Metal Cutting & Machining

MODULE-5

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Prepared By:

Dr. Soumya Ranjan Parimanik

Guest Faculty

Department of Mechanical Engineering,

Government College of Engineering, Kalahandi

Dr. Ajit Kumar Pattanaik

Assistant Professor

Department of Mechanical Engineering,

Government College of Engineering, Kalahandi

Syllabus

Non-Traditional Machining Processes: Ultrasonic Machining (USM), Electrochemical Machining (ECM), Electric Discharge Machining (EDM), Wire EDM, Abrasive Jet Machining (AJM), Plasma Arc Machining (PAM) and Laser Beam Machining (LBM).

Learning Outcomes

After completing Module V, students will be able to:

- **Explain the need** – why non-traditional processes are required for hard materials, complex shapes and high accuracy.
- **Classify the processes** – by energy type, mechanism of material removal and energy source.
- **Compare the two approaches** – traditional vs non-traditional machining on tool, energy, accuracy and cost.
- **Describe each process** – principle, equipment and process parameters of USM, AJM, ECM, EDM, Wire EDM, PAM and LBM.
- **Select a suitable process** – for a given material, shape and accuracy, with its advantages and limitations.

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Reference Book

A. Ghosh and A. K. Mallik, *Manufacturing Science*, East-West Press

Contents

No.	Section	Slides
1	Introduction to Non-Traditional Machining	4–7
2	Ultrasonic Machining (USM)	8–28
3	Electrochemical Machining (ECM)	29–46
4	Electric Discharge Machining (EDM)	47–77
5	Wire Electric Discharge Machining (WEDM)	78–90
6	Abrasive Jet Machining (AJM)	91–104
7	Laser Beam Machining (LBM)	105–112
8	Plasma Arc Machining (PAM)	113–116
9	Solved Questions (Q&A)	117–125

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Dr. S.K. Parimanik
Dr. A.K. Pattanaik

Introduction to Non-Traditional Machining

- **Machining:** removing excess material from a workpiece to obtain the desired shape and size.
- **Traditional (conventional) machining:** turning, milling, drilling, grinding. A cutting tool harder than the workpiece shears material away as chips.
- **Non-traditional (unconventional) machining:** removes material using mechanical, electrical, thermal or chemical energy, usually without a sharp cutting tool.
- **Machinability:** the response of a workpiece material to the cutting process. Low machinability means the material is difficult to cut.

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Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Two approaches to tackle difficult machining jobs

1. **Modify a traditional process**
   Example: hot machining, where the workpiece is heated to soften it before cutting.

2. **Develop new processes**
   The non-traditional processes studied in this module (USM, AJM, ECM, EDM, PAM, LBM).

Need for Non-Traditional Machining

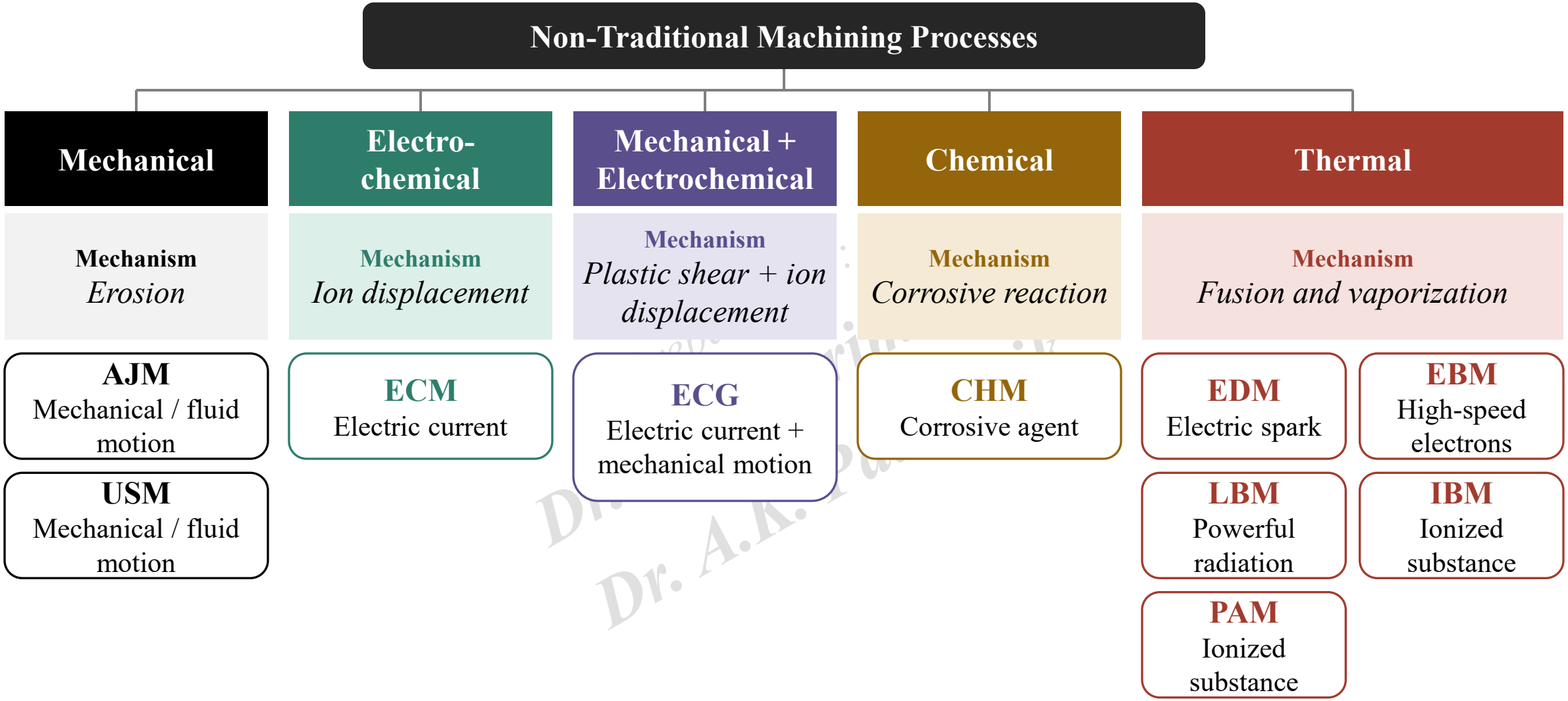
Traditional processes become difficult, or impossible, to use for three main reasons:

New materials with low machinability	Dimensional and accuracy requirements	Higher production rate and economy
Superalloys, ceramics, carbides, glass and semiconductors are too hard, tough or brittle to cut with conventional tools. *Example: a complex turbine blade made of a superalloy.*	Complex shapes and very small or unusual features are hard to produce accurately with a conventional cutting tool. *Example: drilling a non-circular hole or a micro-hole.*	Industry needs more parts at a lower cost; for hard materials and complex shapes, conventional machining is too slow. *Example: holes and slots in glass and semiconductors.*

Result: these processes are becoming unavoidable, so every mechanical engineer should know them.

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Classification of Non-Traditional Machining Processes



Each process box shows the energy source. AJM abrasive jet, USM ultrasonic, ECM electrochemical, ECG electrochemical grinding, CHM chemical, EDM electric discharge, EBM electron beam, LBM laser beam, IBM ion beam, PAM plasma arc machining.

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Traditional vs Non-Traditional Machining

Aspect	Traditional machining	Non-traditional machining
Energy used	Mechanical (cutting action)	Mechanical, thermal, chemical, electric
Material removal	Macroscopic chips by shearing	Microscopic particles, not chips
Tool contact	Tool touches the workpiece	No direct tool–work contact (mostly)
Tool hardness	Tool harder than the workpiece	Tool need not be harder than work
Tool wear	High wear, shorter tool life	Little or no wear, longer tool life
Accuracy and finish	Lower	Higher
Material removal rate	Higher	Lower
Capital cost	Lower	Higher
Equipment set-up	Simple	Complex; needs skilled operators

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Ultrasonic Machining

(USM)

Contents

1. Need and principle of USM
2. Mechanisms of material removal
3. Ultrasonic drilling machine: acoustic head, transducer and concentrators
4. Feed mechanisms
5. Tool and abrasive slurry
6. Shaw's model of material removal rate
7. Worked example: square hole in a WC plate
8. Effect of process parameters on MRR and surface finish
9. Why USM suits brittle materials

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Dr. S.R. Parimanik
Dr. A.K. Pattanaik

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Ultrasonic Machining (USM): Need

- **USM** is a mechanical non-traditional process: a tool vibrating at ultrasonic frequency drives abrasive grains in a slurry against the work and chips away tiny particles.

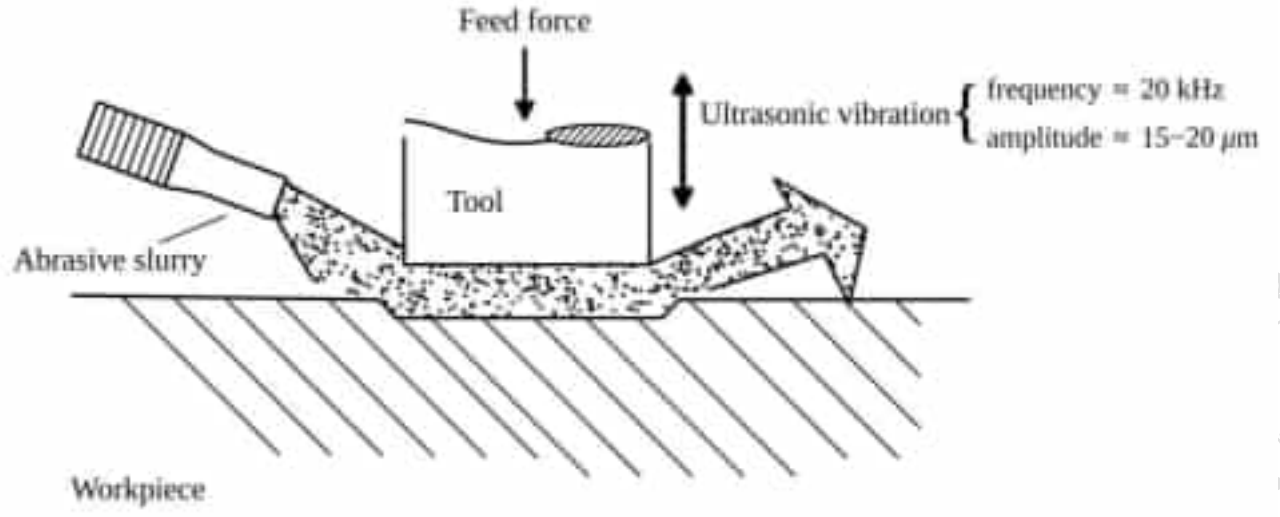
Why hard, brittle, non-conductive materials need a non-thermal process

Hard and brittle	Electrically non-conductive	Heat-sensitive
Glass, ceramics, quartz, germanium and silicon crack or chip under a conventional cutting tool.	ECM and EDM need a conductive workpiece, so they cannot machine glass or ceramics.	Thermal processes (LBM, EBM, PAM) can crack the work and leave a heat-affected zone. USM's small cutting force causes no appreciable heating or stress.

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History: L. Balamuth first proposed ultrasonic machining in 1945; USM machine tools were built by 1954.

Principle of Ultrasonic Machining



Ultrasonic machining

Typical tool vibration

Frequency ≈ 20 kHz

Amplitude ≈ 15–20 μm

- **Tool:** made of a tough, ductile material, vibrates at ultrasonic frequency.
- **Abrasive slurry:** flows continuously through the small gap between tool and work.
- **Feed:** the tool is fed with a uniform force.
- **Cutting:** hard grains strike and fracture the hard, brittle work surface into small wear particles.
- **Tool wear:** the ductile tool wears out at a much slower rate.

Dr. S.K. Patnaik
Dr. A.K. Pattanaik

Mechanisms of Material Removal in USM

Material is removed by four mechanisms acting together:

MAIN MECHANISM

1. Hammering

The vibrating tool hammers abrasive grains into the work surface. This removes most of the material.

2. Free-grain impact – loose grains in the slurry strike the work surface.

3. Cavitation erosion – collapsing bubbles in the slurry erode the surface.

4. Chemical action – reaction of the slurry fluid with the work surface.

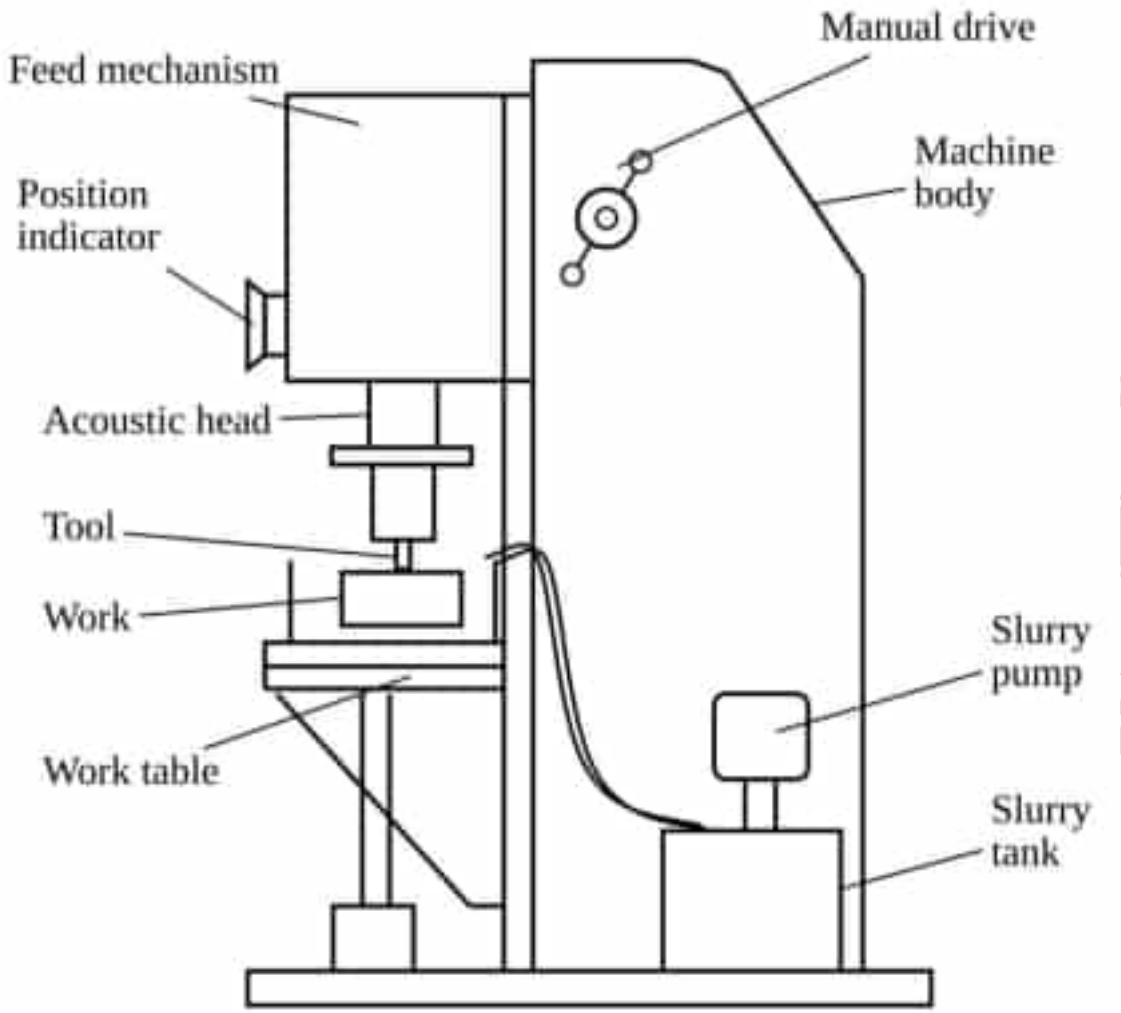
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Shaw's model: the generally accepted model of M.C. Shaw considers only hammering, the direct impact of the tool on grains touching the work.

$$Q \propto vZv$$

Q = volume MRR; v = volume removed per impact; Z = grains impacting per cycle; ν = frequency

Ultrasonic Drilling Machine



Ultrasonic drilling machine

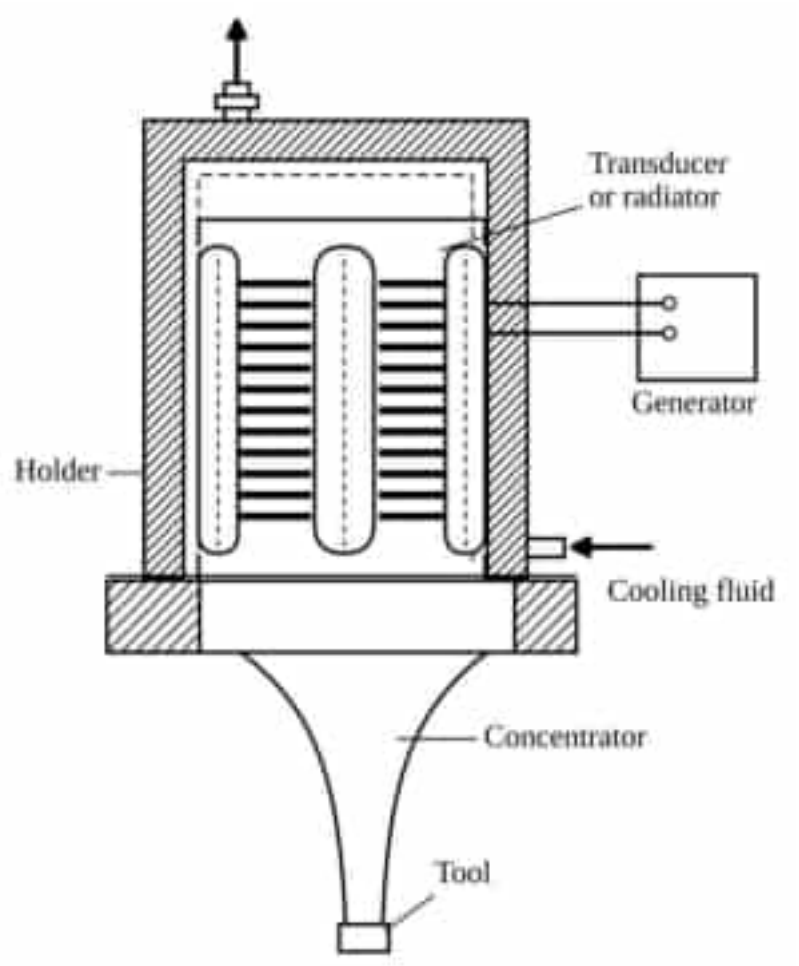
Main units of a USM machine

1. **Acoustic head**
   produces the vibration in the tool
2. **Feeding unit**
   applies the working force; shows depth
3. **Tool**
   shapes the hole or cavity
4. **Abrasive slurry and pump unit**
   feeds grains to the gap, removes debris
5. **Body with work table**
   supports and positions the work

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Acoustic Head and Transducer



Simplified diagram of acoustic head

Generator → **Transducer** → **Concentrator** → **Tool**

Holder clamps the head to the machine body at a nodal point.

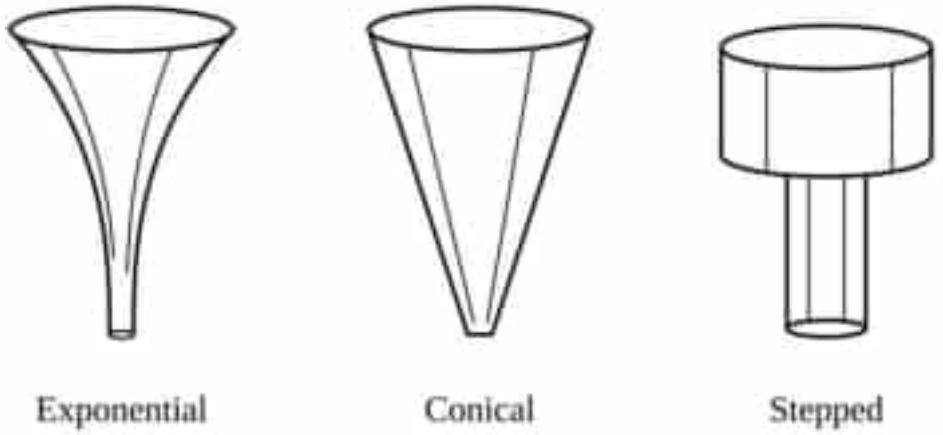
Types of transducer

Magnetostrictive (most common)	Piezoelectric
➢ Nickel stampings (0.1–0.2 mm) change length in an alternating magnetic field ➢ Reliable at 15–30 kHz; low voltage, simple cooling ➢ Natural frequency matched to supply frequency	➢ Quartz or PZT crystal changes thickness under an alternating voltage ➢ Conversion efficiency up to about 95%; no cooling needed ➢ Crystal is brittle; power output is limited

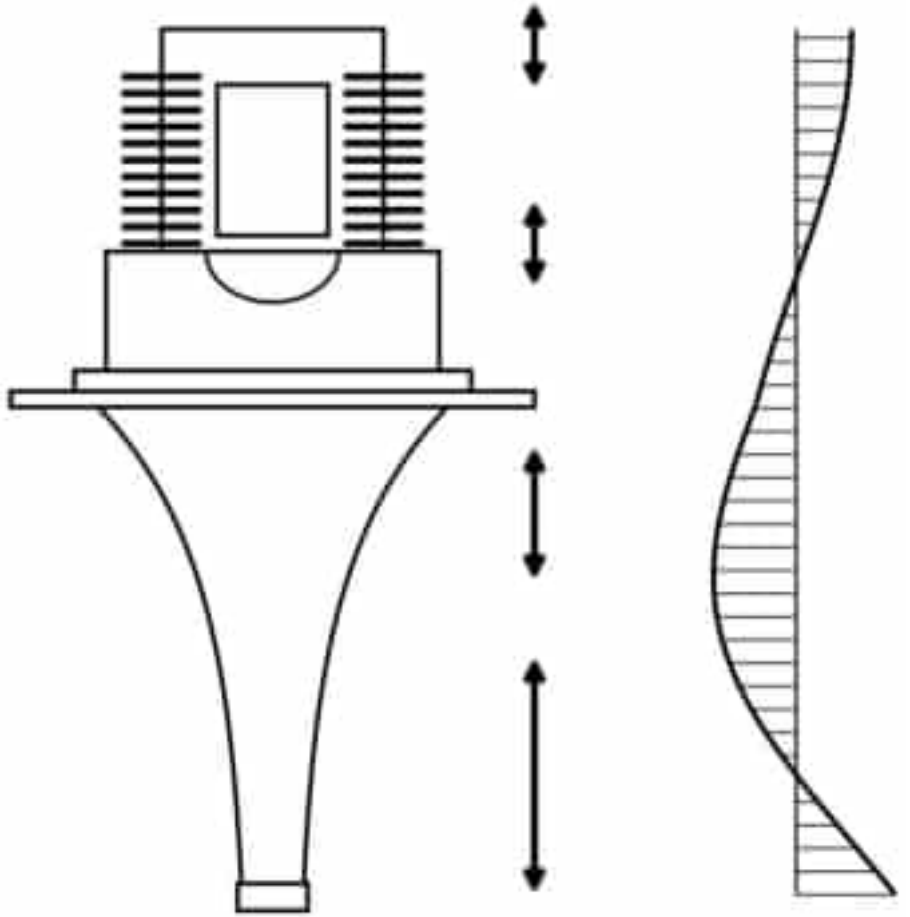
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Concentrators

- **Purpose:** increases the vibration amplitude to the level needed for cutting.
- **Principle:** as the cross-section narrows, the amplitude rises.
- **Types:** exponential, conical and stepped.
- **Mounting:** held to the machine body at a nodal point (zero amplitude), so the body does not vibrate.



Types of concentrators

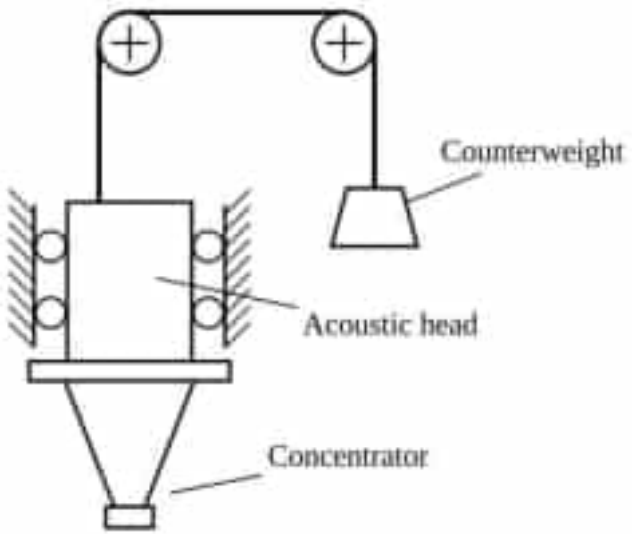


Amplitude magnified along the assembly

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Parima
K. Patta

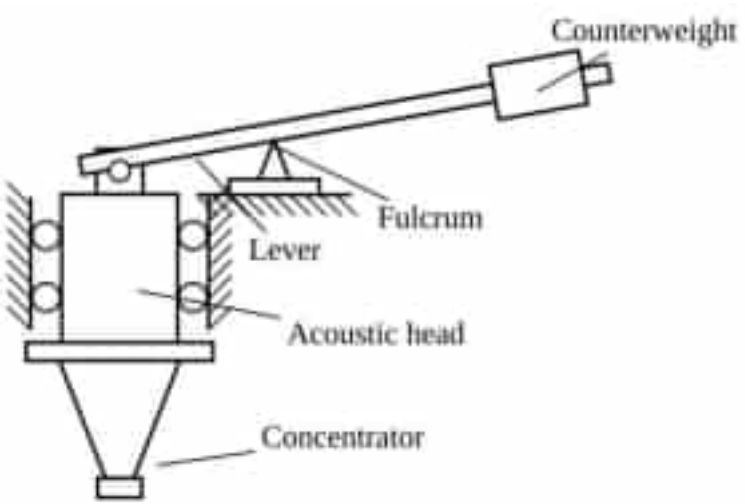
Feed Mechanisms – I (Counterweight and Solenoid Types)

Feed mechanism applies the working force during machining; an indicator shows the depth. Basic types: counterweight, spring, pneumatic/hydraulic and motor.



