_2 > a_1$.

Uncut chip thickness (a_1) = $S_o \sin \phi$, where ϕ = principal cutting edge angle

Chip width (b_2) = $t / \sin \phi$, Shear area (A_s) = $t S_o / \sin \beta_o$

A larger value of ξ means more thickening, i.e. more effort in terms of forces or energy is required to accomplish the machining work.

$$\text{Cutting ratio } (r) = 1/\xi = a_1/a_2$$

The value of the chip reduction coefficient ξ (and hence the cutting ratio) depends mainly upon:

- Tool rake angle, γ_o
- Chip-tool interaction, mainly friction, μ

For orthogonal cutting:

$$\xi = e^{\mu(\pi/2 - \gamma_o)}$$

The total volume of chip produced before and after cut in a given time:

$$a_1 \times b_1 \times L_1 = a_2 \times b_2 \times L_2$$

where a_1, a_2 = chip thickness before and after cut, and L_1, L_2 = total length of the chip before and after cut.

The width of chip generally does not change significantly during machining; therefore $b_1 = b_2$, and

$$\xi = a_2/a_1 = L_1/L_2$$

Considering unchanged material flow (volume) ratio, $Q = (a_1 b_1) V_c$, where V_c is the cutting velocity and V_f is the chip velocity. Therefore,

$$\xi = a_2/a_1 = V_c/V_f$$

Shear plane: The plane of separation of the work material layer, in the form of chip, from the parent body due to shear along that plane.

Shear angle (β_o): The angle of inclination of the shear plane from the direction of the cutting velocity. From the geometry, with $AC = a_2 = OA \cos(\beta_o - \gamma_o)$ and $AB = a_1 = OA \sin\beta_o$:

$$\xi = a_2/a_1 = \cos(\beta_o - \gamma_o) / \sin\beta_o = (\cos\beta_o \cos\gamma_o + \sin\beta_o \sin\gamma_o) / \sin\beta_o = (\cos\gamma_o + \tan\beta_o \sin\gamma_o) / \tan\beta_o$$

$$\tan\beta_o = \cos\gamma_o / (\xi - \sin\gamma_o)$$

During machining, particularly of ductile materials, the chip sharply changes its direction of flow (relative to the tool) from the direction of the cutting velocity V_c to that along the tool rake surface (V_f) after thickening by shear deformation, where V_s is the shear velocity:

$$V_c / \cos(\beta_o - \gamma_o) = V_s / \cos\gamma_o = V_f / \sin\beta_o$$

$$V_c / V_f = \cos(\beta_o - \gamma_o) / \sin\beta_o = \xi > 1$$

$$V_s = V_c \cos\gamma_o / \cos(\beta_o - \gamma_o) \quad \text{and} \quad V_f = V_c \sin\beta_o / \cos(\beta_o - \gamma_o)$$

Cutting strain (ϵ): The magnitude of strain that develops along the shear plane due to the machining action is called cutting strain.

$$\epsilon = \Delta S/Y = PM/ON = (PN + NM)/ON = PN/ON + NM/ON$$

$$\epsilon = \cot\beta_o + \tan(\beta_o - \gamma_o)$$

Experimentation

For metal removal by turning of the given MS work-piece:

- Cutting tool used: _____
- RPM applied: _____
- Principal cutting edge angle (ϕ): _____
- Rake angle (γ_o): _____

Measuring instruments used

- Vernier Caliper (Mitutoyo make)
- Tachometer
- Stop watch

Observation Table

No. of obs.	Initial dia (mm)	Final dia (mm)	Turning length (mm)	Time taken (sec)
1.				

No. of obs.	Initial dia (mm)	Final dia (mm)	Turning length (mm)	Time taken (sec)
2.				