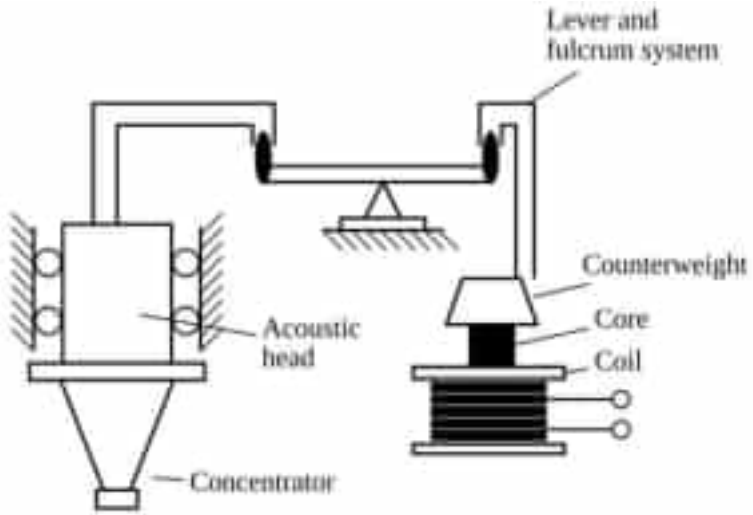
Rope and pulley

A counterweight on a rope over two pulleys balances the head; the difference gives the feed force.



Lever and fulcrum

A counterweight on a lever arm presses the head down about a fulcrum.

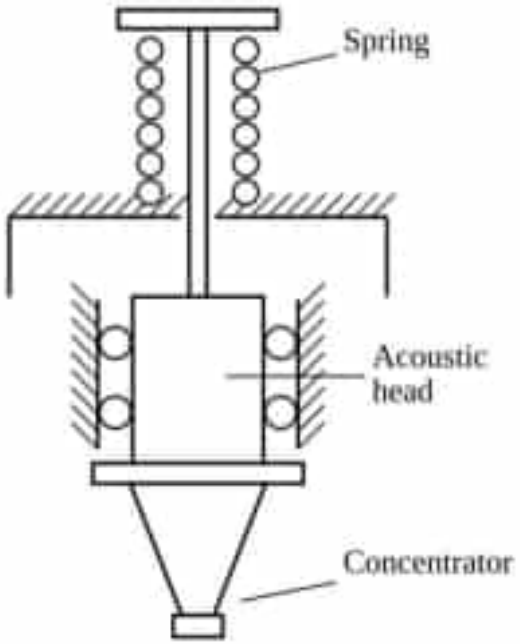


Electric solenoid

A coil pulls an iron core; through a lever this sets the feed force electrically.

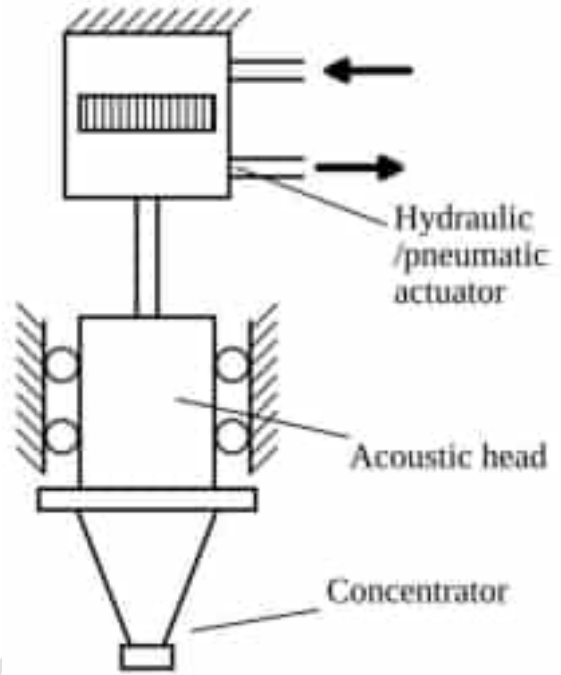
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Feed Mechanisms – II (Spring, Fluid and Motor Types)



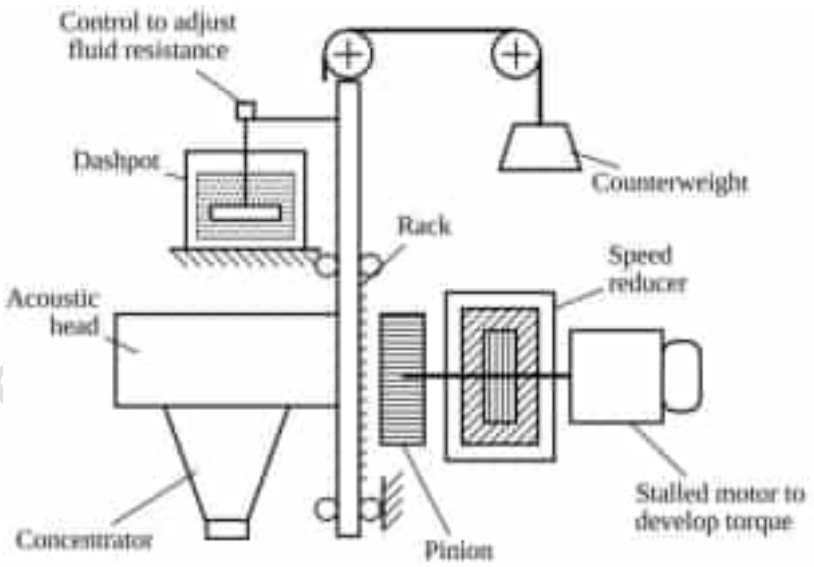
Spring control

A compressed spring pushes the head down; the force falls as the spring extends.



Hydraulic / pneumatic

Fluid pressure in a cylinder gives a steady, adjustable feed force.



Stalled motor

A stalled motor gives steady torque to a rack and pinion via a speed reducer; a dashpot damps motion.

Dr. A.K. Saha

Tool and Abrasive Slurry

Tool

- **Material:** strong but ductile – stainless steel or low-carbon steel. Aluminium and brass tools wear 10 and 5 times faster.
- **Shape:** short and rigid; circumscribed diameter ≤ 1.5–2 times the concentrator end diameter.
- **Hollow tool:** inner contour parallel to the outer; wall ≥ 0.5–0.8 mm and ≥ 5 times the grain size.
- **Side clearance:** 0.06–0.36 mm, set by grain size.

Abrasive Slurry

Abrasives (fastest cutting first):

- **B_4C** – most efficient, but expensive
- **SiC** – 20–40% more cutting time; glass, Ge, ceramics
- **Al_2O_3 (corundum)** – 3–4 times the B_4C time
- **Diamond dust** – only for diamonds and rubies

Slurry:

- Abrasive : water ≈ 1 : 1; benzene, glycerol or oil also used
- MRR falls as viscosity rises

Prepared By: Dr. S.K. Parimanik Dr. A.K. Pattanaik

Shaw's Model: Assumptions and Grain Geometry

Assumptions (M.C. Shaw)

- $Q \propto$ volume of work removed per impact, v
- $Q \propto$ number of grains impacting per cycle, Z
- $Q \propto$ frequency, ν (cycles per second)
- All impacts are identical
- All grains are identical rigid spheres of diameter d

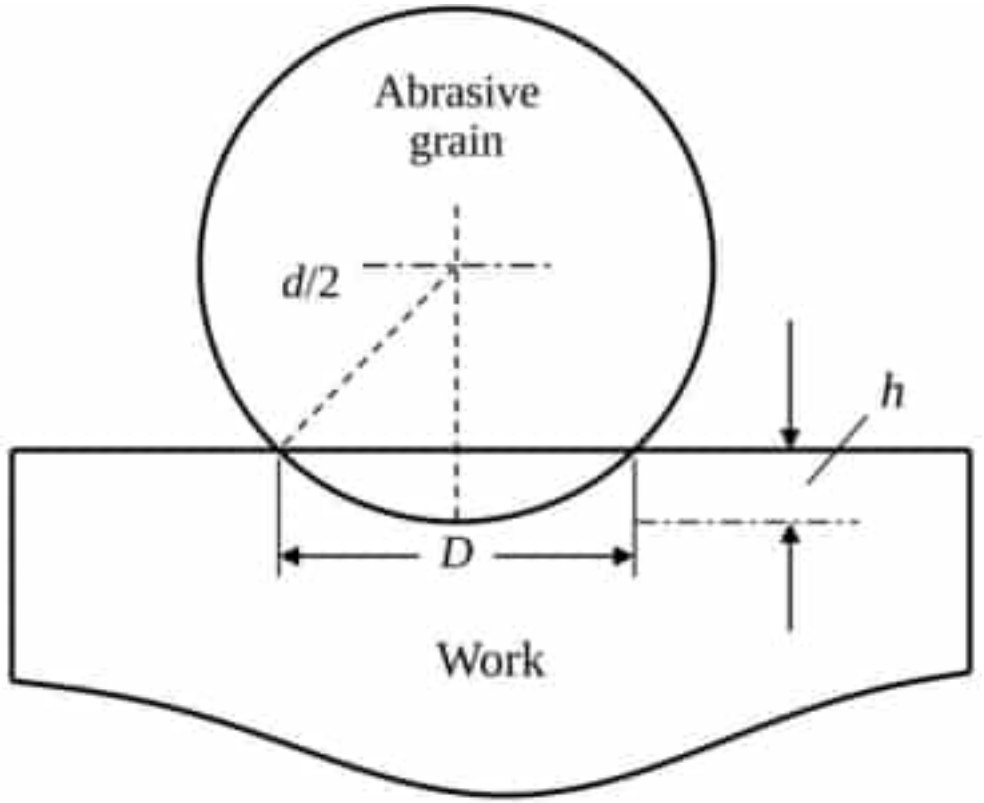
Geometry of Grain: D = indentation diameter, h = depth

$$\left(\frac{D}{2}\right)^2 = \left(\frac{d}{2}\right)^2 - \left(\frac{d}{2} - h\right)^2 \quad \Rightarrow \quad D^2 = 4dh - 4h^2$$

Since $h \ll d$: $\quad D \approx 2\sqrt{dh}$

Volume per impact $\propto D^3$, so

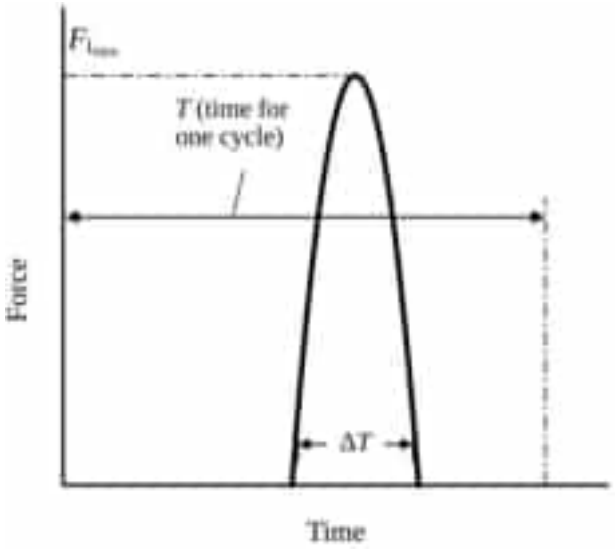
$$Q \propto (dh)^{3/2} Z\nu$$



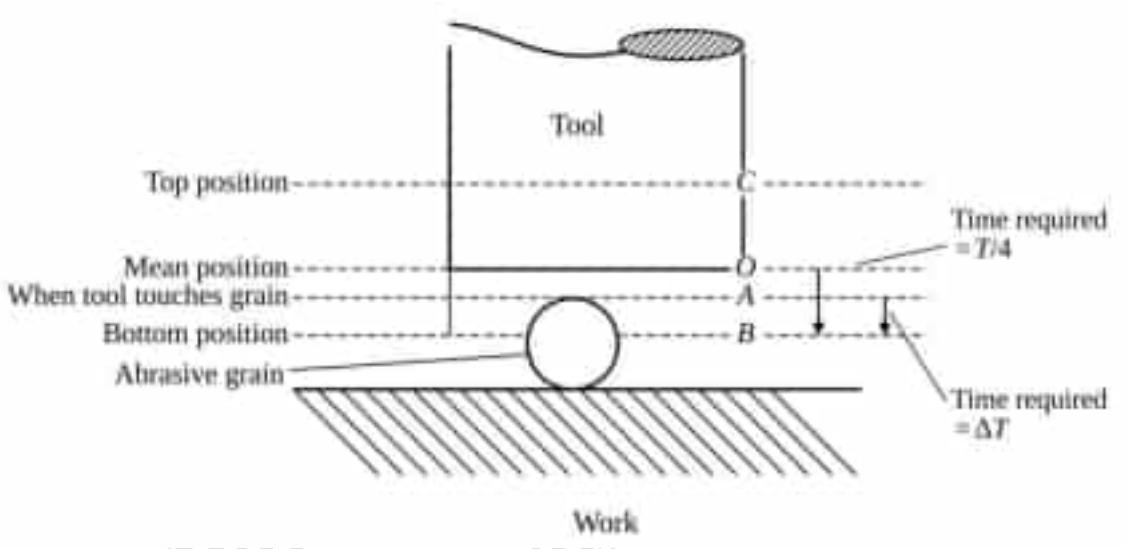
Scheme of idealized grain indentation

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Force During Impact



Force during indentation



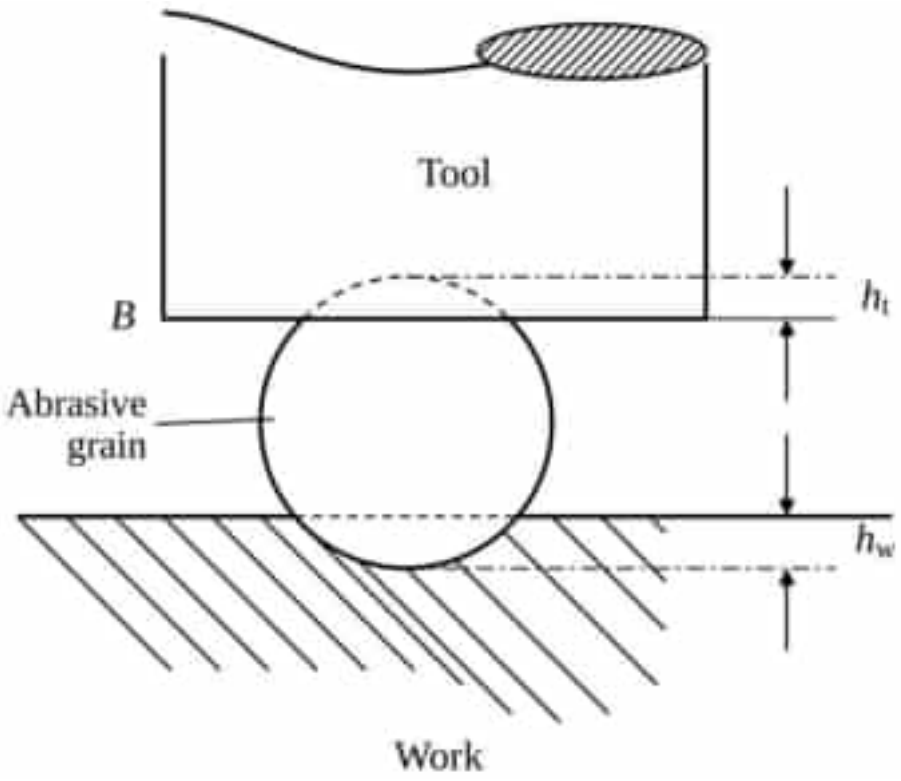
History of one-quarter cycle in USM

Dr. S.R. Pa
Dr. A.K. Pattanai

- **Mean feed force = mean impact force:** $F = \frac{1}{T}\int_0^T F_i(t)\mathrm{d}t$
- **Triangular pulse:** $F \approx \frac{1}{2} F_{i\max} \frac{\Delta t}{T}$
- **Quarter cycle O → B:** $\Delta t \approx \frac{h}{A} \cdot \frac{T}{4} = \left(\frac{h_t + h_w}{A}\right)\frac{T}{4}$

Substituting: $F_{i\max} \approx \frac{8FA}{h_w + h_t}$

Indentation in Tool and Work



Indentations on tool and work at bottom position of tool

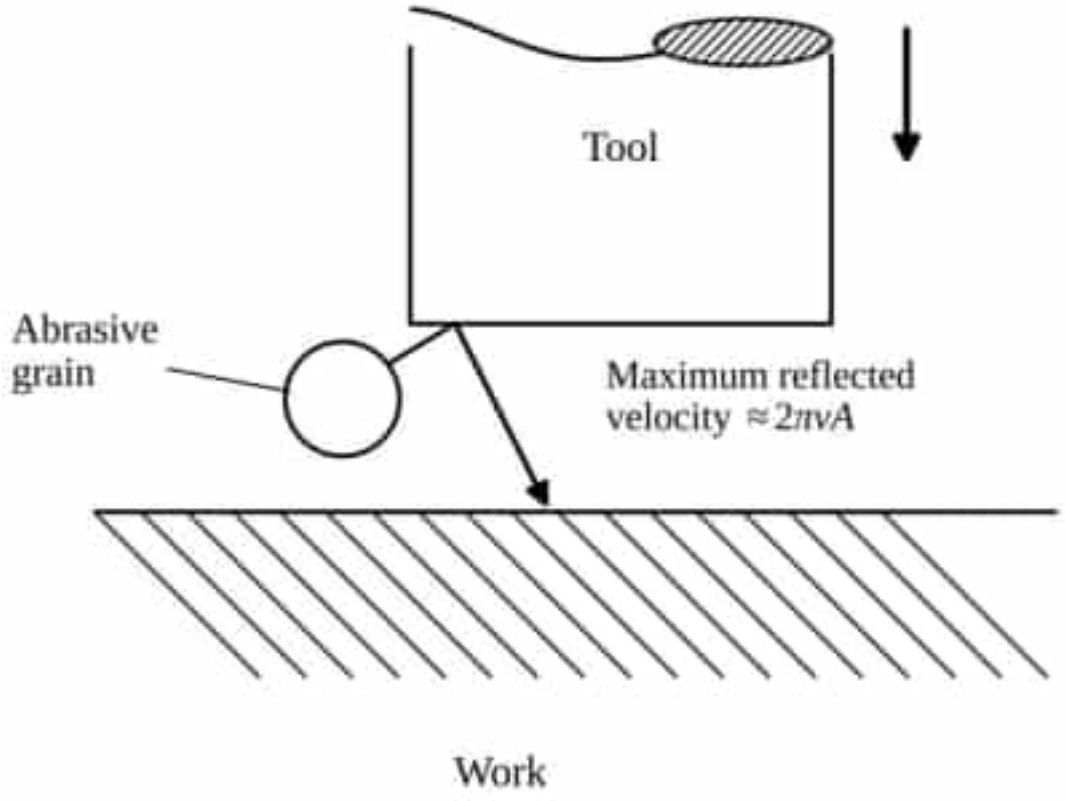
- **Total indentation:** $h = h_w + h_t$
- **Contact area per grain:** $\frac{\pi}{4}D^2 = \pi d h_w$; force per grain = $F_{i\max}/Z$
- **Stress in work:** $\sigma_w = \frac{8FA}{\pi Z d h_w (h_w + h_t)}$
- **Depth $\propto$ 1/flow stress:** $\lambda = \frac{h_t}{h_w} = \frac{\sigma_w}{\sigma_t} = \frac{H_w}{H_t}$
- **Grains acting:** $Z = \chi \frac{C}{d^2}$, C = concentration

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Indentation in the work

$$h_w = \sqrt{\frac{8FAd}{\pi \chi H_w C(1+\lambda)}}$$

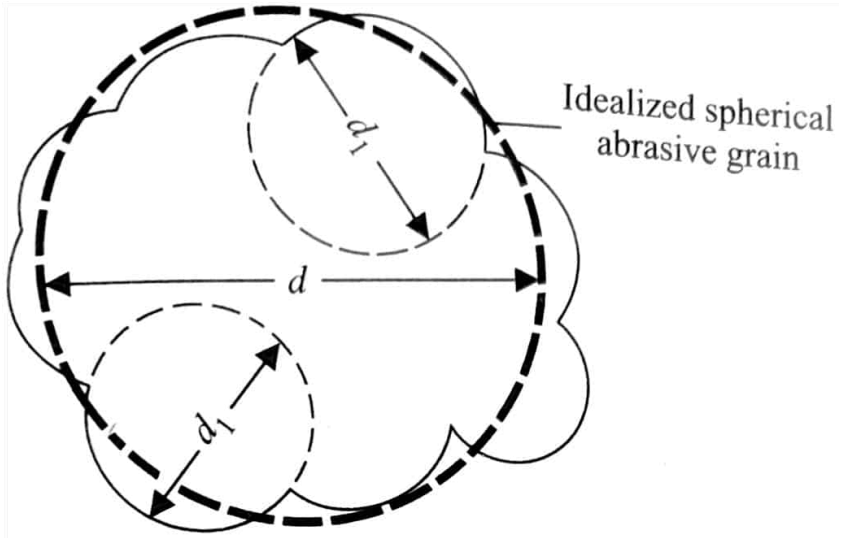
Free-Grain Impact



Rebounding abrasive grain during ultrasonic machining

Conclusion: the indentation by a free, rebounding grain, h'_w, is much smaller than h_w; so most material is removed by grains hammered directly by the tool.

Projection Correction and Final MRR Equation



Spherical projections on abrasive grain

- **Problem:** theory gives $Q \propto d^{1/4}$; experiments give $Q \propto d$.
- **Shaw's correction:** real grains carry projections of mean diameter $d_1 = \mu d^2$
- **Effective diameter is d_1:** $Q \propto (d_1 h_w)^{3/2} Z v$
- **Limitation:** effects of A, F and v are not predicted well; Q falls at high F as grains crush.

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Dr. S.R. Parimanik
Dr. A.K. Pattanaik

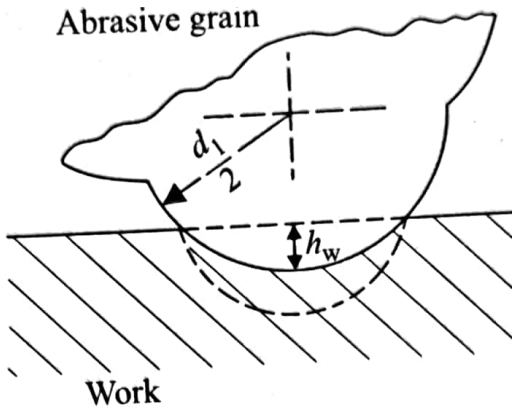
Final MRR equation (Shaw)

$$Q \propto \frac{d F^{3/4} A^{3/4} C^{1/4} v}{H_w^{3/4} (1+\lambda)^{3/4}}$$

Worked Example: Square Hole in a WC Plate

Given

- Hole 5 mm × 5 mm; WC plate 4 mm thick
- $d = 0.01$ mm; $F = 3.5$ N
- $A = 25$ μm; $\nu = 25$ kHz
- $H_w = 6900$ N/mm^2; slurry 1 : 1
- Assume $\lambda = 5$, $d_1 = d^2$



Volume removed per grit

Solution

- **Volume per grit** $\approx \frac{2}{3}\pi\left(\frac{D}{2}\right)^3$, with $D = 2\sqrt{d_1 h_w}$
- **So** $Q \approx \frac{2}{3}\pi(d_1 h_w)^{3/2} Z\nu$
- $Z \approx \frac{1}{2}\cdot\frac{4a^2}{\pi d^2} = 159{,}155$ $(a = 5$ mm$)$
- $h_w^2 \approx \frac{8FA}{\pi Z d_1 H_w(1+\lambda)} \Rightarrow h_w \approx 0.0006$ mm
- $Q \approx 0.122$ mm^3/s; volume $= 5\times5\times4 = 100$ mm^3

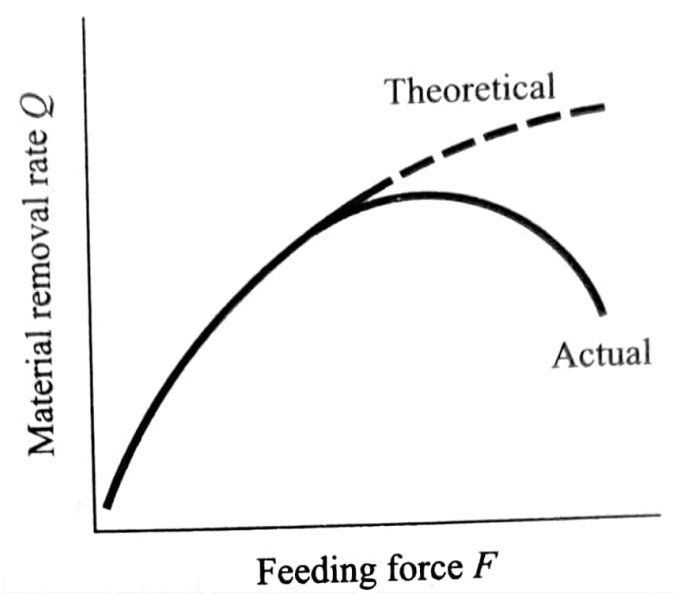
$$t = \frac{100}{0.122} \approx 820\ \text{s} \approx 13.7\ \text{min}$$

Actual time is longer: not every impact causes brittle fracture.