Analysis

1. Uncut chip thickness = _____
1. Chip width = _____
2. Shear area (A_s) = _____
3. Chip reduction coefficient = _____
4. Shear angle = _____
5. Velocity of chip = _____
6. Cutting strain = _____

Precaution

- Ensure that the workpiece is firmly clamped and properly centred in the lathe chuck before starting the machining operation.
- Ensure that the cutting tool is sharp, securely fixed, and set at the correct centre height.
- Set the specified RPM, feed rate, depth of cut, principal cutting-edge angle, and rake angle accurately before machining.
- Keep the cutting conditions constant for all observations to obtain consistent chip-formation results.
- Measure the initial and final diameters of the workpiece accurately using a properly calibrated vernier caliper.
- Collect the chips carefully without disturbing or deforming them, as chip thickness and length are required for calculating the chip reduction coefficient.
- Avoid excessive deformation, bending, or breaking of the chips during collection and measurement.
- Record the machining time accurately using a stopwatch for each observation.
- Ensure that the cutting tool engages the workpiece smoothly and avoid sudden changes in feed or depth of cut.
- Do not touch the rotating workpiece, cutting tool, chuck, or chips while the lathe is running.
- Remove chips only after stopping the machine, using a suitable brush or chip-removal tool; never remove chips by hand.
- Use appropriate safety goggles, safety shoes, and other required workshop PPE during the experiment.
- Switch off the machine before making any adjustment to the workpiece, cutting tool, or machine settings.
- Take all dimensional and chip measurements carefully and use consistent units throughout the calculations.

INSTRUCTION ITEM-1(II 5)		
Experiment No.	Name of the experiment	CO Congruence
EX5	Verification of Taylor's Tool Life Equation for a Given Tool–Workpiece Combination by Variation of Cutting Velocity	CO5

Theory: Tool life generally indicates the amount of satisfactory performance or service rendered by a fresh tool or a cutting point until it is declared failed. Tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limits of tool wear.

Tool wear describes the gradual failure of a cutting tool due to regular operation. The common mechanisms of cutting tool wear are:

i) Mechanical wear

- Thermally insensitive type, like abrasion, chipping and de-lamination
- Thermally sensitive type, like adhesion, fracturing, flaking, etc.

ii) Thermo-chemical wear

- Macro-diffusion by mass dissolution
- Micro-diffusion by atomic migration

iii) Chemical wear: leading to damages like grooving wear

iv) Galvanic wear: based on electrochemical dissolution

Cutting tools generally fail by:

- **Flank wear** in which the portion of the tool in contact with the finished part erodes
- **Crater wear** in which contact with chips erodes the rake face
- **Quick dulling** by plastic deformation due to intensive stresses and temperature
- **Catastrophic failure** of the cutting tools due to excessive forces and shock

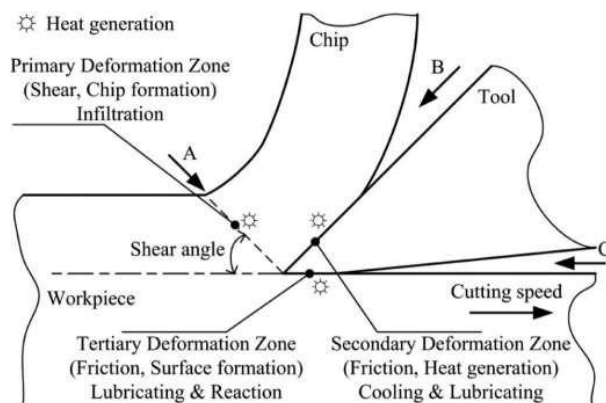


Fig.: Heat generation and deformation zones in cutting

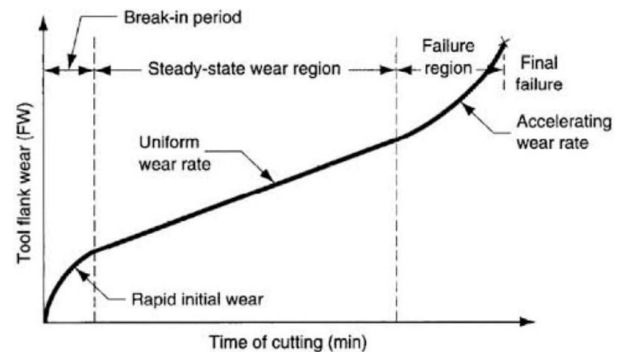


Fig.: Typical tool wear curve

Taylor's equation for tool life expectancy provides a good approximation:

$$V_c T^n = C$$

A more general form of the equation is

$$V_c T^n D^x S^y = C$$

where V_c = cutting speed

T = tool life

D = depth of cut

S = feed rate

x and y are determined experimentally

n and C are constants found by experimentation or published data; they are properties of the tool material, workpiece and feed rate ($n < 1$, C is very large).