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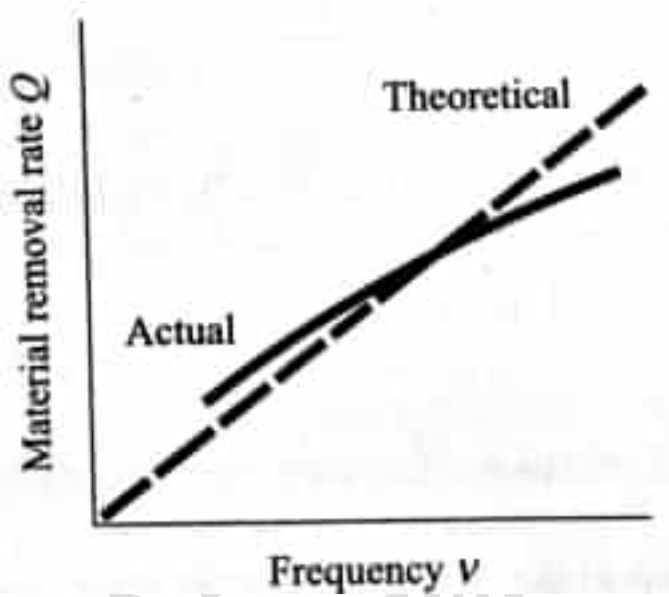
Effect of Feed Force, Frequency and Amplitude

Process parameters: frequency, amplitude, feed force, hardness ratio, grain size, concentration



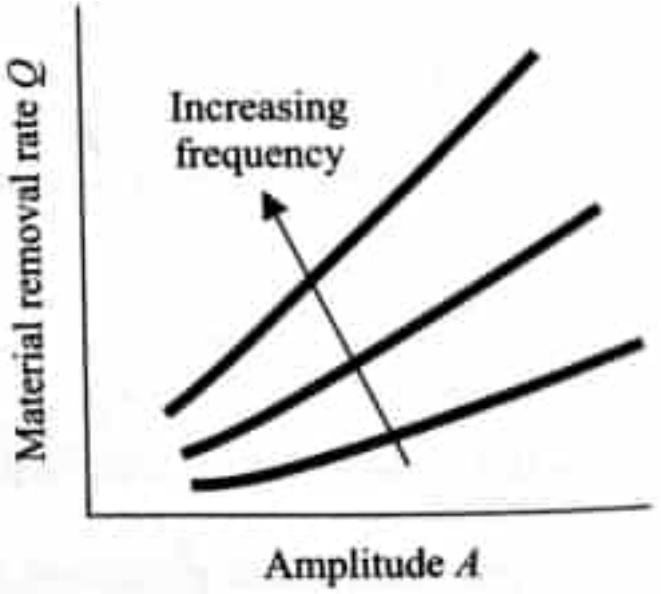
MRR vs feed force

MRR rises with feed force, then falls beyond a critical force as the grains are crushed.



MRR vs frequency

MRR rises almost linearly with frequency; the actual curve lies slightly below theory.

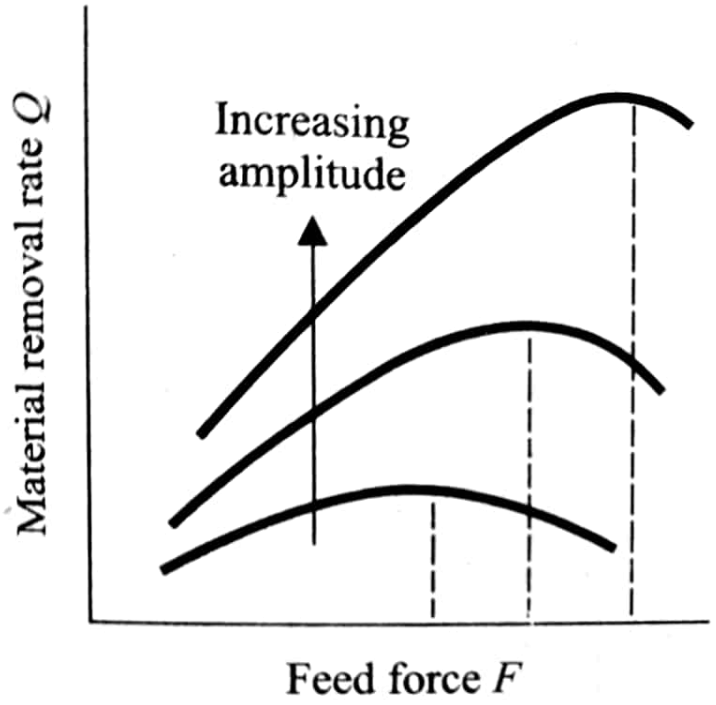


MRR vs amplitude

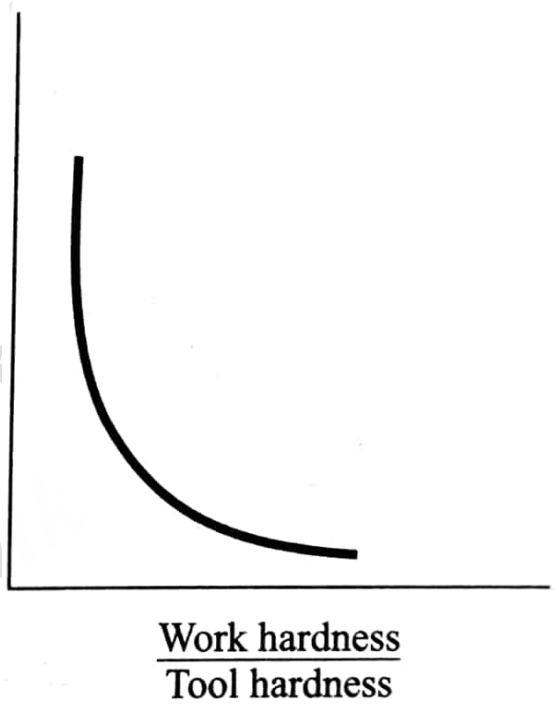
MRR rises with amplitude, faster at higher frequency. Theory errs because Δt used the average tool velocity.

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Effect of Feed Force at Different Amplitudes, and of Hardness Ratio



MRR vs feed force at different amplitudes



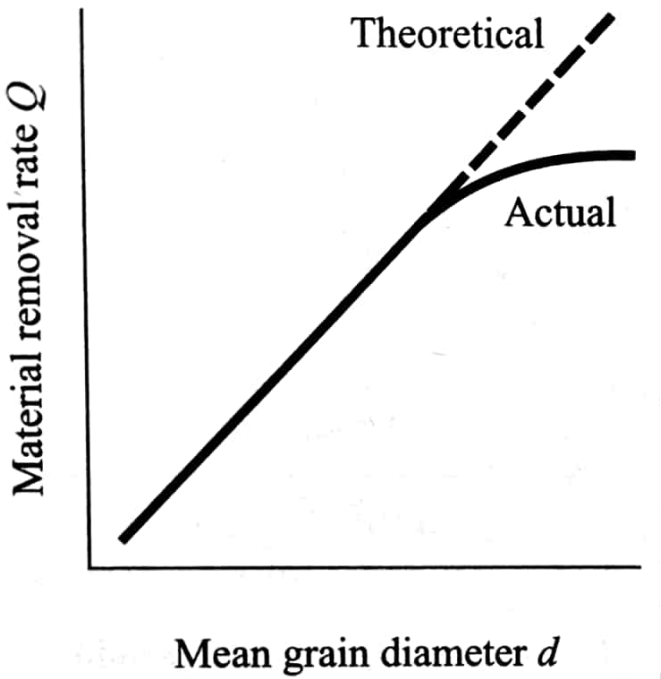
MRR vs hardness ratio

At every amplitude, MRR peaks at a critical feed force and then falls as grains crush. A larger amplitude gives a higher peak at a higher force.

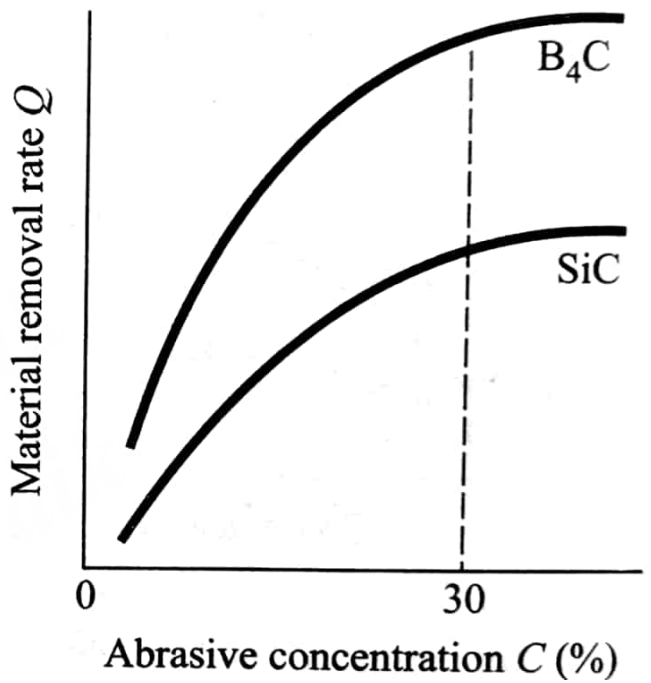
MRR falls steeply as the ratio of work hardness to tool hardness rises. Brittleness of the work also plays a dominant role.

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Effect of Grain Size and Abrasive Concentration



MRR vs mean grain diameter



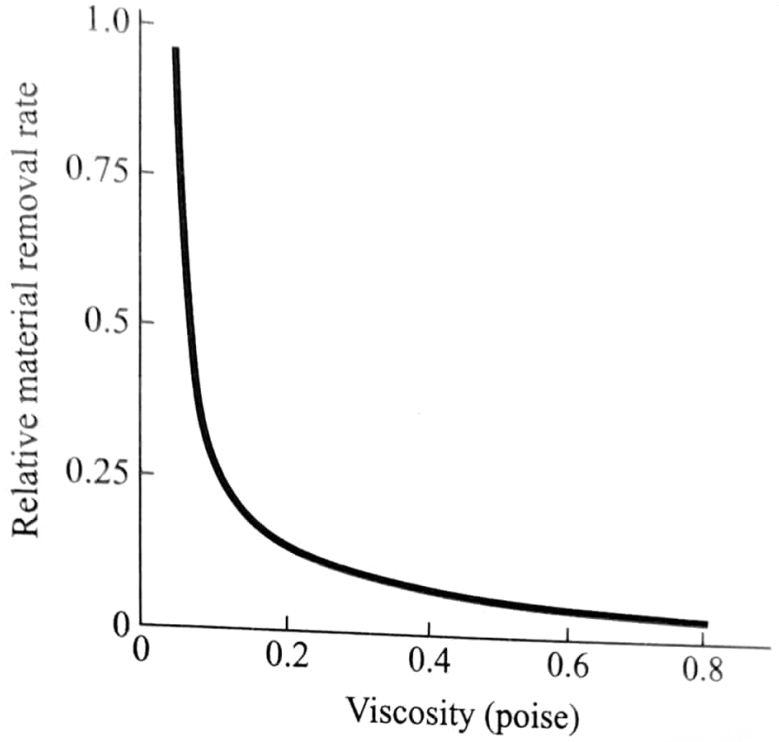
MRR vs abrasive concentration

MRR rises in proportion to grain diameter d, but levels off once d approaches the amplitude A, as grains crush.

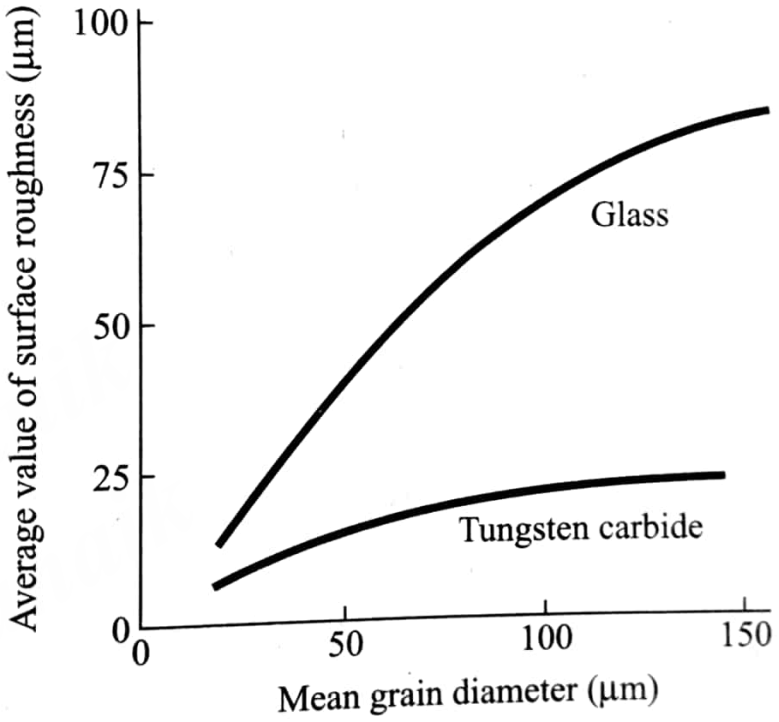
$Q \propto C^{1/4}$, so little is gained beyond $C \approx 30\%$. B_4C gives a higher MRR than SiC.

Prepared By: Dr. S.R. Parimani Dr. A.K. Pattan

Effect of Slurry Viscosity, and Surface Finish vs Grain Size



MRR vs slurry viscosity



Surface roughness vs grain size

Relative MRR drops sharply as slurry viscosity rises, to under 0.1 beyond about 0.3 poise. Water is therefore the usual carrier.

Surface finish depends mainly on grain size. Glass is far more sensitive than tungsten carbide, whose fragment size barely depends on grain size.

Prepared By: Dr. S.R. Parimo Dr. A.K. Patt

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Why USM Suits Brittle Materials

Relative MRR (ν = 16.3 kHz, A = 12.5 μm, 100-mesh grains)

Work material	Relative removal rate
Glass	**100.0**
Brass	6.6
Tungsten	4.8
Titanium	4.0
Steel	3.9
Chrome steel	**1.4**

- **Glass is removed about 70 times faster** than chrome steel (100 vs 1.4) under the same conditions.
- **Brittle materials** fail by small brittle fractures under each grain impact.
- **Ductile metals** absorb the impact by plastic deformation, so little material chips off.

Prepared By
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Electrochemical Machining

(ECM)

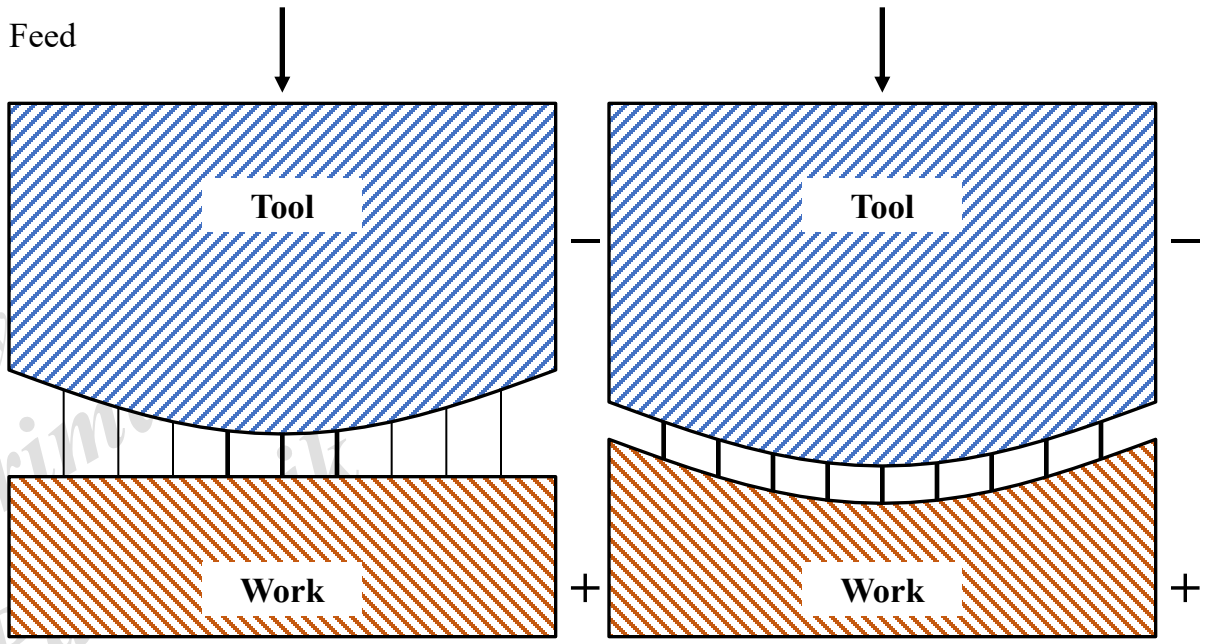
Contents

1. Principle of ECM
2. Basic setup, operating values and complete ECM plant
3. Faraday's laws and electrochemistry with NaCl electrolyte
4. MRR of a pure metal and of an alloy
5. Worked examples on current and MRR
6. Current flow, gap kinematics and equilibrium gap
7. Electrolyte flow and surface finish
8. Tool design for electrolyte flow and insulation
9. Electrolytes and the effect of ECM on work materials

Prepared By
Dr. S.R. Parimanik
Dr. A.K. Parimanik

Electrochemical Machining (ECM): Principle

- **Reverse of electroplating:** based on electrolysis, but metal is removed instead of deposited.
- **Conduction by ions:** in a metal, current is carried by free electrons; in an electrolyte, by moving ions, so current flow always moves matter.
- **Polarity:** work → positive terminal (anode); tool → negative terminal (cathode); the gap is filled with electrolyte.
- **Current density ∝ 1/gap:** the anode dissolves fastest where the gap is smallest.
- **Shape copying:** with a downward tool feed, the work takes the shape of the tool and the gap becomes uniform.



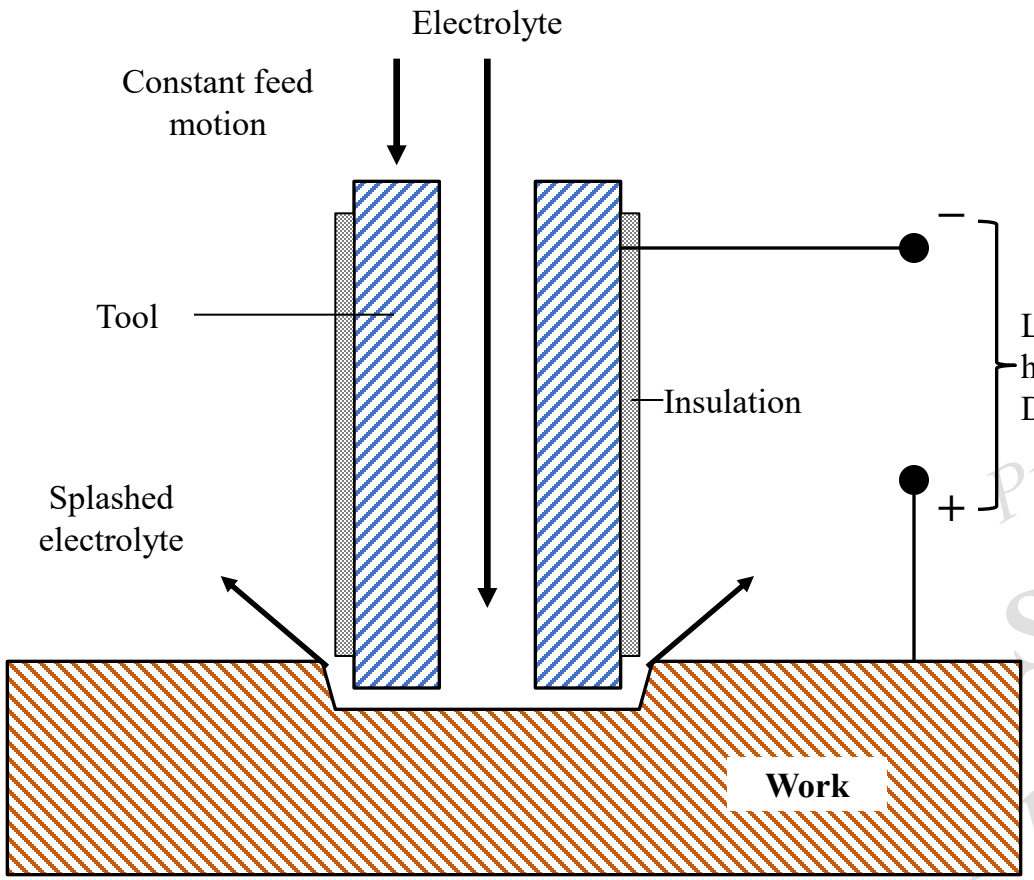
(a) Start of machining (b) Steady state

Scheme of electrochemical machining

Key
Blue hatching: tool (cathode, −)
Orange hatching: work (anode, +)
Lines: current; thicker where the gap is small

Prepared By Dr. S.R. Parimi & Dr. A.K. Parimi

Basic Setup and Operating Values



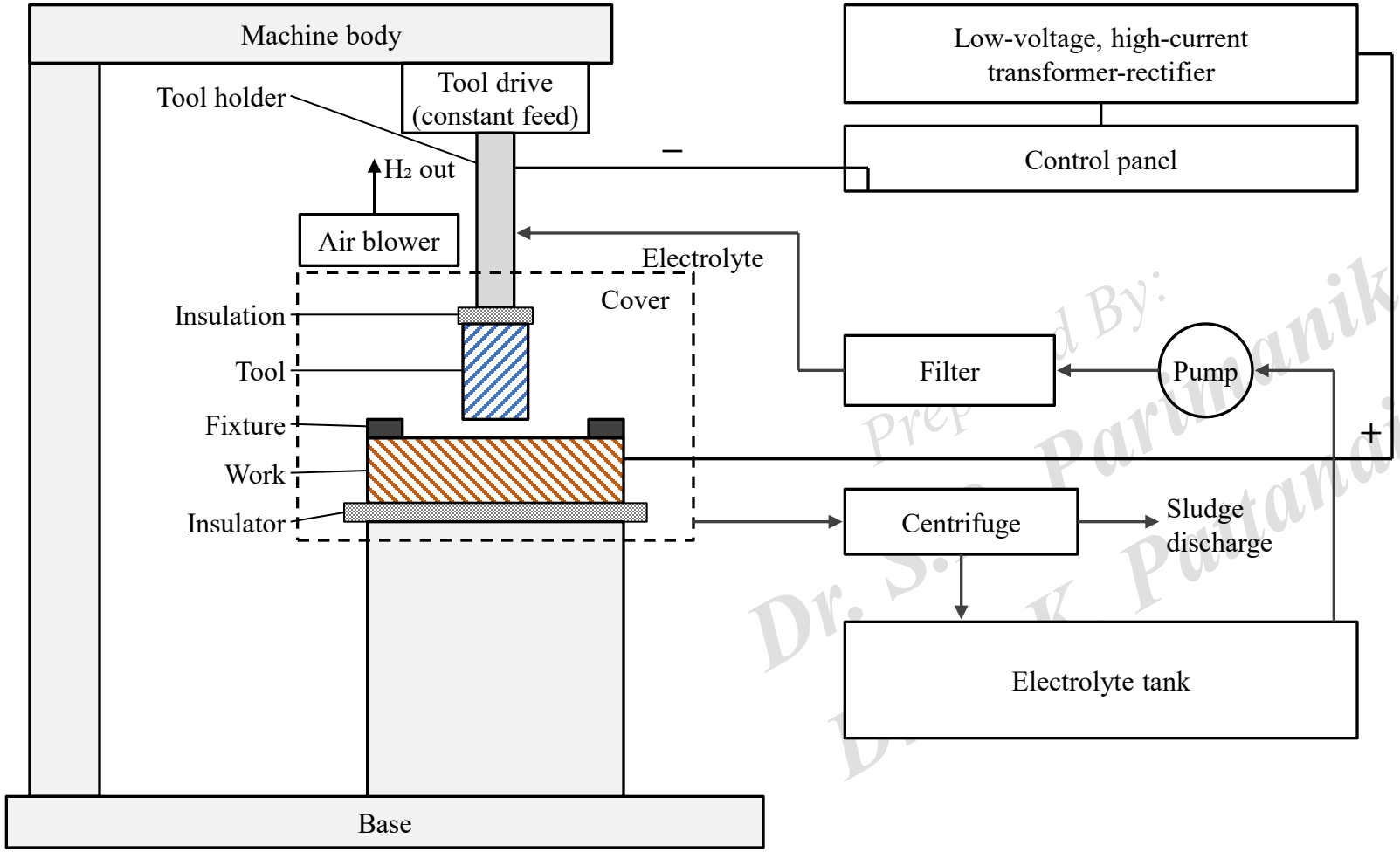
Electrochemical machining

Quantity	Typical value
Current	A few thousand amperes
Voltage	8–20 V (DC)
Gap	0.1–0.2 mm
MRR	≈ 1600 mm³/min per 1000 A

- **Feed and flow:** the tool moves at a constant feed; electrolyte is pumped at high pressure through the tool and the gap.
- **Hardness does not matter:** MRR is independent of work hardness.
- **Tool wear:** practically none.
- **Forces:** the high-pressure electrolyte exerts large forces on the tool and the work.

Prepared By S.R. Parimanik & Dr. A.K. Pattanaik

Complete ECM Plant



Electrochemical machining plant

Design points

- **Rigidity:** the body and tool feed must be stiff to resist the large electrolyte forces.
- **Corrosion:** every part touched by the electrolyte is protected against corrosion.
- **Pumps:** made of stainless steel.
- **Tank and pipeline:** PVC, which the electrolyte does not attack.

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Faraday's Laws of Electrolysis

First law	Second law
The amount of material dissolved or deposited is proportional to the quantity of electricity passed.	The amounts of different substances dissolved or deposited by the same quantity of electricity are proportional to their chemical equivalent weights.

$$m \propto It\varepsilon \quad \Rightarrow \quad m = \frac{It\varepsilon}{F}$$

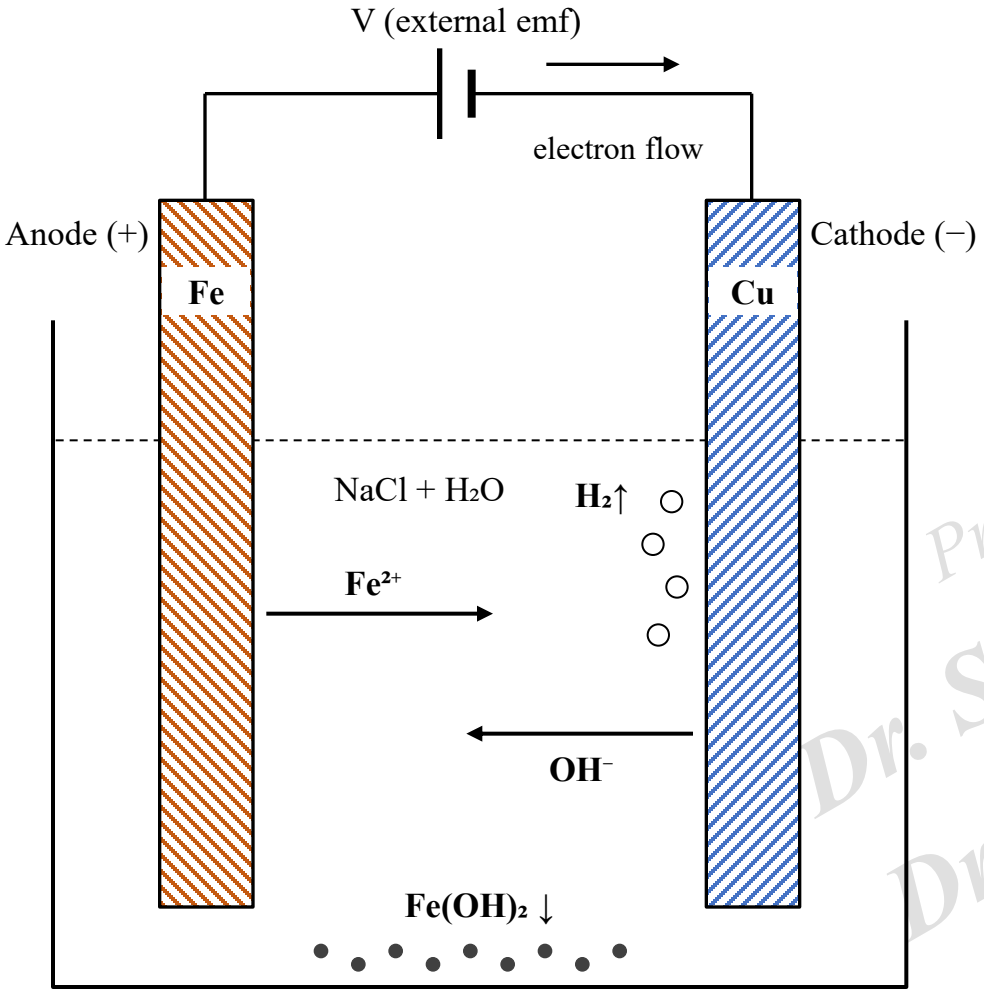
Faraday constant $F = 96{,}500$ C; with t in hours, $m = \frac{It\varepsilon}{26.8}$

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Dr. S.K. Parimanik
Dr. A.K. Pattanaik

where

- m = mass dissolved or deposited (g)
- I = current (A)
- t = time (s)
- ε = gram equivalent weight of the material
- F = Faraday constant = 96,500 C

Electrochemistry of ECM with NaCl Electrolyte



Principle of electrolysis (with extra source of emf)

At the anode: iron dissolves

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

At the cathode: hydrogen gas forms

$$2H_2O + 2e^{-} \rightarrow H_2 \uparrow + 2OH^{-}$$

In the electrolyte: insoluble precipitate

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \downarrow$$

- **Result:** the work (anode) dissolves and H_2 is released at the tool (cathode). Nothing deposits on the tool, so its shape stays unchanged.
- **Removal mechanism:** ion displacement; metal atoms leave the anode as ions.

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MRR in ECM: Derivation for a Pure Metal

Step 1. Faraday's law gives the mass dissolved:

$$m = \frac{It\varepsilon}{F}$$

Step 2. Gram equivalent weight of the metal:

$$\varepsilon = \frac{A}{Z}$$

Step 3. Divide by time to get the mass removal rate:

$$\dot{m} = \frac{m}{t} = \frac{AI}{ZF} \text{ g/s}$$

Step 4. Divide by the anode density for the volume removal rate:

$$Q = \frac{\dot{m}}{\rho} = \frac{AI}{\rho ZF} \text{ cm}^3/\text{s}$$

where

- A = gram atomic weight of the metal ions
- I = current (A)
- ρ = density of the anode (g/cm³)
- Z = valency of the cation
- F = 96,500 C

$Q \propto I$: MRR depends only on the current, not on the hardness of the work.

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Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Example: Current Needed for a Given MRR (Iron)

Given

- Pure iron workpiece
- $Q = 5\ \text{cm}^3/\text{min}$
- $A = 56\ \text{g},\ Z = 2$
- $\rho = 7.8\ \text{g/cm}^3$
- $F = 96{,}500\ \text{C}$

Find: current I

Solution

From $Q = \frac{AI}{\rho ZF}$:

$$\frac{5}{60} = \frac{56 \times I}{7.8 \times 2 \times 96{,}500}$$

$$I = \frac{5 \times 7.8 \times 2 \times 96{,}500}{60 \times 56} \approx 2240\ \text{A}$$

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Specific removal rate of iron (volume removed per ampere-second):

$$C = \frac{Q}{I} = \frac{A}{\rho ZF} = \frac{56}{7.8 \times 2 \times 96{,}500} \approx 3.72 \times 10^{-5}\ \text{cm}^3/\text{A} - \text{s} \approx 3.7 \times 10^{-2}\ \text{mm}^3/\text{A} - \text{s}$$

Answer: $I \approx 2240$ A. The value of C is used in the next problem.

Solved PYQ: Square Hole in an Iron Plate

Given

- Plate thickness $h = 14$ mm
- Hole 20 mm × 20 mm
- Current $I = 1250$ A
- Efficiency $\eta = 0.95$
- $C = 3.69 \times 10^{-2}$ mm^3/A − s

Find: feed rate f and time T

Solution

1. MRR: $Q = \eta C I = 0.95 \times 3.69 \times 10^{-2} \times 1250 = 43.82$ mm^3/s

2. Area: $a = 20 \times 20 = 400$ mm^2

3. Feed: $f = \frac{Q}{a} = \frac{43.82}{400} = 0.1095$ mm/s

4. Time: $T = \frac{h}{f} = \frac{14}{0.1095} = 127.8$ s

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Answer

$f \approx$ **0.11 mm/s (6.57 mm/min)** $\quad T \approx$ **128 s (2.13 min)**

MRR of an Alloy

Each element of the alloy needs its own charge, so the volume removed per unit charge is:

$$Q = \frac{0.1035 \times 10^{-2}}{\rho} \cdot \frac{1}{\sum_i x_i Z_i / A_i} \ \text{cm}^3/\text{A} \cdot \text{s}$$

Alloy density:

$$\rho = \frac{100}{\sum_i x_i / \rho_i}$$

x_i = % by weight of element i; A_i, Z_i, ρ_i = its atomic weight, valency and density

Example: Nimonic 75 at 1000 A (results)

72.5 Ni, 19.5 Cr, 5 Fe, 0.4 Ti, 1 Si, 1 Mn, 0.6 Cu (% by weight)

- $\rho = 8.18\ \text{g/cm}^3;\ \sum_i x_i Z_i / A_i = 3.62$
- $Q = 0.35 \times 10^{-4}\ \text{cm}^3/\text{A} \cdot \text{s}$
- At 1000 A: $0.35 \times 10^{-4} \times 1000 \times 60 = 2.1\ \text{cm}^3/\text{min}$

Metal	Gram atomic weight	Valency	Density (g/cm³)
Iron	55.85	2/3	7.86
Nickel	58.71	2/3	8.90
Chromium	51.99	2/3/6	7.19
Copper	63.57	1/2	8.96

Atomic weight, valency of dissolution and density

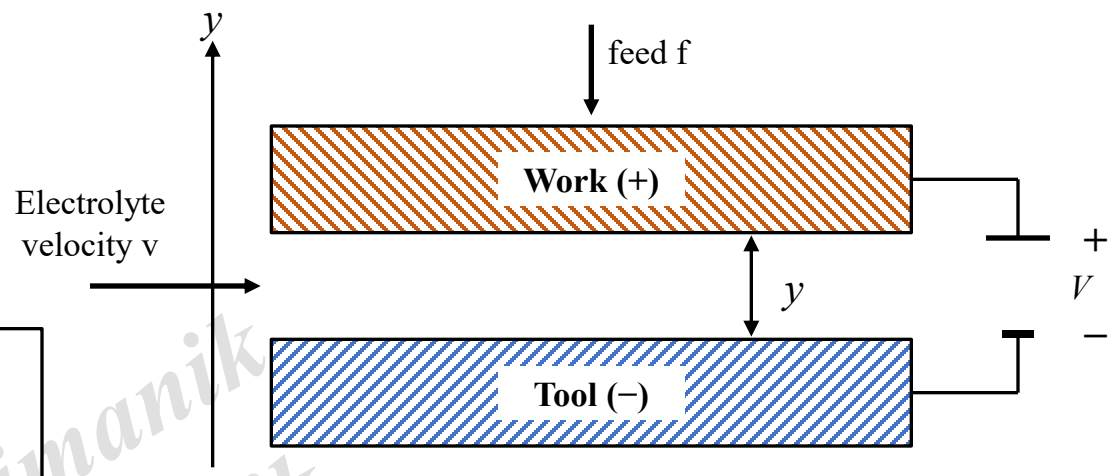
Measured MRR is about 2 cm³/min, close to the calculated 2.1. Use the **lowest valency** of each element unless told otherwise.

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Current Flow and Gap Kinematics

Total overvoltage ΔV = electrode potentials + activation and concentration polarization + ohmic overvoltage, so

$$I = \frac{V - \Delta V}{R}, \quad R = \text{ohmic resistance of electrolyte}$$



Kinematic scheme of ECM

Current density across gap y**:**

$$J = \frac{\kappa(V - \Delta V)}{y}$$

Gap change = surface recession − feed:

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \frac{AJ}{\rho ZF} - f = \left[\frac{\kappa A(V - \Delta V)}{\rho ZF}\right]\frac{1}{y} - f$$

$$\lambda = \frac{\kappa A(V - \Delta V)}{\rho ZF} \quad \Rightarrow \quad \frac{\mathrm{d}y}{\mathrm{d}t} = \frac{\lambda}{y} - f$$

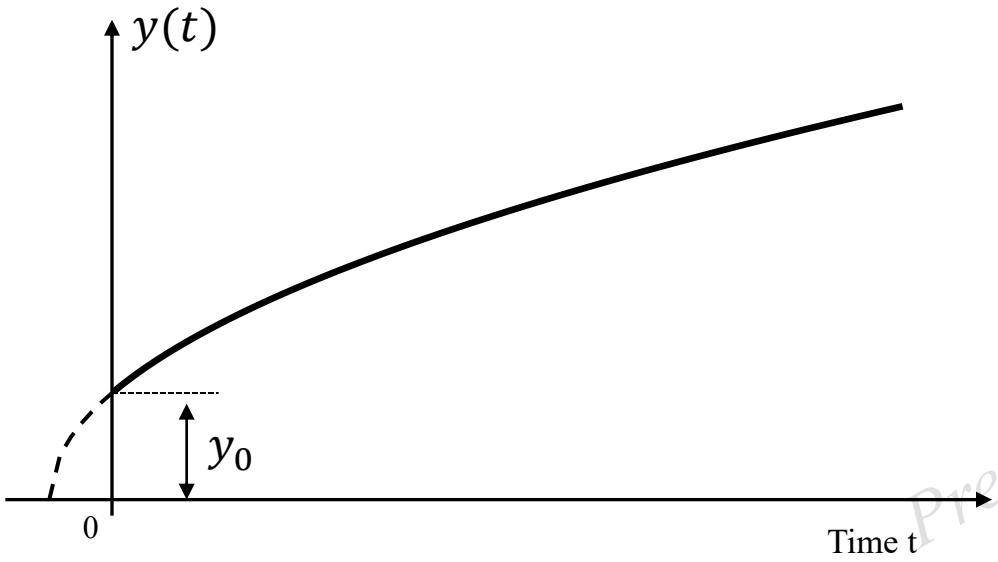
Basic equation of ECM dynamics

where

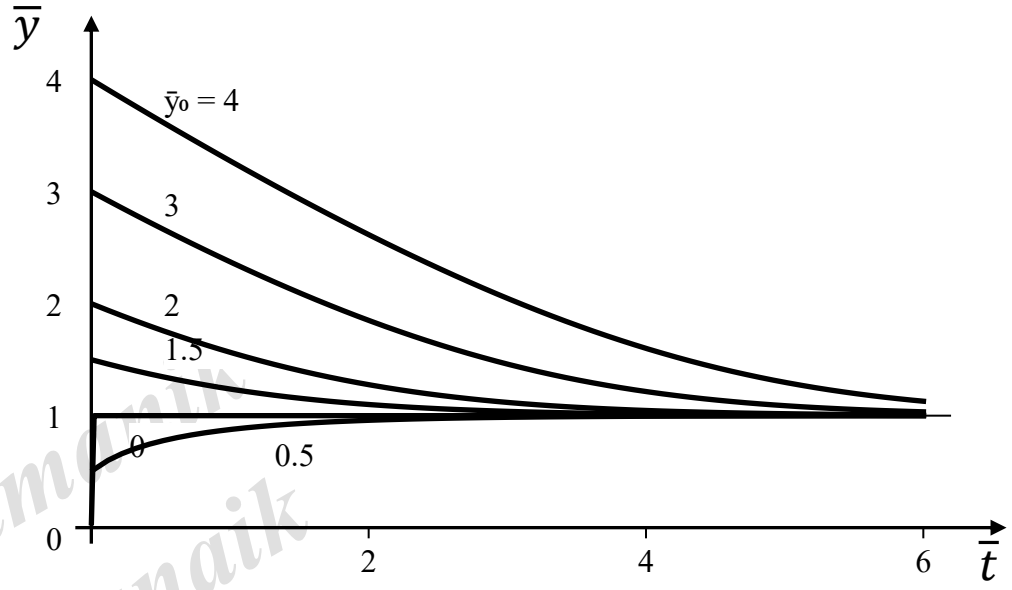
- κ = electrolyte conductivity, 0.1–1.0 $\Omega^{-1}\mathrm{cm}^{-1}$ (iron: 10^5), so tool and work surfaces are equipotential
- y = instantaneous gap
- f = feed velocity of the work

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Equilibrium Gap



Variation of electrode gap with time for zero feed



Plot of ȳ versus t̄

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Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Zero feed ($f = 0$): gap keeps growing

$$y^2 = {y_0}^2 + 2\lambda t \quad \Rightarrow \quad y = \sqrt{{y_0}^2 + 2\lambda t}$$

Constant feed: gap settles at y_e

$$0 = \frac{\lambda}{y_e} - f \quad \Rightarrow \quad y_e = \frac{\lambda}{f}$$

from any initial gap (all curves reach $\bar{y} = 1$)

Feed inclined at θ to the surface normal: only $f \cos\theta$ acts across the gap, so $y_e = \frac{\lambda}{f \cos\theta}$

Worked Examples: Equilibrium Gap and Maximum Feed

Equilibrium gap (iron, flat surfaces)

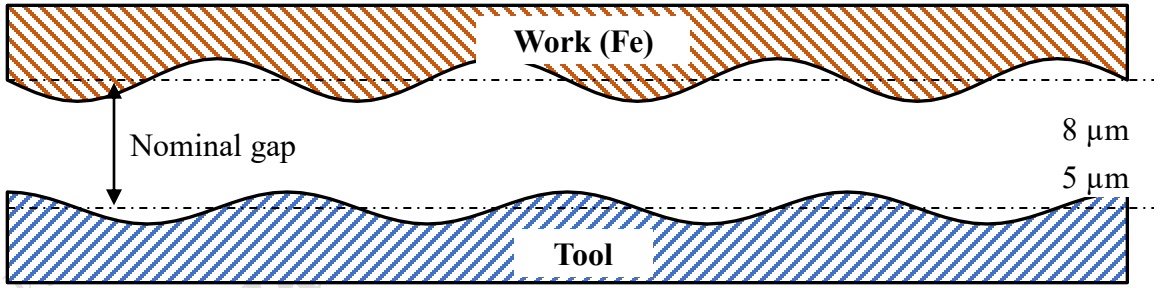
- Iron: $A = 55.85,\ Z = 2,\ \rho = 7.86\ \text{g/cm}^3$
- $V = 10\ \text{V},\ \Delta V = 1.5\ \text{V},\ \kappa = 0.2\ \Omega^{-1}\text{cm}^{-1}$
- $f = 1\ \text{mm/min} = 0.1/60\ \text{cm/s}$

$$y_e = \frac{\lambda}{f} = \frac{\kappa A(V - \Delta V)}{\rho Z F f}$$

$$y_e = \frac{0.2 \times 55.85 \times (10 - 1.5)}{7.86 \times 2 \times 96{,}500 \times (0.1/60)}$$

Answer: $y_e \approx 0.04\ \text{cm}$

Largest feed rate with rough electrodes



Nominal gap between undulating work and tool surfaces

- Asperities 5 μm and 8 μm; $V = 12$ V; κ and ΔV as before
- Minimum gap: $y_e = 0.0005 + 0.0008 = 0.0013\ \text{cm}$

$$f_{\max} = \frac{\kappa A(V - \Delta V)}{\rho Z F y_e} = \frac{0.2 \times 55.85 \times (12 - 1.5)}{7.86 \times 2 \times 96{,}500 \times 0.0013}$$

Answer: $f_{\max} \approx 0.059\ \text{cm/s} = 35.7\ \text{mm/min}$

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Electrolyte Flow and Surface Finish

Why the electrolyte must flow

1. **Avoid ion concentration** near the electrodes.
2. **Avoid deposition** on the tool.
3. **Remove the precipitate** formed in the gap.
4. **Avoid overheating** of the electrolyte.

Causes of poor surface finish

1. **Selective dissolution:** different phases of the alloy dissolve at different rates.
2. **Breakdown of the anodic film:** the surface film breaks at random spots, causing pits.
3. **Flow separation and eddies:** uneven flow leaves streaks and ridges.
4. **Hydrogen evolution:** H_2 bubbles change the local conductivity and give uneven removal.

Heat is the deciding factor: the required electrolyte flow rate is worked out so that the heat from the current does not overheat the electrolyte along the gap.

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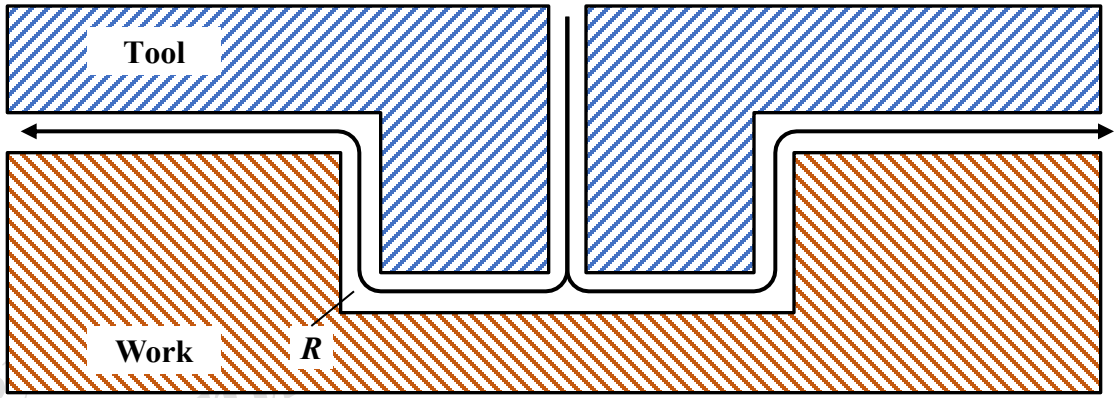
Tool Design for Electrolyte Flow

Two aspects of tool design

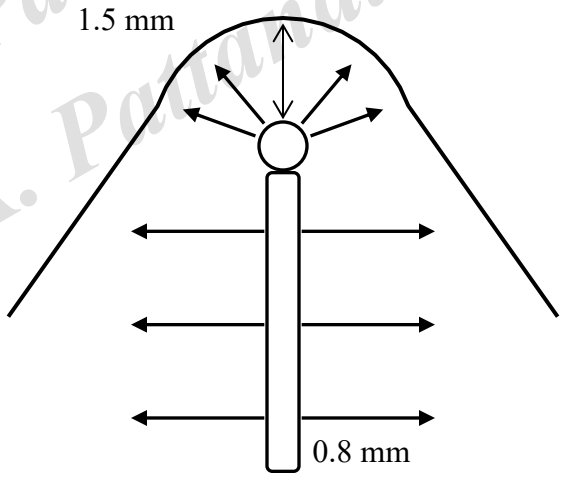
1. **Tool shape,** so that the job gets the required shape.
2. **Other design,** for electrolyte flow, insulation, strength and fixing.

Rules for electrolyte flow

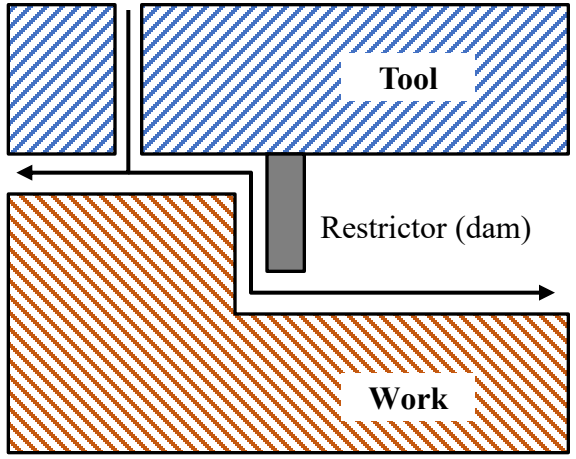
- **Corners:** radius in the flow path at least 0.7–0.8 mm.
- **Supply slot:** width 0.7–0.8 mm.
- **Slot end:** at least 1.5 mm from corners.
- **Passive areas:** avoid regions the flow cannot reach.
- **Restrictor dams:** next to the close-proximity area, at the entry or exit, without lengthening the flow path.



Avoiding sharp corners in flow path



Slot in tool face with rounded corner



Control of electrolyte flow by restrictor dams

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Tool Design for Insulation

Purpose

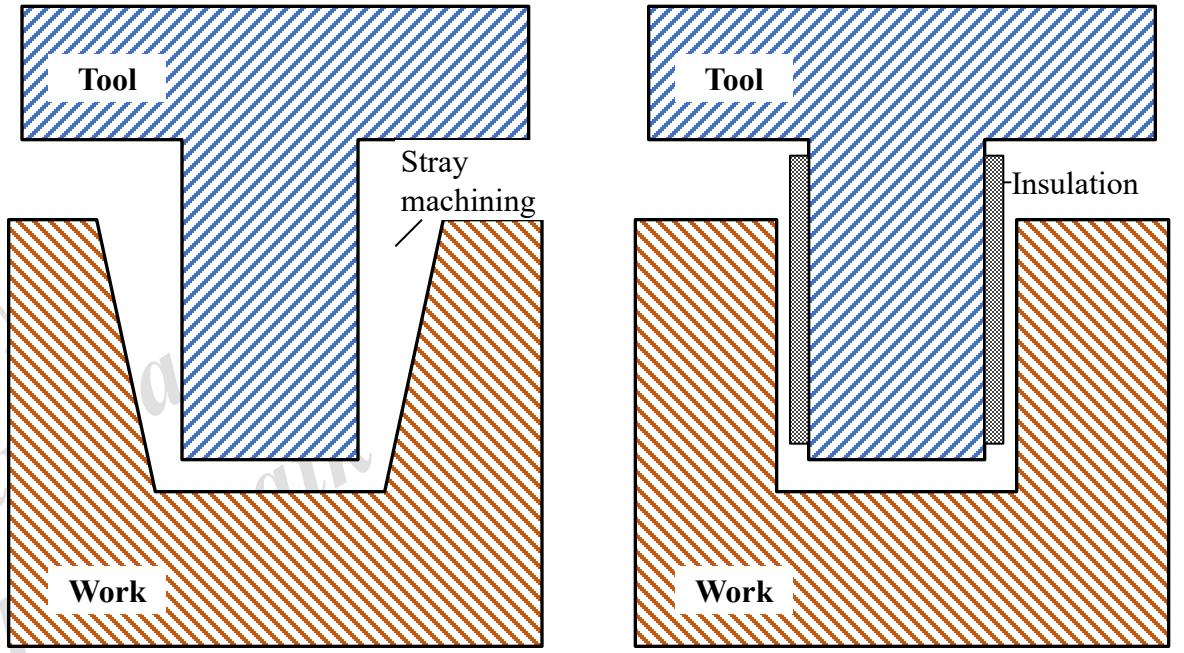
- Areas of the tool where machining is not wanted are insulated, to minimise stray machining.

Insulating materials

- **Reinforced solid plastic,** fixed with epoxy cement and plastic screws
- **Synthetic rubber coating** on the tool surface
- **Artificially oxidised copper** (hot chemical oxidising solution)

Requirement

- The insulation must be tough and securely bonded; its edges must not face high-velocity flow, which can tear it off.



(a) Tool without insulation (b) Insulated tool

Effect of insulation

Without insulation the side walls of the cavity are also machined and flare out; with insulation the walls stay straight.

Prepared By Dr. S.R. Pa... Dr. A.K. ...

Electrolytes in ECM

Three functions

1. Complete the electrical circuit and carry large currents.
2. Sustain the electrochemical reactions.
3. Carry away the heat and the waste products.

Requirements

- **High electrical conductivity**
- **No deposition** on the cathode (tool)
- **High anodic efficiency**
- **Chemical stability**
- **Low cost**
- **Safe and non-corrosive**

Alloy	Electrolyte
Iron based	Chloride solutions in water (mostly 20% NaCl)
Nickel based	HCl, or brine + H_2SO_4
Titanium based	10% HF + 10% HCl + 10% HNO_3
Co-Cr-W based	NaCl
WC based	Strong alkaline solutions

Types of electrolytes

An aqueous solution of inorganic compounds is generally used.

Prepared By
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Effect of ECM on Work Materials

Property	ECM	Turning and milling
Hardened surface layer	≈ 0.001 mm	0.5–1.5 mm
Residual stress	Almost zero	≈ 50 kg/mm²
Fatigue strength	10–25% lower	Baseline

Why fatigue strength falls

ECM removes metal atom by atom without cold work, so the tips of micro-cracks in the surface are left exposed instead of being closed by a deformed layer.

How it is restored

- Mechanical polishing
- Glass bead blasting
- Vapour blasting

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Electric Discharge Machining

(EDM)

Contents

1. Principle of EDM and servo control
2. Mechanics of spark formation
3. Single-spark thermal model and the role of cavitation
4. Empirical MRR relations, dielectric circulation and deionization
5. EDM circuits: RC relaxation, rotary impulse generator, controlled pulse
6. Average power, optimum discharge voltage, MRR and worked example
7. Factors affecting MRR in the RC circuit
8. Surface finish and machining accuracy
9. Tool electrode and dielectric fluids
10. Effects on metal surfaces; summary, advantages and applications

Prepared By Dr. S.R. Parmanik Dr. A.K. Parmanik

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Principle of EDM

"The use of a thermoelectric source of energy in developing the nontraditional techniques has greatly helped in achieving an economic machining of the extremely low machinability materials and difficult jobs. The process of material removal by a controlled erosion through a series of electric sparks, commonly known as electric discharge machining, was first started in the USSR around 1943."