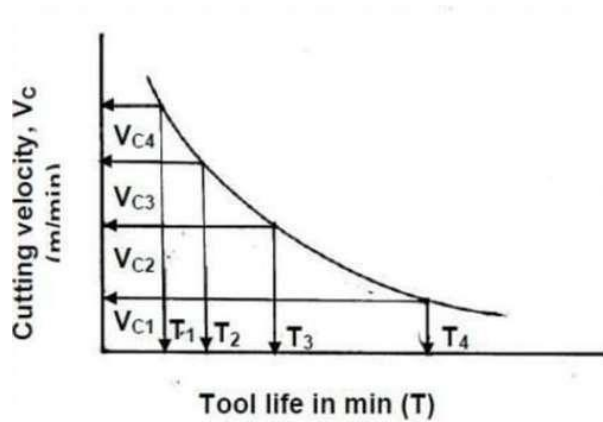


Fig.: Cutting velocity versus tool life

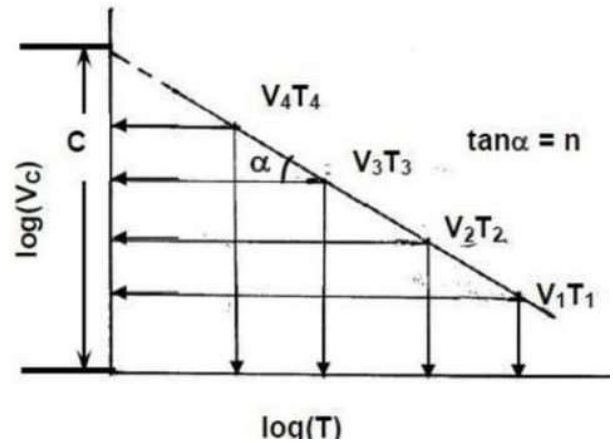


Fig.: $\log V_c$ versus $\log T$ ($\tan \alpha = n$)

Experimentation

For metal removal by turning of the given MS work-piece:

- Cutting tool used: _____
- RPM applied: _____
- Principal cutting edge angle (ϕ): _____
- Rake angle (γ_o): _____

Measuring instruments used

- Vernier Caliper (Mitutoyo make)
- Tachometer
- Stop watch

Observation Table

Turning length (L) = _____

Feed rate (S_o) = _____

Depth of cut (t) = _____

Sl. No.	Initial dia (mm)	Final dia (mm)	Turning length (mm)	Time taken (sec)
1.				

Sl. No.	Initial dia (mm)	Final dia (mm)	Turning length (mm)	Time taken (sec)
2.				

Analysis

- Experimental value of tool life:

-
- Analytical value of the constant 'n':
-

Precaution

- Ensure that the workpiece is firmly clamped and properly centred in the lathe chuck before starting the experiment.
- Ensure that the cutting tool is sharp, securely fixed, and positioned at the correct centre height.
- Set the required cutting speed, feed rate, depth of cut, and tool geometry accurately before machining.
- Keep the feed rate, depth of cut, and other machining conditions constant while comparing tool-life observations.
- Measure and record the initial and final diameters of the workpiece accurately using a properly calibrated vernier caliper.
- Measure the spindle speed using the tachometer before or during the machining operation and ensure that the required speed is maintained.
- Record the machining time accurately using a stopwatch for each observation.
- Inspect the cutting tool periodically for flank wear, crater wear, chipping, or other visible damage without touching the tool while it is moving.
- Stop the machine before examining, measuring, or replacing the cutting tool.
- Do not allow the tool to continue machining after the specified tool-wear limit or signs of catastrophic failure are reached.
- Remove chips only after stopping the machine and use a suitable brush or chip-removal tool; never remove chips by hand.
- Use appropriate safety goggles, safety shoes, and other required workshop PPE throughout the experiment.
- Maintain the same measurement procedure and tool-wear criterion for all observations to obtain reliable tool-life data.
- Switch off the machine before making any adjustment to the workpiece, cutting tool, or machine settings.