Typical operating values

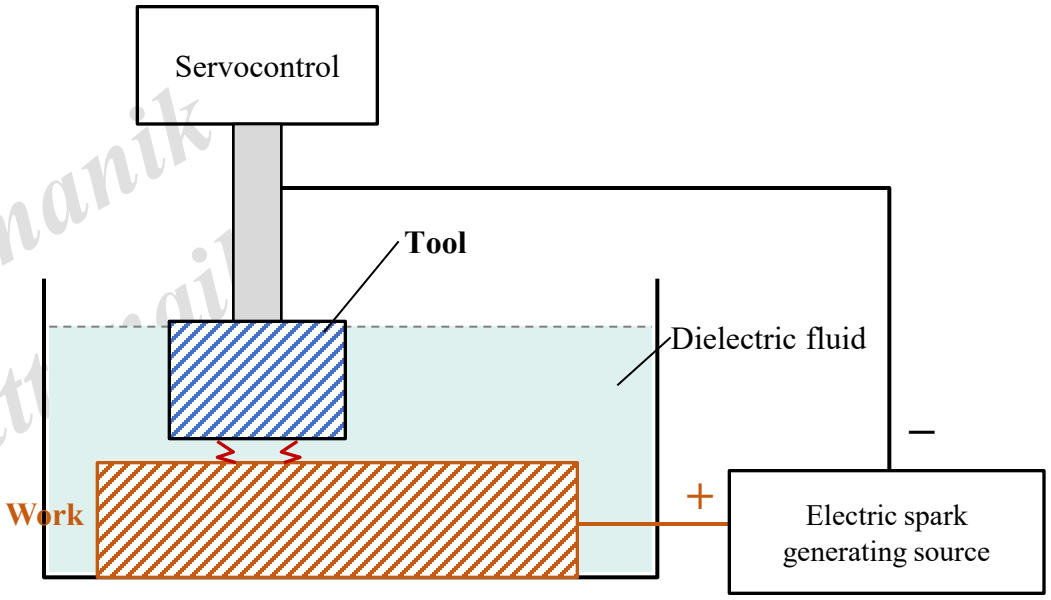
Spark frequency: 200–500,000 Hz

Spark gap: 0.025–0.05 mm

Peak voltage across the gap: 30–250 V

Material removal rate (MRR): up to 300 mm^3/min

Specific power: about 10 W/mm^3/min



Basic scheme of electric discharge machining

Dr. S.R. Patimanik
Dr. A.K. Patnaik

Principle of EDM (contd.)

1. Spark erosion

A discharge takes place between two points of the anode and the cathode. The intense heat **melts and evaporates** the materials in the sparking zone.

2. Dielectric

Both electrodes are submerged in a **dielectric fluid** (hydrocarbon or mineral oil) to improve the effectiveness of the process.

3. Polarity

If both electrodes are of the same material, the one connected to the positive terminal erodes faster. So the work is made the **anode (+)** and the tool the **cathode (−)**.

4. Spark gap

A suitable gap (the **spark gap**) is kept between the tool and the work, and sparks are made to discharge at a **high frequency**.

5. Wandering spark

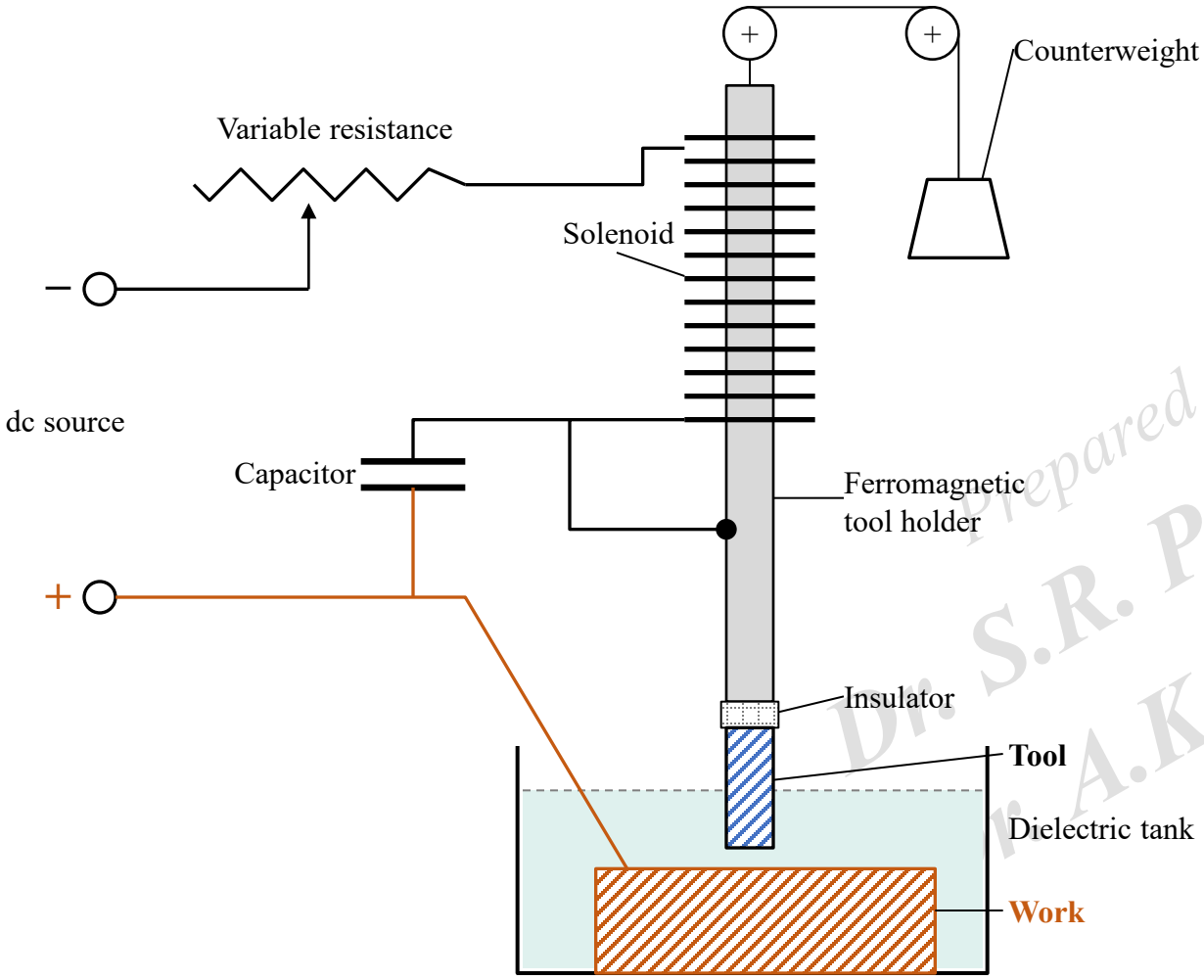
A spark occurs at the spot where the surfaces are **closest**. That spot changes after each spark, so the sparks travel all over the surface.

6. Shape copying

Removal is uniform over the surface, so the work face conforms to the tool and the tool produces its **impression** in the work.

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Servo Control and the Solenoid-Controlled EDM Machine



Solenoid controlled electric discharge machine

Servo control of the spark gap

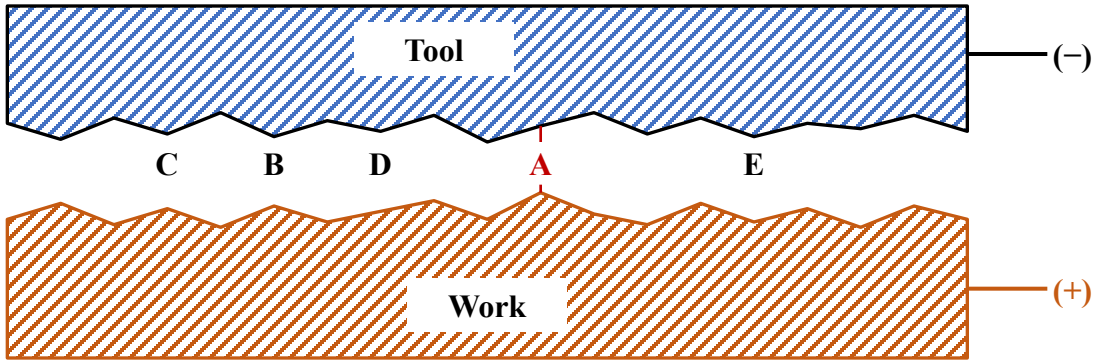
- The gap is sensed through the **average voltage** across it.
- This voltage is compared with a **preset value**, and the difference drives a **servomotor** that moves the tool.
- Sometimes a **stepper motor** is used instead of the servomotor.
- For very primitive operations a **solenoid control** is used. The machine then becomes extremely inexpensive and simple to construct (figure on the left).
- Without servo feed, the gap would grow as material is removed and a higher voltage would be needed to start each spark.

Dielectric and tool

- **Forced circulation** of the dielectric fluid improves the efficiency and the accuracy of performance.
- **Kerosene** is the most commonly used dielectric fluid.
- The tool is generally made of **brass or a copper alloy**.

Prepared By: Dr. S.R. Parimanik & A.K. Parimanik

Mechanics of EDM: Spark Formation



Details of electrode surface characteristics

Local gap is minimum at A, so the first spark occurs there.

Sequence of events in one spark

(1) The surfaces carry asperities, so the local gap varies and is minimum at one point, A.

(2) A suitable voltage between the tool (cathode) and the work (anode) sets up an electrostatic field strong enough to cause **cold emission** of electrons from the cathode at A.

Why removal from the cathode is less (so the tool is the cathode)

(i) The momentum of the electron stream striking the **anode** is much more than that of the positive ions striking the **cathode**, though an electron has less mass than an ion.

(ii) Pyrolysis of the hydrocarbon dielectric forms a thin film of carbon on the cathode.

(iii) A compressive force develops on the cathode surface.

For these reasons the tool is normally connected to the negative terminal of the dc source.

Prepared By Dr. S.R. Patnaik Dr. A.K. Pattanaik

Mechanics of EDM: Spark Formation (contd.)

Sequence of events in one spark (contd.)

(3) The electrons accelerate towards the anode and collide with dielectric molecules, breaking them into electrons and positive ions. The new electrons dislodge more electrons.

(4) A narrow column of ionized dielectric forms at A. Its conductivity is very large, and the **avalanche of electrons** is seen as a spark.

(5) A compression shock wave forms and a temperature of **10,000–12,000 °C** develops on the electrodes.

(6) The electrode materials melt and vaporize. A mechanical blast evacuates the molten metal, leaving small **craters on both electrodes** at A.

(7) The gap at A increases, so the next spark occurs at the new shortest gap, B. The sparks wander over the surface, giving a uniform gap and an impression of the tool on the work.

A stationary tool would let the gap grow, needing a higher voltage. A **servodrive** feeds the tool to keep the average gap constant.

Prepared By:
Dr. S.K. Parimanik
Dr. A.K. Pattanaik

Single-Spark Thermal Model: Assumptions and Governing Equation

Aim: estimate the material removed by one discharge from the crater diameter and the depth to which the melting temperature is reached.

Assumptions

(i) The spark is a uniform circular heat source on the electrode surface, with constant diameter $2a$.

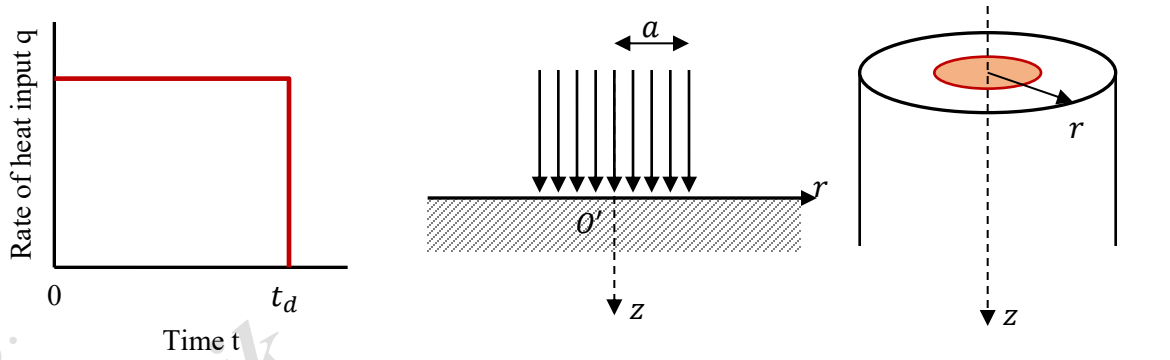
(ii) The electrode surface is a semi-infinite region.

(iii) Except for the heat source portion, the electrode surface is insulated.

(iv) The rate of heat input is constant throughout the discharge.

(v) The electrode material properties do not change with temperature.

(vi) Vaporization of the electrode material is neglected.



(a) Constant rate of heat input **(b) Uniform heat flux** **(c) Circular heat source**

Description of idealized heat source during EDM

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Symbols

H = amount of heat input (cal); θ = temperature (°C)

t = time (s); t_d = discharge duration (s)

k = thermal conductivity (cal/cm-s-°C)

α = thermal diffusivity (cm^2/s)

θ_m = melting temperature (°C); a = radius of the heat source (cm)

r, z = radial and depth coordinates from the centre O' (cm)

Single-Spark Thermal Model (contd.)

Heat conduction equation (circular symmetry)

Because of circular symmetry, θ depends only on r and z:

$$\frac{\partial \theta}{\partial t} = \alpha \left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r} + \frac{\partial^2 \theta}{\partial z^2} \right)$$

Initial and boundary conditions

- **Initially,** $t \leq 0$: $\theta(r, z, t) = 0$
- **Outside the source,** $t > 0, r > a$ (insulated surface):

$$\frac{\partial \theta}{\partial z} = 0$$

- **Over the spark area,** $t > 0, 0 < r \leq a$ (uniform heat flux):

$$-k\frac{\partial \theta}{\partial z} = \frac{H}{\pi a^2 t_d}$$

Prepared By: Dr. S.R. Parimanik, Dr. A.K. Pattanaik

Single-Spark Thermal Model: Solution

Temperature on the axis and melting depth

Melting depth is greatest at the centre, so the solution at $r = 0$ is used. The maximum temperature is reached at $t = t_d$, when the heat input stops:

$$\theta(0, z, t_d) = \frac{1}{2}\frac{H}{\pi k a t_d}\int_0^\infty J_0(\xi a)J_1(\xi a)\left[e^{-\xi z}\operatorname{erfc}\left\{\frac{z}{2\sqrt{\alpha t_d}} - \xi\sqrt{\alpha t_d}\right\}\right]\frac{d\xi}{\xi}$$

ξ = dummy variable of integration; J_0, J_1 = Bessel functions of order 0 and 1.

If Z = depth (cm) to which the melting temperature θ_m is reached:

$$\theta_m = \frac{2H\sqrt{\alpha t_d}}{\pi k a^2 t_d}\left[\operatorname{ierfc}\frac{Z}{2\sqrt{\alpha t_d}} - \operatorname{ierfc}\frac{\sqrt{Z^2 + a^2}}{2\sqrt{\alpha t_d}}\right]$$

where

$$\operatorname{ierfc}(\zeta) = \frac{1}{\sqrt{\pi}}e^{-\zeta^2} - \zeta\operatorname{erfc}\zeta$$

$$\operatorname{erfc}(\zeta) = 1 - \operatorname{erf}(\zeta), \quad \operatorname{erf}(\zeta) = \frac{2}{\sqrt{\pi}}\int_0^\zeta e^{-x^2}dx$$

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Single-Spark Thermal Model: Solution (contd.)

Latent heat correction

Heat used to melt the material is subtracted from the total heat. Rate of heat input:

$$\frac{H_{total} - H_m \rho \pi a^2 Z}{\pi a^2 t_d} \text{ cal/cm}^2\text{-s}$$

H_{total} = total heat released (cal); H_m = latent heat (cal/g); ρ = density (g/cm^3)

Conclusion: Z gives an indication of the volume of material removed by each spark.

Crater diameter and crater volume

Crater diameter = spark diameter $2a$ (uniform strength):

$$2a = KW^{n_1} t_d^{n_2} \text{ cm}$$

W = total pulse energy (J); n_1, n_2, K = constants for the electrodes and the dielectric.

Melting depth Z is related to the crater volume:

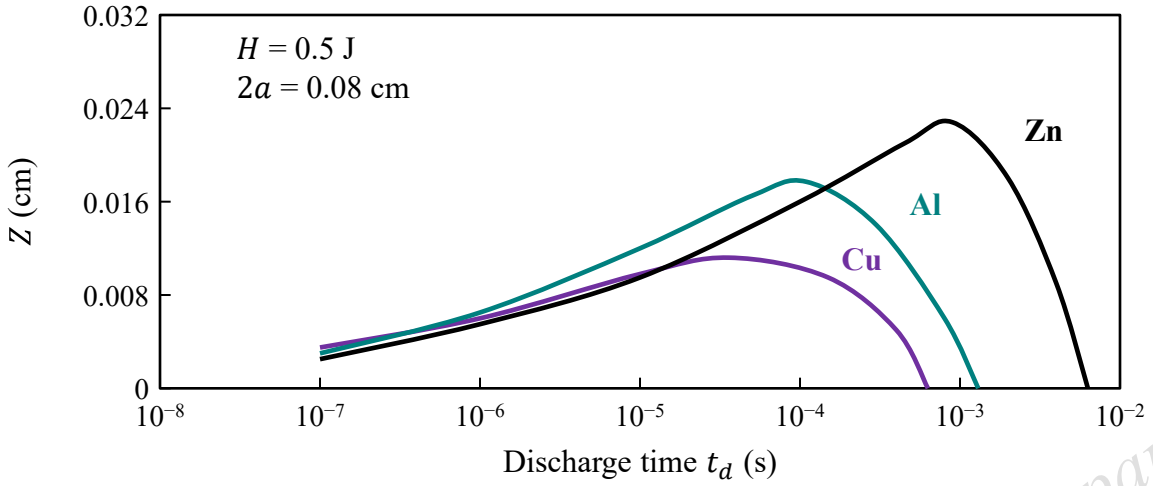
$$v_c = \frac{\pi}{6} h_c (3a^2 + h_c^2) \text{ cm}^3$$

v_c = crater volume (cm^3); h_c ($\propto Z$) = crater depth (cm)

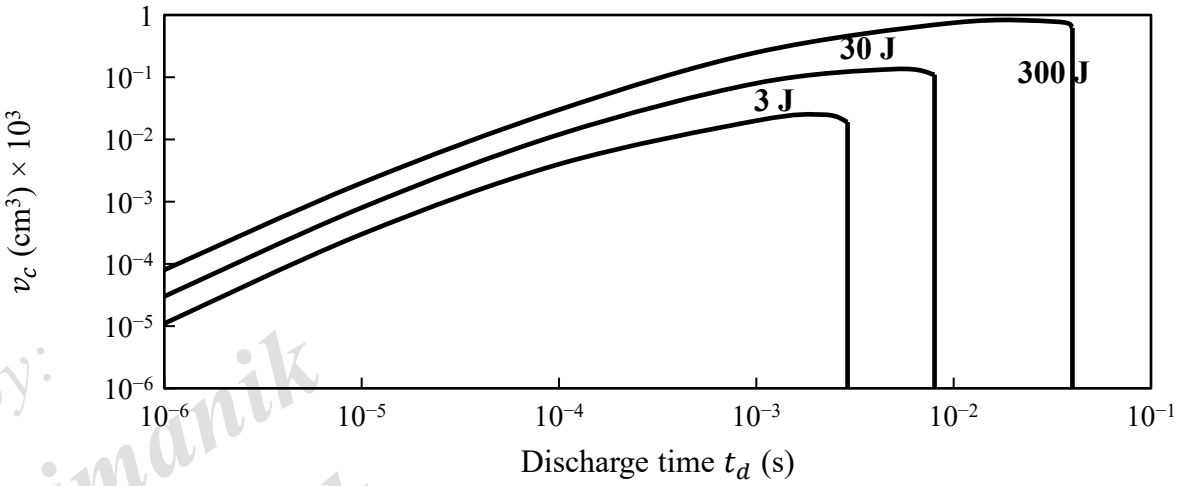
For the exam: learn the assumptions, the governing equation, the boundary conditions and the conclusions. The solution is shown for completeness.

Prepared By: Dr. P. Parimanik Dr. A.K. Parimanik

Results of the Model and the Role of Cavitation

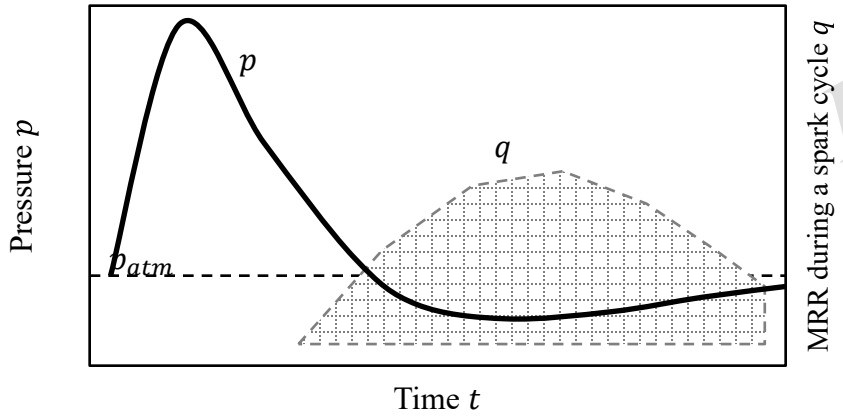


(a) Variation of Z



(b) Variation of v_c

Variation of melting temperature depth Z and crater volume v_c with discharge time t_d



Role of cavitation in material removal

What the results show

- Removal is very low for a small t_d. It rises with t_d, reaches a peak and then **suddenly drops to zero**.
- Removal per discharge depends strongly on the **melting point** of the material: Zn peaks highest and latest, then Al, then Cu.
- A higher spark energy gives a larger crater volume and a later drop.
- **Cavitation:** the mrr is maximum when the pressure is **below atmospheric**, showing the importance of cavitation.

Prepared By: Dr. S. Parimanik Dr. A.K. Parimanik

Empirical MRR Relations and Deionization

Crater size from spark energy

The crater size depends on the spark energy (other conditions unchanged):

$$h_c = K_1 W^{1/3} \text{ cm}$$
$$2a = K_2 W^{1/3} \text{ cm}$$

h_c = crater depth (cm); $2a$ = crater diameter (cm); W = spark energy (J); K_1, K_2 = constants.

For Cu electrodes and kerosene: $K_1 \approx 0.4$ and $K_2 \approx 0.045$.

Using these in the crater-volume equation, the crater volume per spark is

$$v_c = \frac{\pi}{6} K_1 \left(\frac{3}{4} K_2^2 + K_1^2 \right) W \text{ cm}^3$$

Rough estimate from the melting point

Under normal working conditions (average sparking):

$$Q \approx 4 \times 10^4 \theta_m^{-1.23} \text{ mm}^3/\text{A-min}$$

Q = metal removal rate (mm³/A-min), i.e. per ampere of current; θ_m = melting temperature of the work (°C).

A higher melting point gives a lower removal rate.

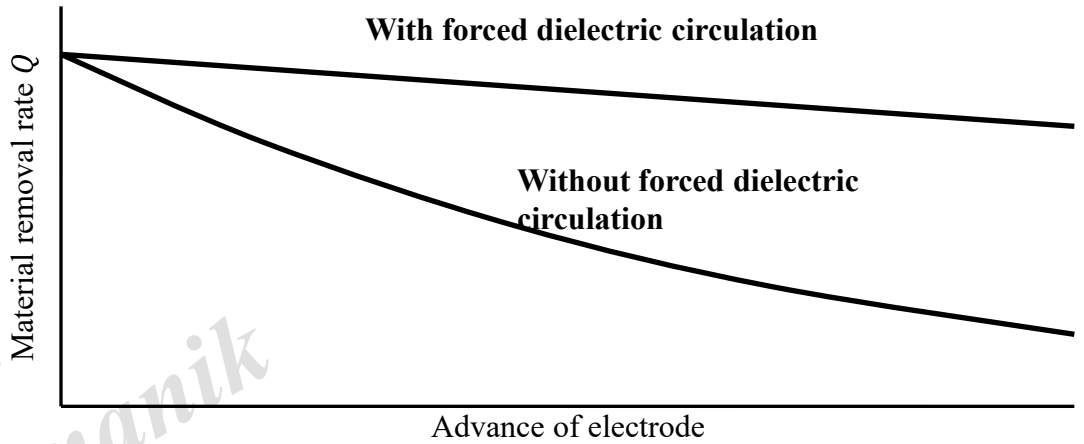
Deionization of the gap

- After a discharge, the dielectric around the last spark must be allowed to **deionize**.
- The gap voltage must stay below the discharge voltage until deionization is complete. Otherwise, current flows again through the gap at the location of the preceding discharge.
- A larger energy release needs a longer deionization time.

Prepared By: Dr. S.R. Pattanaik Dr. A.K. Pattanaik

Dielectric Circulation and EDM Circuits

- The mrr depends strongly on the circulation of the dielectric fluid.
- Without forced circulation, the wear particles repeatedly melt and reunite with the electrode, so the mrr falls as the electrode advances.



Effect of forced circulation of dielectric fluid

Prepared By: Parimanik

EDM circuits

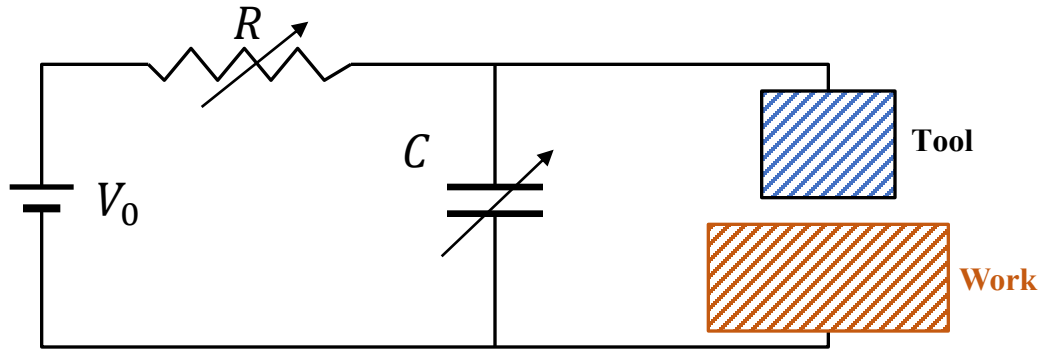
A pulsating dc is supplied across the work–tool gap. Almost all circuits use a **capacitor** to store the charge before the discharge. The circuits fall into three groups:

(i) Resistance-capacitance (RC) relaxation circuit with a constant dc source

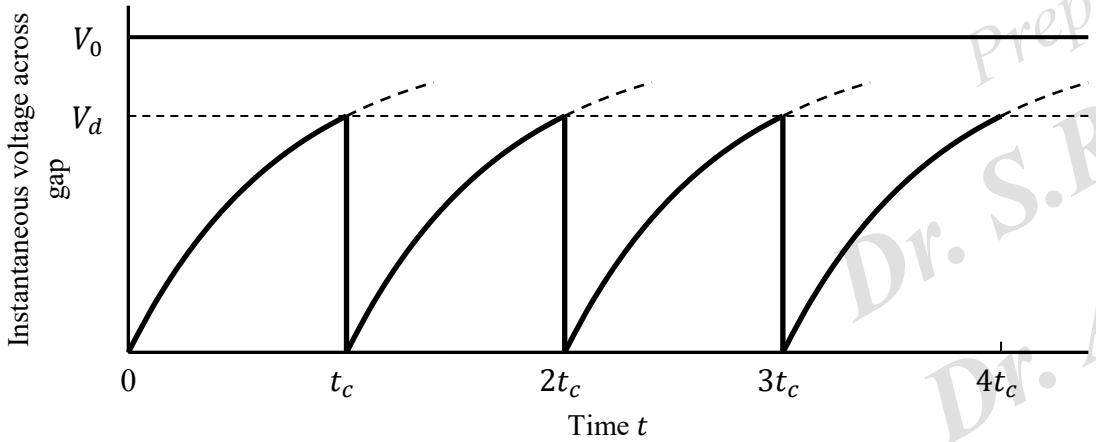
(ii) Rotary impulse generator

(iii) Controlled pulse circuit

The RC Relaxation Circuit



(a) Relaxation circuit



(b) Variation of gap voltage
Principle of RC relaxation circuit

- The capacitor C is charged through the variable resistance R by the dc source of voltage V_0.
- The gap voltage V is almost the same as the capacitor voltage. It rises towards V_0 along the exponential curve.
- When V reaches the discharge voltage V_d, a spark occurs and the capacitor discharges completely. The cycle then repeats.

Gap voltage, with t measured from the instant V_0 is applied:

$$V = V_0\left(1 - e^{-t/(RC)}\right)$$

Discharge time ≈ 10% of charging time and deionization time is very small, so the sparking frequency is

$$\nu \approx \frac{1}{t_c} = \frac{1}{RC \log_e\left(\frac{V_0}{V_0 - V_d}\right)}$$

Energy released per spark: $E = \frac{1}{2}CV_d^2$

V_0 = supply voltage (V); V_d = discharge voltage (V); R = resistance (Ω); C = capacitance (F); t_c = charging time to reach V_d (s); ν = frequency of sparking (Hz); E = energy per spark (J)

Prepared By: Dr. S.R. Parmanik Dr. A.K. Parmanik

Average Power, Optimum Discharge Voltage and MRR

Average power delivered

If t_c (= $1/\nu$) is the cycle time, the average power is $W_{av} = \frac{E}{t_c + t_s}$, with t_s the spark (discharge) time, small compared with t_c.

Since

$$V_d = V_0[1 - \exp\{-t_c/(RC)\}]$$

using the spark-energy equation the average power becomes

$$W_{av} = \frac{1}{2}\frac{C}{t_c}V_0^2[1 - \exp\{-t_c/(RC)\}]^2$$

Rearranging, with $\zeta = t_c/(RC)$:

$$W_{av} = \frac{V_0^2}{2R}\frac{1}{\zeta}\left(1 - e^{-\zeta}\right)^2$$

For maximum power, $\frac{\partial W_{av}}{\partial \zeta} = 0$ at $\zeta = \zeta_{opt}$, which gives

$$(2\zeta_{opt} + 1)\exp(-\zeta_{opt}) = 1 \quad \Rightarrow \quad \zeta_{opt} = 1.26$$

$$\left(\frac{V_d}{V_0}\right)_{opt} = 1 - \exp(-\zeta_{opt}) = 1 - e^{-1.26} = 0.72$$

For maximum power delivery, the discharge voltage should be 72% of the supply voltage V_0.

Prepared By: Dr. S.R. Parimanik, A.K. Patianaik

Average Power, Optimum Discharge Voltage and MRR (contd.)

Material removal rate (mrr)

Assume the material removed per spark is proportional to the energy released per spark:

$$Q \approx K\left(\frac{1}{2}V_d^2 C\right)\nu$$

Using the sparking-frequency equation for ν:

$$Q \approx K\frac{1}{2}V_d^2 C\frac{1}{RC\log_e[V_0/(V_0 - V_d)]}$$

$$Q \approx K\frac{V_d^2}{2R\log_e[V_0/(V_0 - V_d)]}$$

K = constant of proportionality, the fraction of power effectively used in material removal.

Limit on R, and an empirical rule for steel

- For a given circuit, mrr increases as R is decreased. Below a critical value, **arcing** takes place instead of sparking. For a purely inductive discharging circuit: $R_{min} = \sqrt{L/C}$, L = inductance of the discharging circuit (H).
- The circuit is seldom purely inductive, so R should not be lowered below $30\sqrt{L/C}$.
- For steel under normal conditions: $Q \approx 27.4W^{1.54}$, Q in mm^3/min, W = power input (kW).

Prepared By: Dr. S.R. Parmanik Dr. A.K. Pattanaik

Example: Time to Drill a Square Hole by EDM

Given

- Electric discharge drilling of a **10 mm square hole**
- Low carbon steel plate, **5 mm thick**
- Brass tool, kerosene dielectric
- RC relaxation circuit: $R = 50\ \Omega$, $C = 10\ \mu F$
- Supply voltage $V_0 = 200$ V
- Discharge (sparking) voltage $V_d = 150$ V

Find

Time required to complete the drilling.

Approach

Work is steel, so use $Q \approx 27.4W^{1.54}$. First find the average power W from the energy per spark and the cycle time.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Example: Time to Drill a Square Hole by EDM (Solution)

Solution

1. Energy per spark:

$$E = \frac{1}{2} C V_d^2 = \frac{1}{2} \times 10 \times 10^{-6} \times 150^2 \text{ J} = 0.113 \text{ J}$$

2. Cycle time:

$$t_c \approx RC \log_e \left(\frac{V_0}{V_0 - V_d} \right) = 50 \times 10 \times 10^{-6} \log_e \left(\frac{200}{50} \right) = 50 \times 10^{-5} \times 1.39 \text{ s}$$

$$= 7 \times 10^{-4} \text{ s}$$

3. Average power:

$$W = \frac{E}{t_c} = \frac{0.113}{7 \times 10^{-4}} \times 10^{-3} \text{ kW} = 0.16 \text{ kW}$$

4. Removal rate:

$$Q = 27.4 \times 0.16^{1.54} \text{ mm}^3/\text{min} = 1.633 \text{ mm}^3/\text{min}$$

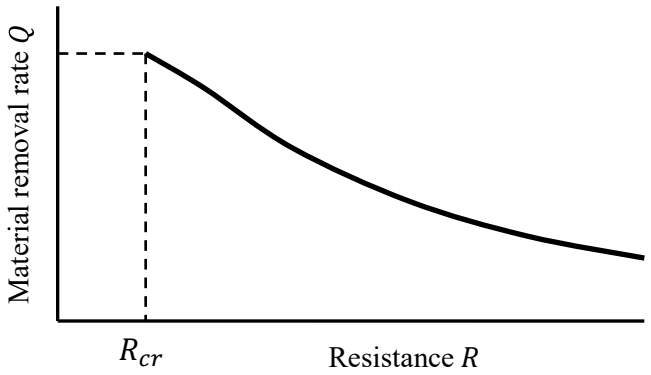
5. Volume to remove: $10^2 \times 5 = 500 \text{ mm}^3$ **6. Time:** $500/1.633 \approx 306 \text{ min}$

Answer: time ≈ 306 min

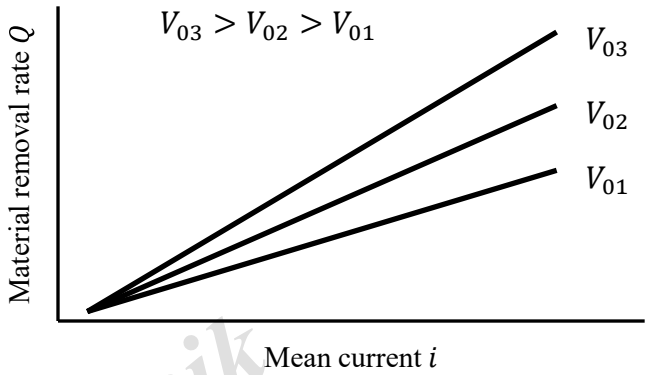
Rounding check: without rounding W to 0.16 kW (W = 0.162 kW), $Q \approx 1.67$ mm^3/min and the time ≈ 300 min. Also, $27.4 \times 0.16^{1.54}$ works out to 1.630, not 1.633.

Prepared By Dr. S.R. Parimanik Dr. A.K. Pattanaik

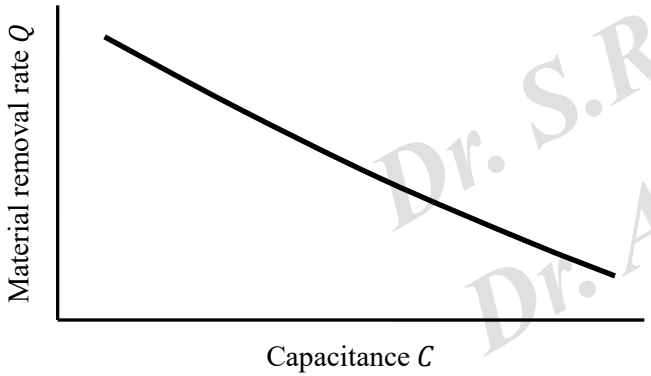
Factors Affecting MRR in the RC Circuit



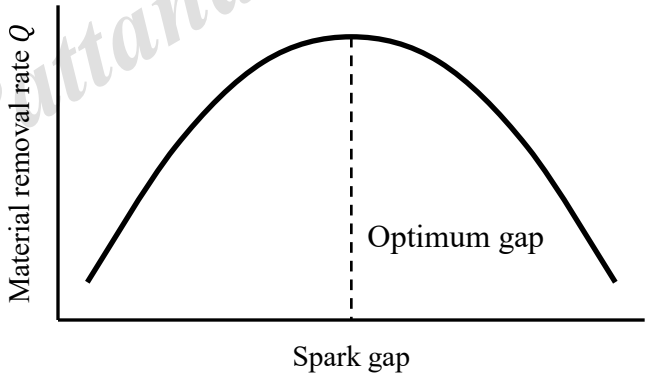
(a) Variation with resistance



(b) Variation with mean current



(c) Variation with capacitance



(d) Variation with spark gap

Material removal rate characteristics in EDM using RC relaxation circuit

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Puttanaik

Factors Affecting MRR in the RC Circuit (contd.)

- **(a) to (c)** follow directly from the MRR equation:

$$Q \approx K \frac{V_d^2}{2R \log_e[V_0/(V_0 - V_d)]}$$

- **(a) Resistance:** mrr increases as R is decreased, but R cannot go below the critical value R_{cr}, or arcing replaces sparking.

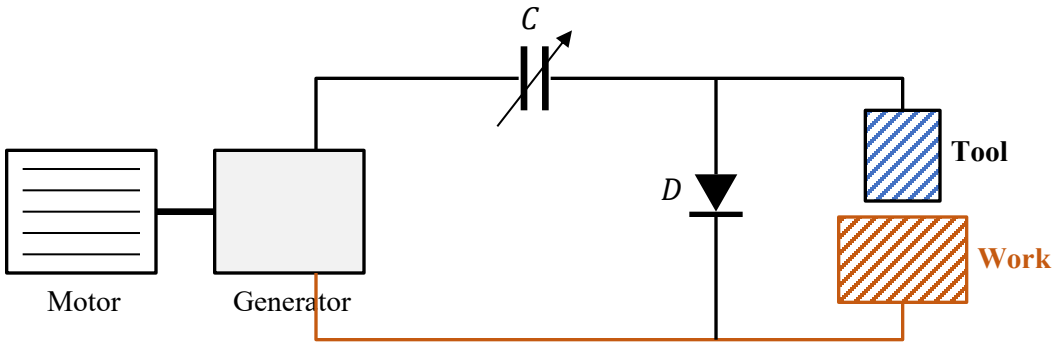
- **(b) Mean current:** mrr rises with mean current i, and a higher supply voltage V_0 gives a higher mrr.

- **(c) Capacitance:** as drawn in the book, Q falls as C increases.

- **(d) Spark gap:** if the gap is too small, the discharge voltage is small and, though the frequency is high, mrr is small. If the gap is too large, the discharge voltage is large but the frequency falls drastically. So an **optimum spark gap** exists.

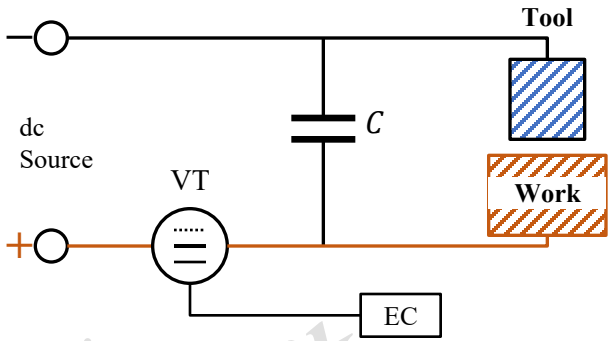
Prepared By: Dr. S.R. Parimanik & Dr. A.K. Pattanaik

Rotary Impulse Generator and Controlled Pulse Circuits

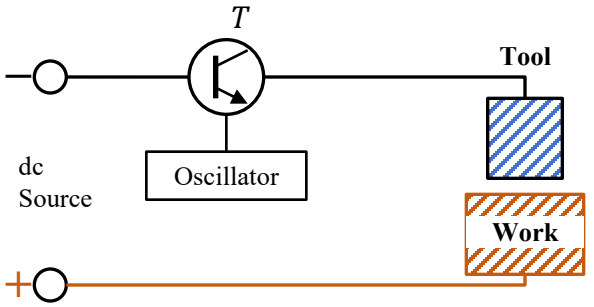


Rotary impulse generator for EDM

- **Why:** the RC relaxation circuit is simple, but its mrr is not high. An impulse generator increases the removal rate.
- The capacitor C is charged through the diode D during the first half cycle.
- In the following half cycle, the generator voltage **plus** the charged capacitor voltage is applied to the work–tool gap.
- The operating frequency is the frequency of the sine wave, which depends on the motor speed.
- The mrr is higher, but the surface finish is not good.



EDM with controlled pulse circuit



EDM with controlled pulse circuit without capacitor

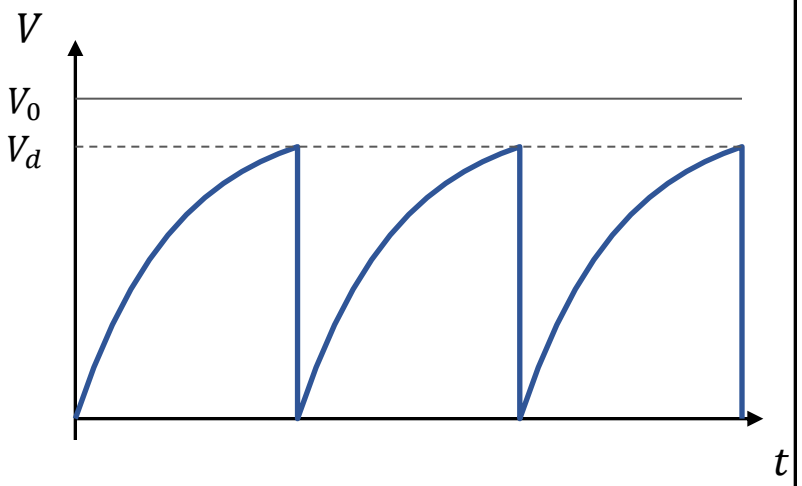
- In the two earlier systems nothing stops the current automatically on a short circuit. Here a vacuum tube (or a transistor) is the switching device.
- During sparking the gap current comes from the capacitor. While current flows through the gap, the tube is biased to cut off and behaves like an infinite resistance (bias set by the electronic control EC).
- When the gap current ceases, the tube conducts and current flows to recharge the capacitor.
- **Without capacitor:** an oscillator controls the transistor bias, so current flows cyclically at the imposed frequency. Stability improves.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Types of Pulses Generated in EDM

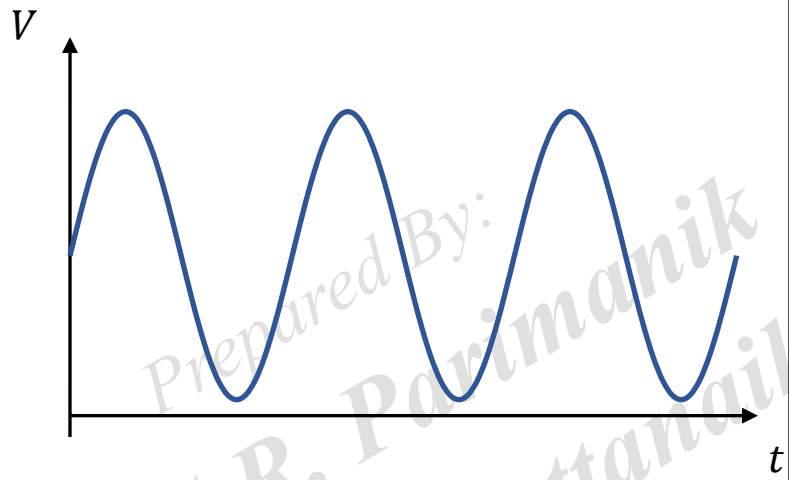
Sketches of the gap voltage against time for the three circuit types

RC relaxation circuit



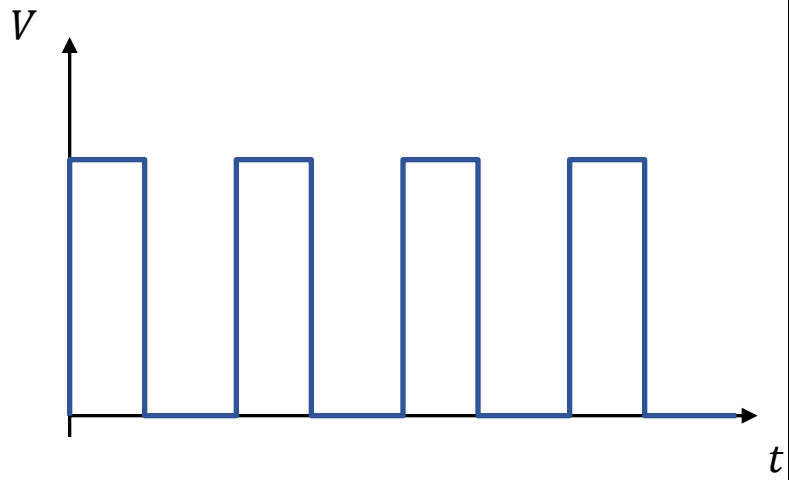
Exponential charging sawtooth. The gap voltage rises towards V_0 along the charging curve and drops to zero when it reaches V_d and the capacitor discharges.

Rotary impulse generator



Pulses follow the sine wave of the generator. The operating frequency equals the sine-wave frequency, which depends on the **motor speed**.

Controlled pulse circuit



Rectangular on/off pulses. A vacuum tube or transistor switches the current; with an oscillator the frequency is imposed and stability improves.

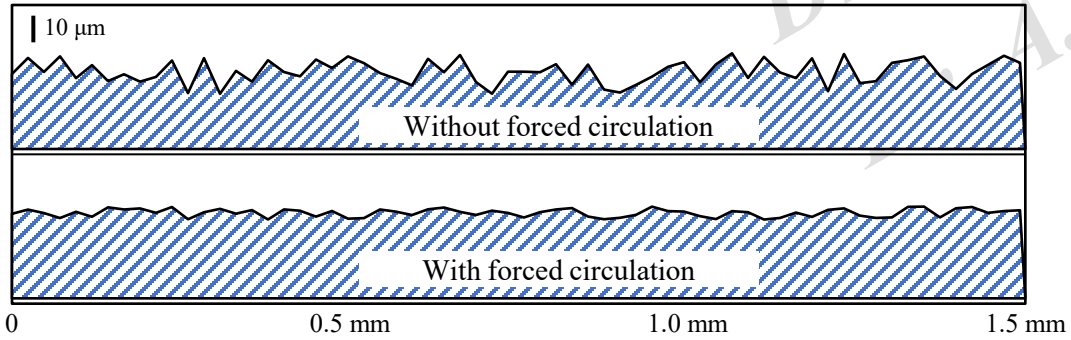
Prepared By: Dr. S. R. Parimanik Dr. A. K. Pattanaik

Surface Finish in EDM

Process	Class	H_{rms} (µm)													
		0.01	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.0	12.0	25.0	50.0	100
Turning	Roughing														
	Finishing														
Milling	Roughing														
	Finishing														
Boring	Roughing														
	Finishing														
Reaming	Roughing														
	Finishing														
Grinding	Roughing														
	Finishing														
Lapping	Roughing														
	Finishing														
Honing															
Polishing															
Superfinishing															

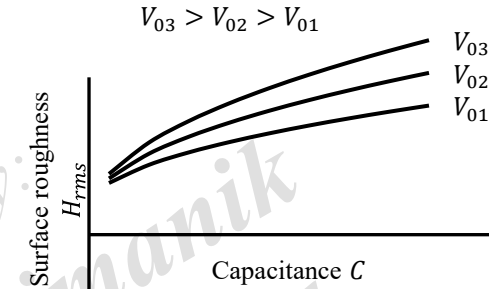


Dependence of surface finish on pulse energy and comparison with conventional processes



Effect of forced circulation on surface finish

Large craters, especially deep ones, make the surface rough. Crater size depends mainly on the **energy per spark**, so it controls surface quality.



Dependence of surface finish on capacitance

H_{rms} = root mean square value of the surface unevenness (µm).

H_{rms} rises with capacitance C and with supply voltage V_0.

Brass electrode, 40 V, 0.2 A, 1.12 kHz: forced circulation clearly improves the finish.

Prepared By: Dr. S.R. Parimanik & A.K. Pattanaik

Surface Finish in EDM (contd.) and Machining Accuracy

- Crater depth: $h_c \approx K_1 E^{0.33}$ mm, E = spark energy (J), K_1 = material constant (≈ 4 for copper work).
- With $E = \frac{1}{2} C V_d^2$: $h_c \approx 0.78 K_1 C^{0.33} V_d^{0.66}$
- Steel, normal conditions: $H_{rms} \approx 1.11 Q^{0.384}$, H_{rms} in μm, Q = mrr (mm³/min).

Example: steel, R = 50 Ω, C = 10 μF, V_0 = 200 V, V_d = 150 V

Conditions match the previous example, so Q = 1.633 mm³/min. By the roughness relation:

$$H_{rms} = 1.11 \times 1.633^{0.384} \approx 1.34\ \mu m$$

Answer: H_{rms} ≈ 1.34 μm

Book uses Q = 56.4 mm³/min here and gives 5.16 μm, which does not match the previous example (and $1.11 \times 56.4^{0.384} = 5.22$). In the crater-depth relation, $(1/2)^{0.33} = 0.80$, printed as 0.78.

Sources of inaccuracy

(i) Taper of the hole (or pocket) machined

(ii) Overcut due to sparks at the side faces of the electrode

(iii) Errors from the gradual change in tool shape and size (tool wear)

Prepared by Dr. A. K. Parimanik

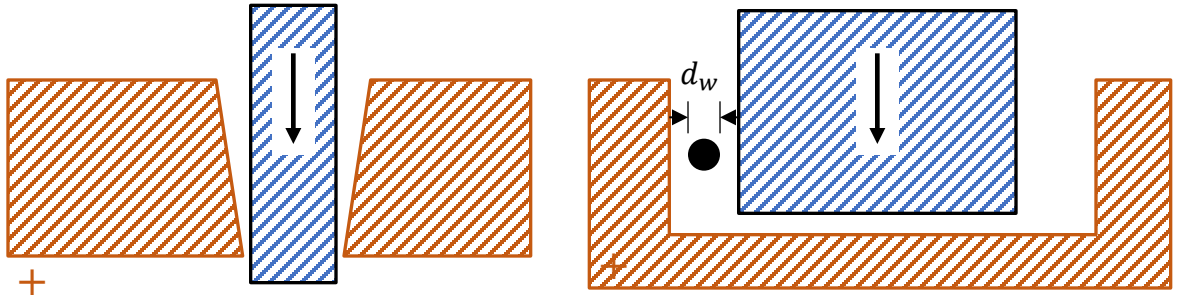
Machining Accuracy in EDM

(i) Taper

- As the tool advances, the hole becomes tapered because the upper part of the hole wall is exposed to more sparks than the bottom.
- For round tools, taper depends on the **square of the tool diameter** (other conditions the same). It is controlled by altering the electrical parameters.

(ii) Overcut

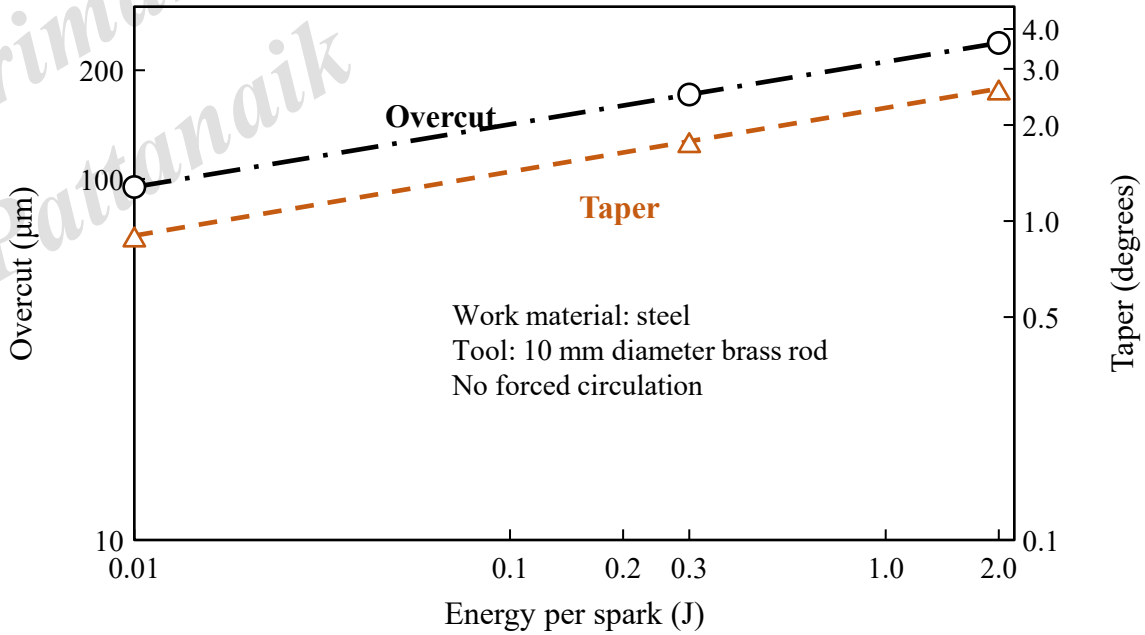
- **Overcut** is the amount by which the hole in the work exceeds the electrode size.
- It depends on the spark length and, to some extent, on the crater dimensions.
- A wear particle in the gap increases the effective spark length, and so the overcut, by d_w = diameter of the wear particle.
- Overcut and taper both increase with the energy per spark (graph).