INSTRUCTION ITEM-1(II 6)		
Experiment No.	Name of the experiment	CO Congruence
EX6	Determination of Surface Finish during Machining Process	CO6

Theory: Surface roughness is like a fingerprint left behind by the manufacturing process.

1. Surface irregularities of small wavelength are called primary texture or roughness. These are caused by the direct action of the cutting elements on the material, i.e. cutting tool shape, feed rate, or by some other disturbances such as friction, wear or corrosion.
2. Surface irregularities of considerable wavelength and of a periodic character are called secondary texture or waviness. These irregularities result from inaccuracies of slides, wear of guides, misalignment of centres, non-linear feed motion, vibrations of any kind, etc.

Elements of surface texture

1. **Actual Surface:** It refers to the surface of a part which is actually obtained after the manufacturing process.
2. **Nominal Surface:** A nominal surface is a theoretical, geometrically perfect surface which does not exist in practice, but it is an average of the irregularities that are superimposed on it.
3. **Profile:** It is defined as the contour of any section through a surface.
4. **Lay:** It is the direction of the predominant surface pattern produced by the tool marks or scratches. Surface roughness is generally measured perpendicular to the lay.
5. **Sampling Length:** It is the length of the profile necessary for the evaluation of the irregularities to be taken into account.
6. **Roughness Height:** This is rated as the arithmetical average deviation, expressed in micrometres, normal to an imaginary centre line running through the profile.
7. **Roughness Width:** Roughness width is the distance, parallel to the normal surface, between successive peaks or ridges that constitute the predominant pattern of the roughness.

Measuring Instruments

1. Profilograph
1. Tomlinson surface meter
2. Taylor-Hobson Talysurf

Advantages

- The main advantage of such instruments is that the electrical signal available can be processed to obtain any desired roughness parameter, or can be recorded for display or subsequent analysis.
- Therefore, stylus-type instruments are widely used for surface texture measurements in spite of the following disadvantages.

Disadvantages

- These instruments are bulky and complex.
- They are relatively fragile.
- Initial cost is high.

- Measurements are limited to a section of a surface.
- They need skilled operators for measurements.
- The distance between stylus and skid, and the shape of the skid, introduce errors in measurement for wavy surfaces.

Observation Table

Sl. No.	R _a (μm)	R _q (μm)	R _z (μm)	R _t (μm)	R _{sk}	R _{ku}
1.						
2.						

Precaution

- Ensure that the surface of the workpiece is clean and free from dust, oil, grease, chips, and other contaminants before measurement.
- Ensure that the surface roughness instrument is properly calibrated and set to zero before taking measurements.
- Place the workpiece firmly on a stable surface and prevent any movement or vibration during measurement.
- Position the stylus correctly on the surface and ensure that it moves perpendicular to the lay unless otherwise specified.
- Use the appropriate sampling length and evaluation length according to the surface condition and instrument settings.
- Avoid applying excessive pressure on the stylus, as it may damage the stylus or affect the measured roughness value.
- Do not touch the measuring stylus or interfere with its movement while the instrument is operating.
- Take measurements at several representative locations on the workpiece to account for surface variations.
- Ensure that the stylus tip is clean and undamaged before conducting the experiment.
- Avoid external vibration and disturbances during measurement, as they can significantly affect the surface roughness readings.
- Record the values of R_a, R_q, R_z, R_t, R_{sk}, and R_{ku} carefully after the readings become stable.
- Use the same measurement direction, sampling length, and instrument settings for all specimens when making comparisons.
- Handle the surface roughness instrument carefully because the stylus and associated components are delicate.
- Switch off the instrument after completing the measurements and keep the equipment properly covered and stored.

Frequently Asked Questions (FAQs) – Manufacturing/Metrology Topics

A. Turning Operation

1. What is Metal Removal Rate (MRR) in turning?

MRR is the volume of material removed per unit time. For turning:

$$MRR = \pi D N f d$$

where D = diameter, N = spindle speed, f = feed/rev, and d = depth of cut.

2. How is cutting speed calculated in turning?

$$V = \pi D N / 1000 \text{ m/min}$$

where D is in mm and N is in rpm.