(a) Tapering of holes drilled by EDM operation

(b) Effect of wear particles on overcut

Sources of dimensional inaccuracy in EDM



Effect of spark energy on overcut and taper

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Tool Electrode and Dielectric Fluids

Tool electrode wear and materials

- The tool also erodes by sparking. Materials with good electrode wear characteristics are those that are difficult to machine.
- **Graphite** is a principal tool material: it goes directly to the vapour phase without melting.
- Wear ratio:

$$r_Q \approx 2.25 r_\theta^{-2.3}$$

  r_Q = material removed from work / material removed from tool; r_θ = melting point of work / melting point of tool.
- **Selection depends on:** (i) material removal rate, (ii) wear ratio, (iii) ease of shaping the electrode, (iv) cost.
- **Common materials:** brass, copper, graphite, Al alloys, Cu-W alloys, Ag-W alloys.
- **Making methods:** (i) conventional machining (Cu, brass, Cu-W, Ag-W, graphite); (ii) casting (Zn-base die-casting alloy, Zn-Sn alloys, Al alloys); (iii) metal spraying; (iv) press forming.
- **Flow holes** are provided for dielectric circulation. For rough cuts they should be as large as possible, to allow large flow rates at low pressure.

Prepared By: Dr. S.K. Parimanik Dr. A.K. Parimanik

Tool Electrode and Dielectric Fluids (contd.)

Dielectric fluids

- **Requirements of an ideal dielectric:** (i) low viscosity, (ii) absence of toxic vapours, (iii) chemical neutrality, (iv) absence of inflaming tendency, (v) low cost.
- **Water** has almost all these properties but is not used: it causes rusting of the work and the machine. Also, the electrodes are always under some potential difference, so its good conductivity starts an ECM action that distorts the work and wastes power. Deionized water is used in some cases.
- **Most common:** hydrocarbon (petroleum) oil. Kerosene, liquid paraffin and silicone oils are also used.

Functions of the dielectric

(i) Insulates the gap until the breakdown voltage is reached.

(ii) Concentrates the spark in a narrow ionized channel.

(iii) Deionizes the gap after each discharge.

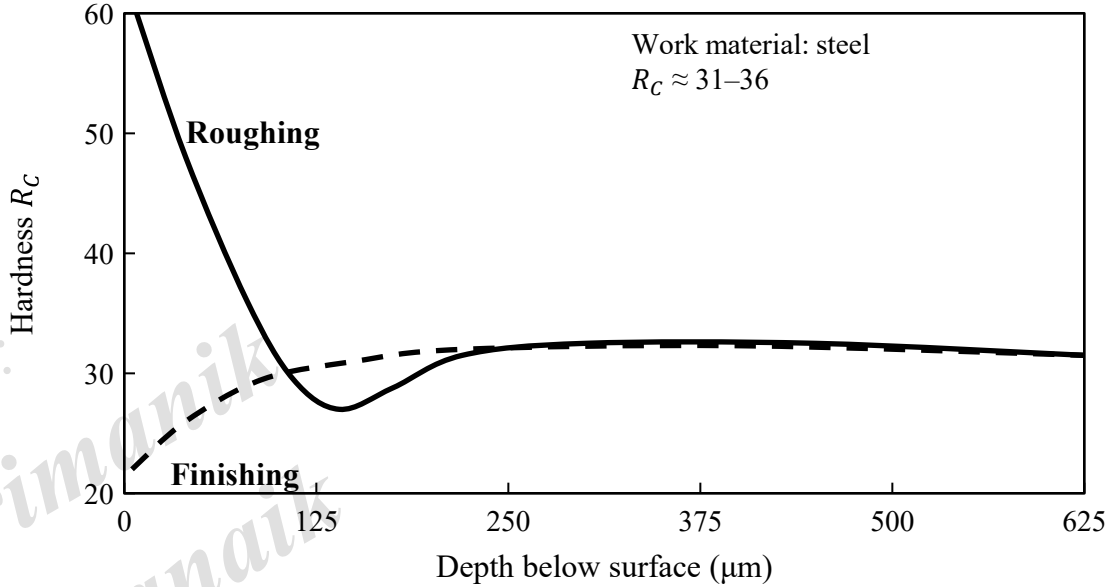
(iv) Cools the tool and the work.

(v) Flushes away the eroded particles.

Prepared by
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Effects of EDM on Metal Surfaces

- The high spark temperature melts and vaporizes the metal, and it changes the properties of the shallow surface layers, **2.5–150 µm** deep.
- The outermost layer is rapidly chilled, so it is **very hard**. The layer below it is in a somewhat **tempered** condition.
- In **finish** machining the hardening is not prominent: the outer layer is tempered and its hardness is low (graph, right).
- The hardened layer gives **better wear resistance**.

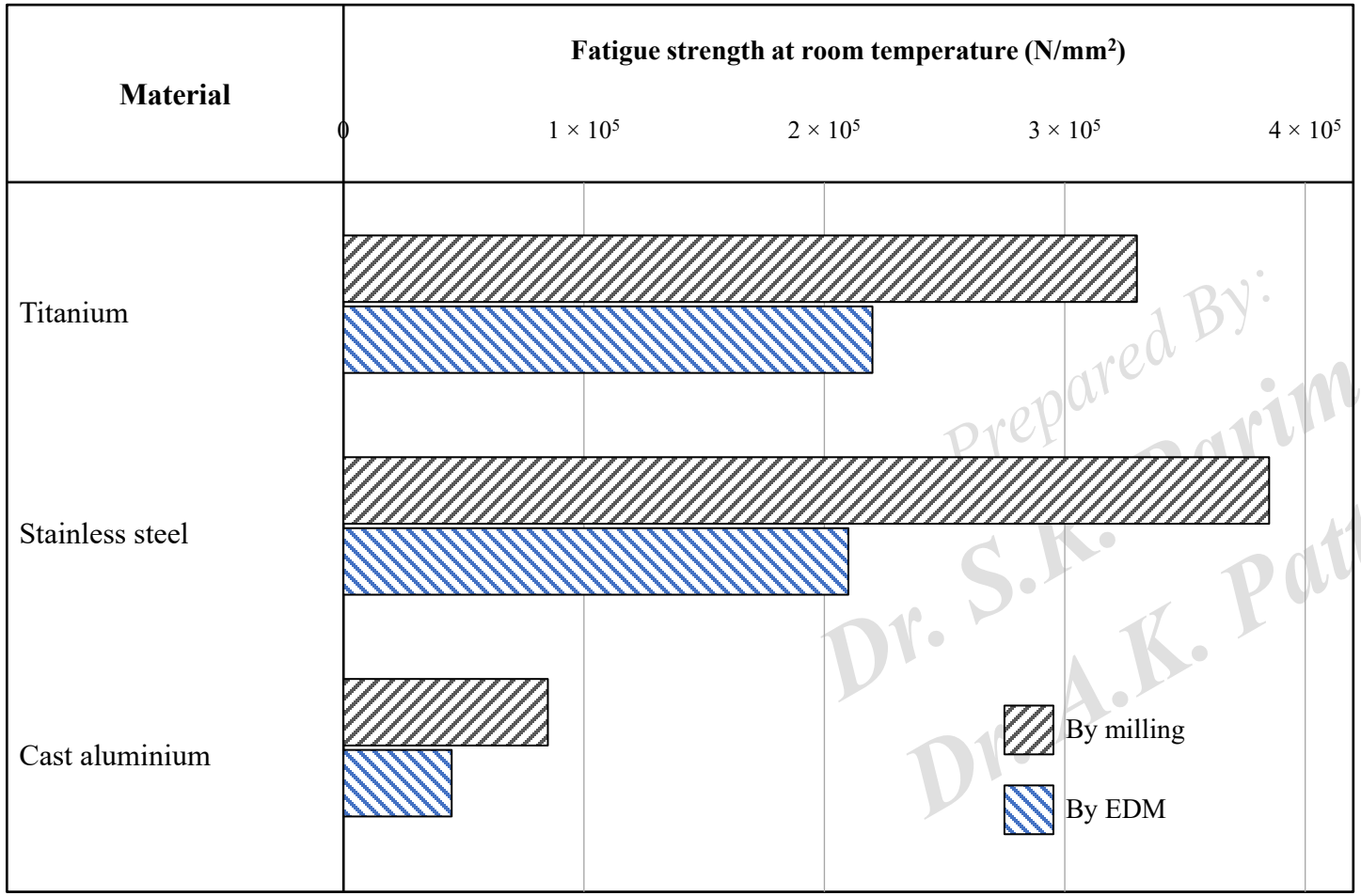


Effect of EDM on subsurface hardness

- **Roughing:** hardness starts near R_C 60 at the surface, falls steeply to about 27 near 125–150 µm (tempered layer), then recovers to the base hardness.
- **Finishing:** hardness starts near 25 and rises to the base hardness by about 200 µm, with no hard peak.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Effects of EDM on Metal Surfaces (contd.)



Effect of EDM on fatigue strength of work

- **Fatigue strength falls** after EDM, because micro-cracks develop in the surface layer during chilling.
- The thin layers have little effect on **tensile strength**. Their structure, and to some extent their chemical composition, change, which generally reduces the erosion resistance.

Prepared By: Dr. S.K. Parimanik & Dr. A.K. Pattanaik

Summary of EDM Characteristics

Characteristic	Value
Mechanics of material removal	Melting and evaporation aided by cavitation
Medium	Dielectric fluid
Tool materials	Cu, brass, Cu-W alloy, Ag-W alloy, graphite
Material removal rate / Tool wear rate	0.1–10
Gap	10–125 μm
Maximum material removal rate	5×10^3 mm^3/min
Specific power consumption (typical)	1.8 $W/mm^3/min$
Critical parameters	Voltage, capacitance, spark gap, dielectric circulation, melting temperature
Materials application	All conducting metals and alloys
Shape application	Blind complex cavities, microholes for nozzles, through cutting of noncircular holes, narrow slots
Limitations	High specific energy consumption (about 50 times that in conventional machining); when forced circulation of dielectric is not possible, removal rate is quite low; surface tends to be rough for larger removal rates; not applicable to nonconducting materials

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

EDM: Advantages, Disadvantages and Applications

Advantages

- Economic machining of extremely low-machinability conducting materials and difficult jobs.
- Reproduces complex tool shapes as blind cavities.
- Microholes for nozzles, noncircular through holes and narrow slots.

Applications (PYQ 2025-26)

- **Materials:** all conducting metals and alloys.
- **Shapes:** blind complex cavities, microholes for nozzles, through cutting of noncircular holes, narrow slots.

Disadvantages

- High specific energy consumption (about 50 times conventional machining).
- Low removal rate if forced dielectric circulation is not possible.
- Rough surface at larger removal rates.
- Not applicable to nonconducting materials.

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Wire Electric Discharge Machining (WEDM)

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

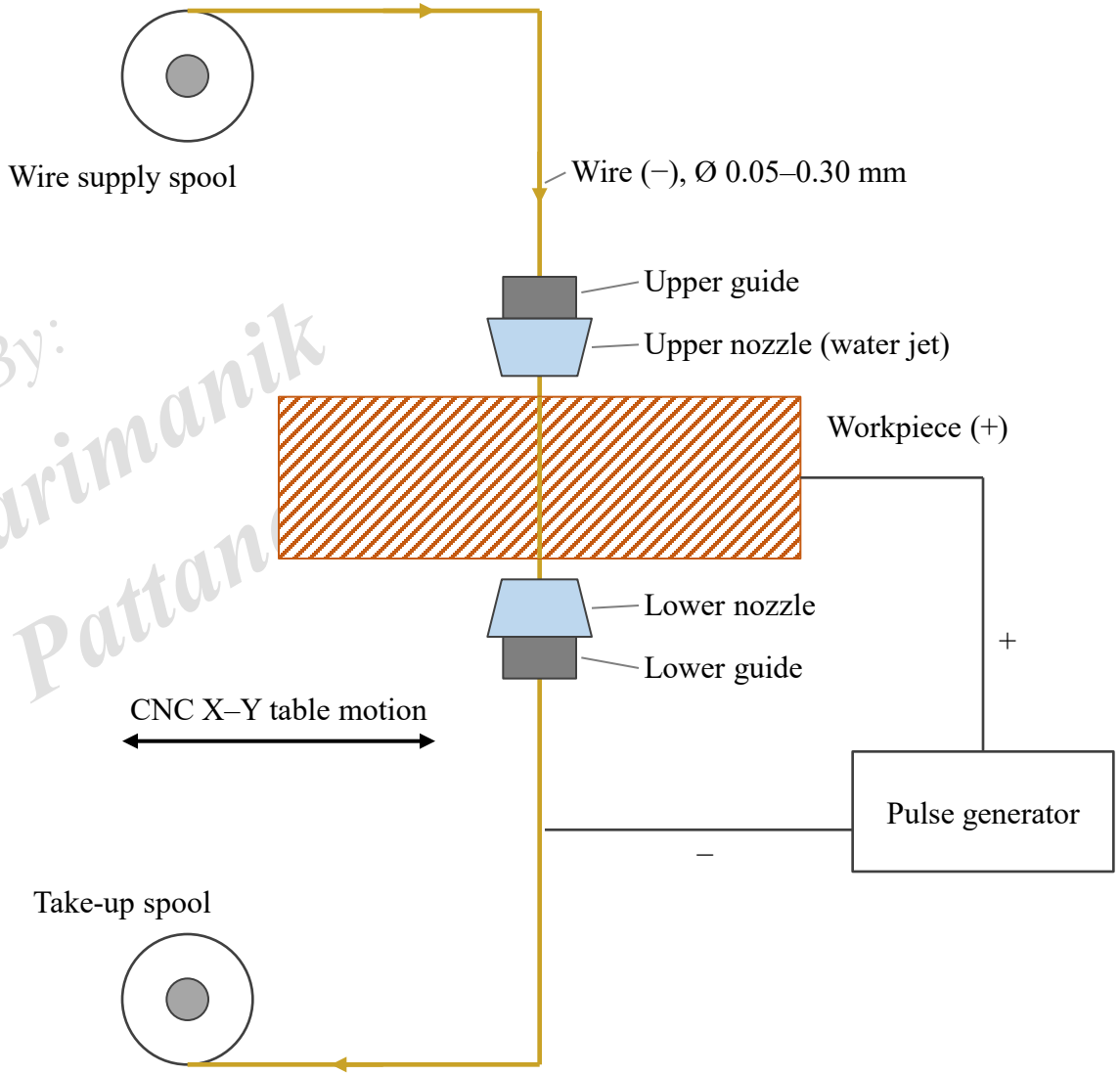
Contents

1. Introduction to wire EDM
2. Principle and mechanism of material removal
3. Wire EDM machine and its components
4. Electrical process variables
5. Non-electrical process variables
6. Kerf, cutting rate and MRR
7. Process characteristics
8. Wire electrodes and their selection
9. Coated (stratified) wires
10. Wire EDM vs die-sinking EDM
11. Applications and limitations
12. Summary of WEDM characteristics

Introduction to Wire EDM

What is wire EDM?

- **Wire EDM (WEDM)** is a form of EDM in which the tool is a thin wire that travels continuously through the work, cutting a through-profile like a CNC-guided band saw.
- **Wire:** brass, coated brass or molybdenum, Ø 0.05–0.30 mm. Each length of wire is used once, so tool wear does not affect accuracy.
- **Dielectric:** deionized water, jetted around the wire by upper and lower nozzles.
- **Motion:** the CNC moves the work table in X–Y; U–V axes offset the upper guide to cut tapers.
- **Work:** any electrically conducting material, whatever its hardness (hardened tool steel, carbide, titanium, nickel alloys).



Schematic of wire EDM (not to scale)

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Principle and Mechanism of Material Removal

One spark cycle (repeated thousands of times per second)

1 Pulse applied
The pulse generator applies a voltage pulse across the small gap between wire and work.

→

2 Breakdown
The water in the narrowest gap ionizes; a plasma channel forms and current flows as a spark.

→

3 Melting
The spark (8,000–12,000 °C) melts and vaporizes a tiny crater on the work, and a smaller one on the wire.

→

4 Ejection
At pulse-off the channel collapses; the vapour bubble implodes and throws out the molten metal as debris.

→

5 Flushing & feed
Water flushes the debris and restores insulation; the CNC advances the cut and fresh wire is fed.

Role of the dielectric (deionized water)

- **Insulates** the gap until breakdown, so each spark stays small and localized.
- **Cools** the wire and work, and **flushes** debris out of the kerf.
- **Conductivity is controlled** by an ion-exchange resin: too high a conductivity causes electrolytic attack and a wider gap.

Typical spark conditions

0.02–0.05 mm	spark gap
8,000–12,000 °C	spark channel temperature
0.1–10 µs	pulse on-time

Prepared by Dr. S.K. Parhi & Dr. A.K. Pattanaik

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Wire EDM Machine and its Components

A CNC wire EDM machine



Wire EDM machine (Electronica Sprintcut 734) showing wire spool, work head quill, spark zone and CNC console

Major components

CNC unit

Stores the part program, drives the X–Y and U–V axes and holds the gap with servo control; adaptive control cuts power when the wire is at risk of breaking.

Power supply (pulse generator)

Produces the controlled pulses and sets pulse on-time, off-time, peak current and gap voltage.

Mechanical section

Work table, wire drive (supply spool, tension rollers, guides, take-up) and the taper unit for U–V tilt.

Dielectric system

Tank, pump, filters, deionizing resin and chiller that keep the water clean, at set conductivity and at constant temperature.

This is for educational purpose only.

Electrical Process Variables

Variable	What it controls	Effect when the setting is increased
Pulse on-time (T_{on})	Duration of each discharge, so the energy per spark	Cutting rate rises; craters, roughness and kerf grow; higher risk of wire breakage
Pulse off-time (T_{off})	Pause between sparks for deionization and flushing	Cutting rate falls but the cut is more stable; too short a pause causes arcing and wire breakage
Peak current (I_p)	Maximum current in each pulse	Cutting rate rises; larger craters and rougher surface; more heat load on the wire
Servo (reference) voltage	Mean gap: the wire advances when gap voltage exceeds it and backs off when below	Wider gap, fewer sparks, slower but more stable cut; a low setting narrows the gap and cuts faster but risks short circuits
Open-circuit voltage	Voltage applied before breakdown	Larger spark gap and kerf, easier flushing; slightly rougher surface

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Trade-off: settings that raise the cutting rate (longer T_{on}, higher I_p, shorter T_{off}, lower servo voltage) also raise surface roughness and the risk of wire breakage.

Non-electrical Process Variables

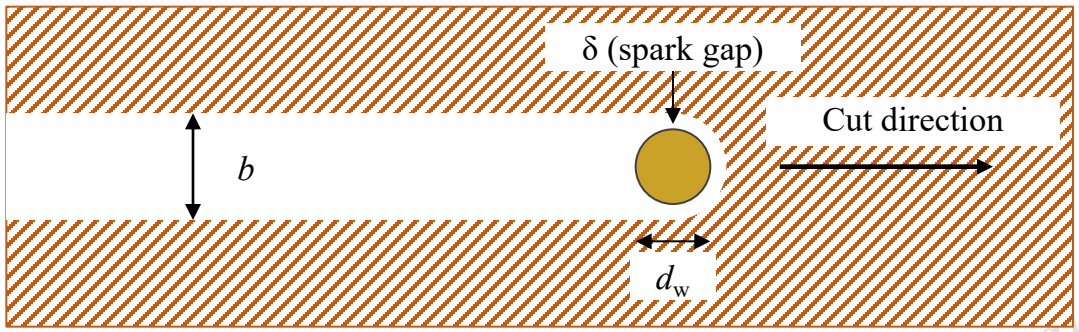
Variable	What it controls	Effect when the setting is increased
Wire feed rate	Speed at which fresh wire passes through the cut	Worn wire is replaced faster, so fewer breakages; wire consumption and cost rise. Too low a feed breaks the wire at high cutting speed
Wire tension	Pull on the wire between the guides	Less vibration and lag, straighter wire, better accuracy at corners; tension above the wire's strength breaks it
Flushing pressure	Pressure of the water jets from the nozzles	Debris removed faster, so a faster and more stable cut; low pressure leaves debris, causing arcing and breakage
Dielectric conductivity	Ion content of the water, held by the deionizing resin	Wider gap, electrolytic attack and stray currents on the work; very low conductivity makes sparks harder to start
Wire diameter	Cross-section of the wire	Thicker wire carries more current, so faster rough cuts; thinner wire gives narrower kerf and smaller corner radius

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Keep the nozzles close to the work: poor flushing is one of the most common causes of wire breakage.

Kerf, Cutting Rate and MRR

Kerf width



Workpiece (top view)

Kerf: $b = d_w + 2\delta$

Smallest inside corner radius: $r_{min} = d_w/2 + \delta = b/2$

The CNC offsets the wire path by $b/2$ so the part comes out to size.

Cutting rate and MRR

Cutting speed v_c (mm/min): feed of the wire along the path.

Cutting rate: $A_c = v_c \times h$ (mm²/min), where h = work thickness. Machines are rated this way.

MRR: $Q = v_c \times h \times b$ (mm³/min)

Time for a path of length *L*: $t = L/v_c$

Prepared By: Dr. S.R. Parimanik
Dr. A.K. Mohanty

Example: $d_w = 0.25$ mm, $\delta = 0.03$ mm, $h = 40$ mm, $v_c = 3$ mm/min, $L = 200$ mm

$b = 0.25 + 2 \times 0.03 = 0.31$ mm

$A_c = 3 \times 40 = 120$ mm²/min

$Q = 120 \times 0.31 = 37.2$ mm³/min

$t = 200 / 3 = 66.7$ min

Process Characteristics

Surface roughness

- Set by crater size, so by the energy per spark (T_{on} and I_p); T_{on} has the largest effect.
- Rough cut: $R_a \approx 2–3$ µm. Low-energy skim (trim) cuts bring it down to $R_a \approx 0.2–0.4$ µm.

Dimensional accuracy

- Typical tolerance ±5 µm (±0.005 mm).
- Limited by wire lag and vibration, gap variation and thermal drift; skim cuts and higher wire tension improve it.

Wire wear and breakage

- Each spark also craters the wire and thins it; the wire breaks when its heat and load exceed its strength.
- Causes: high T_{on} or I_p, short T_{off}, poor flushing, sparks concentrated at one spot. Cures: faster wire feed, adaptive power control.

Surface integrity

- A thin recast (white) layer and heat-affected zone, a few µm deep, remain on the cut face.
- No cutting force acts on the work, so thin, fragile or hardened parts cut without distortion; skim cuts remove most of the recast layer.

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Wire Electrodes and their Selection

What a good wire needs

- **High tensile strength:** to carry tension without breaking, so the wire stays straight.
- **High electrical conductivity:** to carry high peak current with little heating.
- **Good flushability:** a surface that vaporizes easily (low boiling point, e.g. zinc) helps eject debris from the gap.
- **Fracture toughness:** to survive repeated spark craters.
- **Uniform diameter and straightness:** for accuracy and reliable automatic threading.
- **Low cost:** the wire is used once.

Common wire types

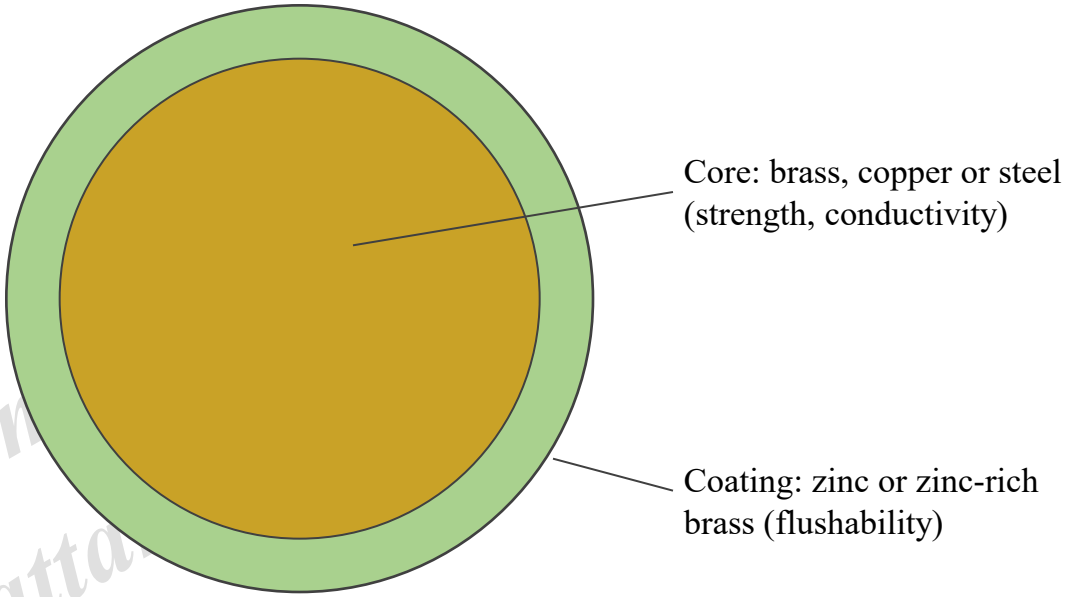
Wire	Typical Ø (mm)	Where it is used
Brass (Cu 63 / Zn 37)	0.10–0.30	Standard general-purpose wire
Zinc-coated brass or copper	0.10–0.30	Faster cutting and better flushing
Steel-core coated	0.10–0.30	Thick work and steep tapers (high strength)
Molybdenum	0.03–0.20	Fine cuts and small radii
Tungsten	0.02–0.05	Micro-machining (highest strength, costly)
Copper	0.10–0.30	Early wire; now rare (low strength)

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Coated (Stratified) Wires

Idea and structure

- A plain wire cannot be both strong and easy to flush. A **stratified wire** joins two materials: a **strong, conductive core** plated with a **low-boiling-point coating**.
- **Core:** brass, copper or steel; carries the current and the tension.
- **Coating:** zinc or a zinc-rich brass (often diffusion-annealed), a few µm thick.