3. What is depth of cut in turning?

Depth of cut is the radial thickness of material removed in one pass:

$$d = (D_1 - D_2) / 2$$

4. How is machining time calculated in turning?

$$T = L / f N$$

where L is the effective length of cut, f is feed/rev and N is spindle speed.

B. Drilling and Milling

5. What is MRR in drilling?

For drilling:

$$MRR = \pi D^2 / 4 f N$$

Where D is drill diameter, f is feed/rev and N is rpm.

6. What are the important drilling parameters?

The major parameters are drill diameter, spindle speed, cutting speed, feed, depth of hole and machining time.

7. What is the difference between up-milling and down-milling?

In up-milling, cutter rotation is opposite to feed direction. In down-milling, cutter rotation and feed direction are the same.

8. What is face milling?

Face milling produces a flat surface with the cutting action primarily occurring at the face/periphery of a rotating cutter, with the cutter axis generally perpendicular to the machined surface.

9. What is peripheral milling?

Peripheral milling removes material mainly using the peripheral teeth of the cutter, with the cutter axis generally parallel to the machined surface.

10. What factors affect milling MRR?

MRR depends mainly on cutter diameter, width/depth of cut, number of teeth, feed per tooth, spindle speed and cutting speed.

C. Shaping Operation

11. What is the principle of a shaping machine?

A shaping machine produces a flat surface by reciprocating a single-point cutting tool over the workpiece.

12. What is stroke length in shaping?

Stroke length is the distance travelled by the ram during one complete cutting-return cycle.

13. What is the relationship between cutting speed and number of strokes?

Approximately,

$$V_c = L_s N_s / 1000$$

where L_s is stroke length in mm and N_s is the number of cutting strokes per minute.

14. How is MRR determined in shaping?

MRR can be determined from:

$MRR = \text{Volume of material removed} / \text{Machining time}$ and can be compared with the analytically calculated value.

D. Cutting Forces and Merchant's Circle

15. What is a lathe tool dynamometer?

A lathe tool dynamometer is an instrument used to measure the cutting forces acting on a tool during turning.

16. What are the three principal cutting forces in turning?

They are cutting/tangential force, feed/axial force and radial/thrust force.

17. What is the resultant cutting force?

It is the vector resultant of the mutually acting cutting-force components. For orthogonal components:

$$F_R = \sqrt{(F_c^2 + F_t^2)}$$

18. What is Merchant's circle diagram?

Merchant's circle is a graphical method used to resolve the cutting-force components into friction force, normal force, shear force and related components during orthogonal cutting.

E. Chip Formation and Tool Life

19. What is chip reduction coefficient?

Chip reduction coefficient is the ratio of uncut chip thickness to chip thickness:

$$r_c = t_1 / t_2$$

where t_1 is uncut chip thickness and t_2 is chip thickness.

20. What is shear plane angle?

The shear plane angle is the angle between the shear plane and the cutting direction. Under Merchant's simplified relationship:

$$\phi = 45^\circ + \alpha/2 - \beta/2$$

21. What is Taylor's tool-life equation?

Taylor's equation relates cutting speed and tool life:

$$VT^n=C$$

where V is cutting speed, T is tool life, n is the tool-life exponent and C is a constant.

22. How is Taylor's tool-life equation experimentally verified?

Machining tests are conducted at different cutting speeds, tool life is measured for each speed, and the data are used to establish the relationship:

$$VT^n=C$$

F. Surface Roughness and Metrology

23. What is the difference between roughness, waviness and lay?

- Roughness: fine, closely spaced surface irregularities.
- Waviness: larger and more widely spaced surface deviations.
- Lay: predominant direction/pattern of surface irregularities produced by machining.

24. What are Ra, Rq, Rz and Rt?

- Ra: arithmetic mean surface roughness.
- Rq: root-mean-square roughness.
- Rz: average maximum height/depth characteristic over specified sampling lengths.
- Rt: total profile height between the highest peak and deepest valley over the assessment length.

25. What are Rsk and Rku, and what instruments are used for surface measurement?

- Rsk: skewness, indicating asymmetry of the surface-height distribution.
- Rku: kurtosis, indicating the sharpness/peakedness of the distribution.

Surface texture can be measured using instruments such as profilograph, Tomlinson surface meter and Taylor-Hobson Talysurf.