Cross-section of a coated wire (coating exaggerated)

Why the coating helps

- Zinc boils at 907 °C, below copper's melting point (1085 °C), so the coating vaporizes first; the vapour pressure blasts debris out of the gap and cools the core.
- Result: faster cutting, better finish and fewer breakages than plain brass.

Selection rule: plain brass for general work; coated wire for speed and finish; steel-core for thick work and tapers; molybdenum or tungsten for fine detail.

Prepared By: Dr. S. R. Parin Dr. A.K. Patta

Wire EDM vs Die-sinking EDM

Feature	Die-sinking EDM	Wire EDM
Tool	Shaped electrode (copper or graphite)	Continuously moving wire, Ø 0.05–0.30 mm
Tool preparation	A separate electrode must be made for each shape	No shaped tool; the profile comes from the CNC program
Tool wear	Affects accuracy; needs compensation or several electrodes	Negligible: fresh wire is always in the cut
Dielectric	Hydrocarbon oil (e.g. kerosene)	Deionized water
Shapes produced	Blind cavities and 3-D forms	Through-cut 2-D profiles, including tapers
Start of cut	Can sink into a solid surface	Needs an edge or a pre-drilled start hole
Typical use	Mould cavities, forging dies, blind holes	Punches, dies, gears, fine profiles

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Applications and Limitations of Wire EDM

Applications

- **Press tools:** punches, dies and stripper plates, often cut from one blank with a taper for die relief.
- **Extrusion dies** and profile gauges.
- **Hardened parts:** gears, splines and keyways cut after heat treatment.
- **Aerospace and medical parts** in titanium and nickel alloys.
- **Hard materials:** carbide and PCD tool blanks.
- **Prototypes and small batches:** no tooling to make.

Limitations

- **Conducting work only:** glass, ceramics and plastics cannot be cut.
- **Through cuts only:** internal profiles need a start hole.
- **Low MRR** compared with conventional machining.
- **Recast layer** on the cut face may need skim cuts or polishing.
- **Running cost:** wire is used once; water filters and resin must be replaced.
- **High machine cost.**

Prepared By
Dr. S.R. Panimanik
Dr. A.K. Pattanaik

Summary of WEDM Characteristics

Characteristic	Value
Mechanics of material removal	Melting and vaporization by repeated electric sparks
Tool	Moving wire: brass, coated brass, molybdenum; Ø 0.05–0.30 mm
Medium	Deionized water
Spark gap	0.02–0.05 mm
Spark temperature	8,000–12,000 °C
Work material	Any electrically conducting material
Accuracy	About ±5 μm
Surface finish	Ra 2–3 μm (rough cut); 0.2–0.4 μm (skim cuts)
Taper cutting	Up to about 30° with U–V axes
Critical parameters	Pulse on/off time, peak current, servo voltage, wire tension, flushing

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Abrasive Jet Machining (AJM)

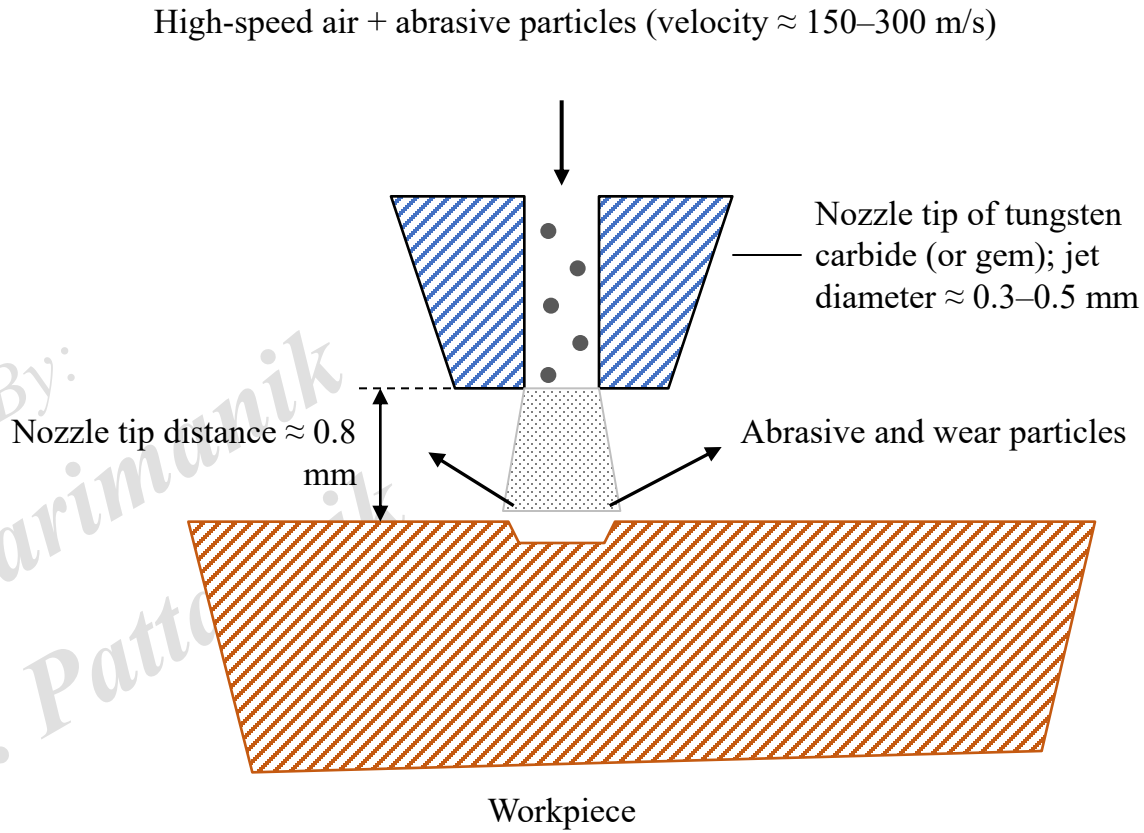
Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Contents

1. Principle of AJM
2. Mechanics of material removal
3. Material removal rate model
4. Process parameters
5. The abrasive
6. MRR vs mixing ratio and abrasive flow
7. The gas
8. The nozzle
9. Nozzle tip distance: size and shape of cut
10. Nozzle tip distance: effect on MRR
11. Abrasive jet machine
12. Summary of AJM characteristics
13. Applications and limitations

Principle of AJM

- **Principle:** fine abrasive grains, carried by a high-speed stream of air (or gas), strike the work surface and remove material.
- **Abrasive:** grains of about 0.025 mm diameter.
- **Jet:** velocity 150–300 m/s; air discharges at a pressure of several atmospheres.
- **Nozzle:** tungsten carbide or sapphire; jet diameter 0.3–0.5 mm.
- **Nozzle tip distance:** about 0.8 mm from the work surface.

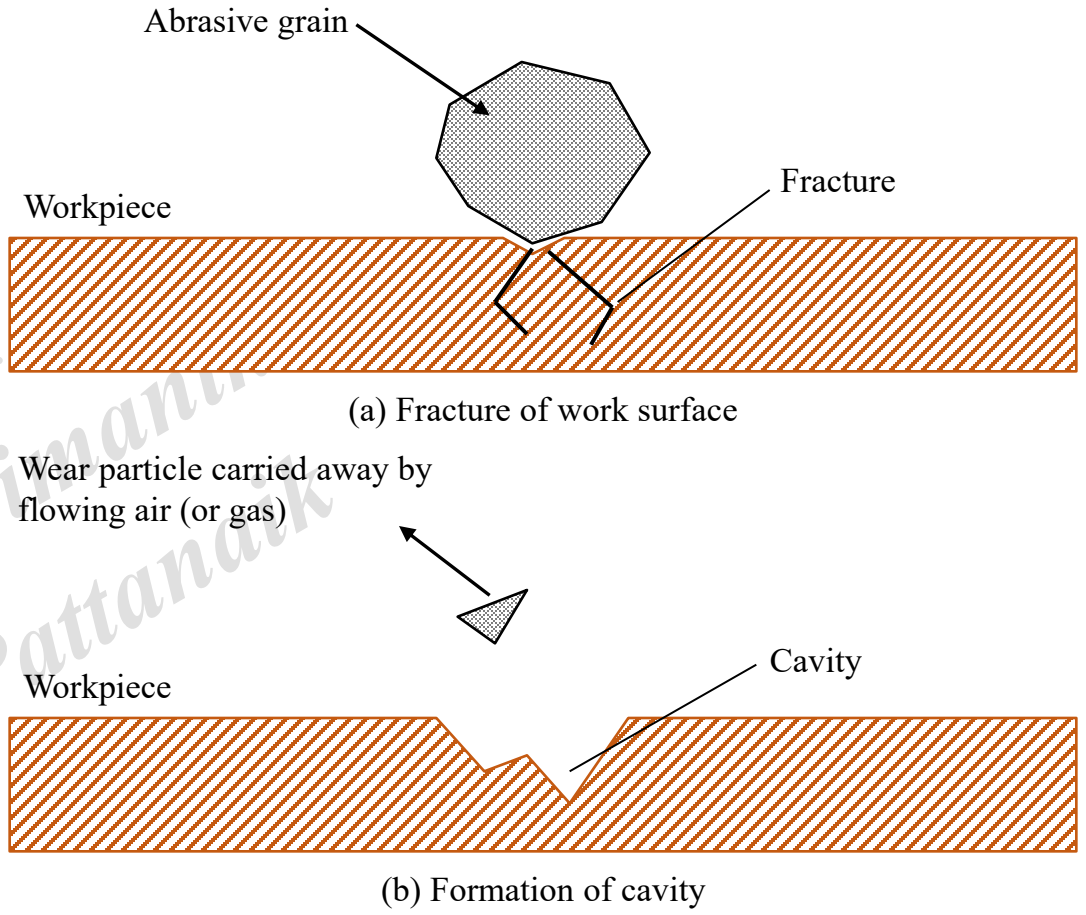


Abrasive jet machining

Prepared By:
Dr. S.K. Parimanik
Dr. A.K. Pattanaik

Mechanics of Material Removal in AJM

- **Impact:** an abrasive grain strikes the work surface at high velocity.
- **Brittle fracture:** the impact causes a tiny fracture that dislodges a small workpiece particle (wear particle).
- **Removal:** the following air (or gas) stream carries the wear particle away, leaving a cavity.
- **Suitability:** AJM works best when the work material is **brittle and fragile**.



Scheme of material removal in AJM

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Material Removal Rate (MRR) Model

$$Q = \chi Z d^3 v^{3/2} \left\{ \rho / (12 H_w) \right\}^{3/4}$$

Where	
Q =	material removal rate
Z =	number of abrasive particles impacting per unit time
d =	mean diameter of the abrasive grains
v =	velocity of the abrasive grains
ρ =	density of the abrasive material
H_w =	hardness of the work material (flow stress)
χ =	a constant

What the model shows

- **Grain size** has the strongest effect: MRR grows with the cube of grain diameter.
- **Grain velocity:** faster grains remove more material.
- **Work hardness:** harder work materials are removed more slowly.
- **Grain density:** denser abrasive grains remove more material.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

Process Parameters

Input parameters

The abrasive
composition, strength, size, mass flow rate

The gas
composition, pressure, velocity

The nozzle
geometry, material, distance from and inclination to the work surface

AJM process

Process characteristics

1. Material removal rate
2. Geometry of the cut
3. Roughness of the surface produced
4. Rate of nozzle wear

Dr. A.K. Panik

The Abrasive

- **Types:** aluminium oxide (Al_2O_3) and silicon carbide (SiC); Al_2O_3 is preferred in most applications.
- **Shape:** not very important, but grains should have sharp edges for good cutting.
- **Size:** powders of 10–50 μm nominal diameter are available.
- **Mass flow rate:** depends on the pressure and flow rate of the gas.

Key values

10–50 μm
grain size available

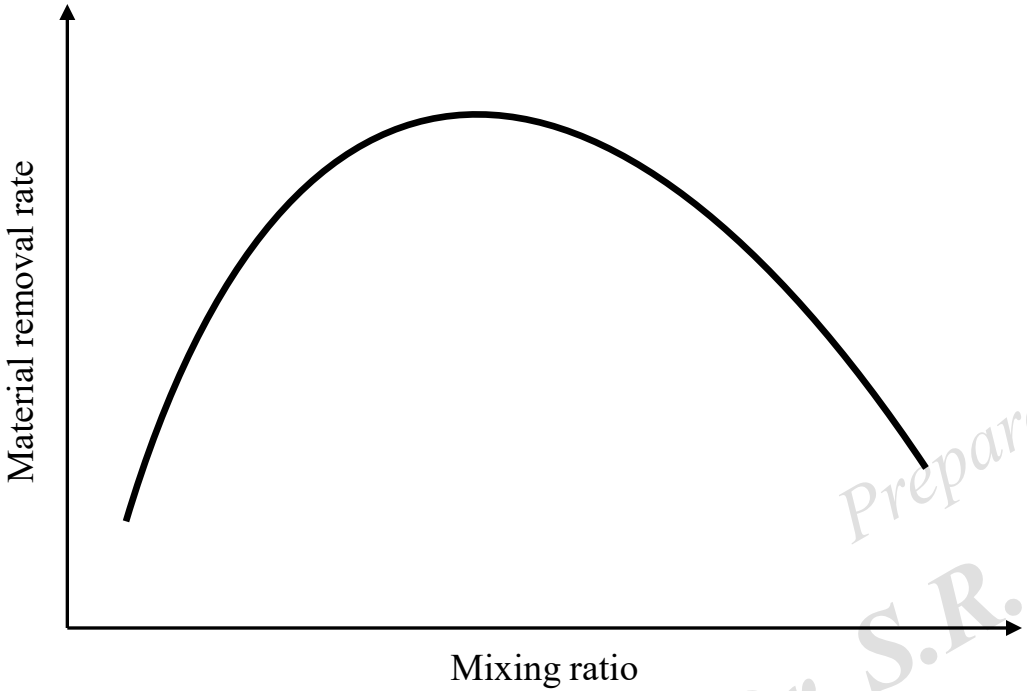
15–20 μm
grain size for best cutting

2–20 g/min
abrasive flow rate

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

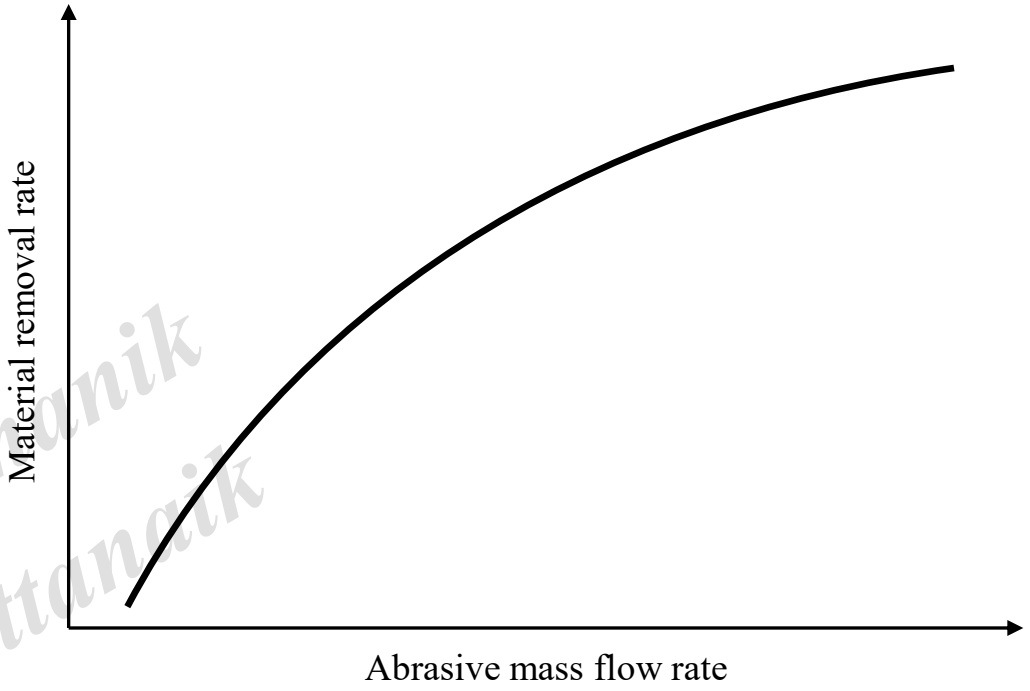
Do not reuse the abrasive: its cutting capacity drops after the first use, and contamination clogs the small nozzle orifices.

MRR vs Mixing Ratio and Abrasive Flow Rate



(a) Variation with mixing ratio

MRR rises with mixing ratio, reaches a maximum, then drops.



(b) Variation with abrasive mass flow rate

MRR keeps rising as the abrasive mass flow rate increases.

Material removal rate characteristics in AJM (qualitative)

Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

The Gas

0.2–1 N/mm²	**150–300 m/s**	**Air, CO_2**
operating pressure (≈ 2–10 atm)	jet velocity	carrier gas

Effect of the gas

- **Pressure:** AJM units normally operate at 0.2–1 N/mm².
- **Composition:** affects MRR indirectly, because the velocity–pressure relation depends on the gas used.
- **Velocity:** a higher jet velocity gives a higher MRR, even when the abrasive mass flow rate is kept constant.
- **Abrasive feed:** the gas pressure and flow rate also set the abrasive mass flow rate.

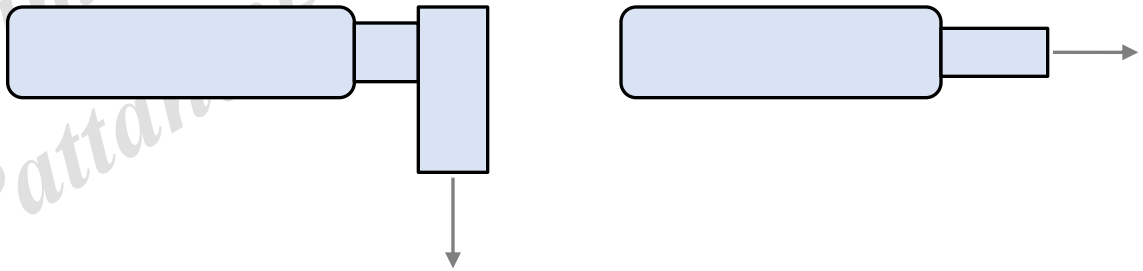
Prepared By: Dr. S.R. Parimanik Dr. A.K. Pattanaik

The Nozzle

- **Role:** one of the most vital elements; it is in continuous contact with high-speed grains, so it must be very hard.
- **Material:** tungsten carbide (WC) or sapphire.
- **Orifice area:** 0.05–0.2 mm^2, circular or rectangular.
- **Life:** hard to predict; WC lasts 12–30 hr, sapphire about 300 hr.
- **Set-up:** distance from and inclination to the work surface also control the process.

Nozzle material	Average life
Tungsten carbide (WC)	12–30 hr
Sapphire	≈ 300 hr

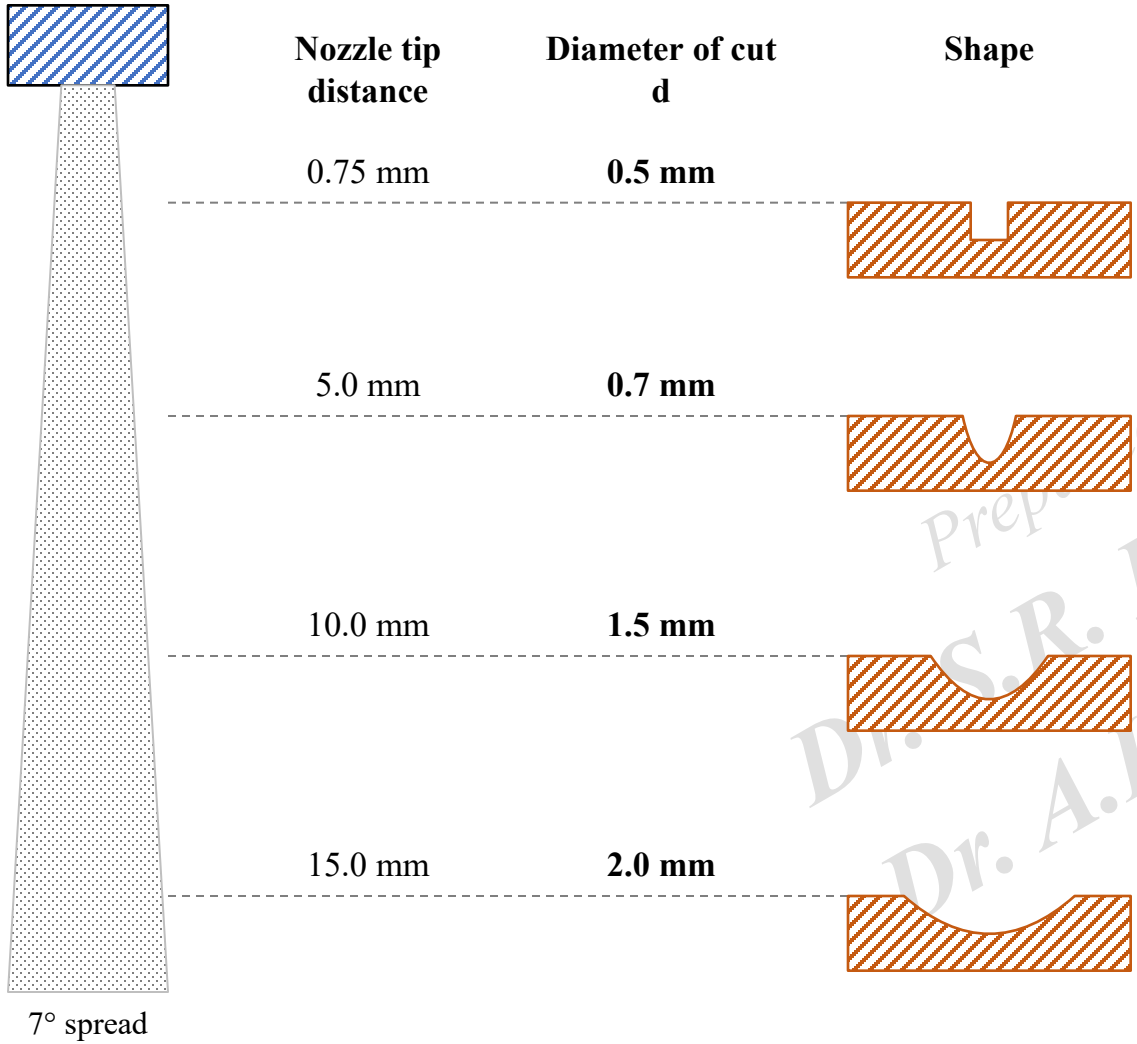
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Dr. S.R. Parimanik
Dr. A.K. Pattanaik



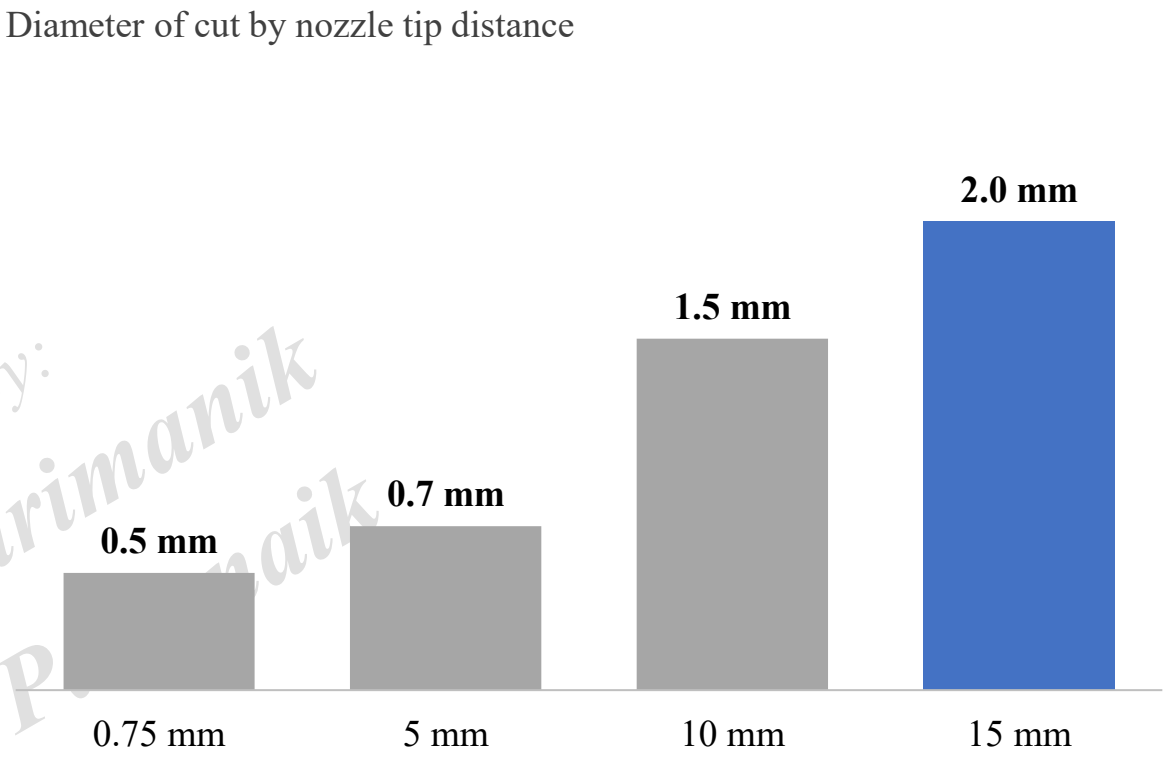
(a) Right angle head (b) Straight head

Types of nozzle heads (arrows show jet direction)

Nozzle Tip Distance (NTD): Size and Shape of Cut



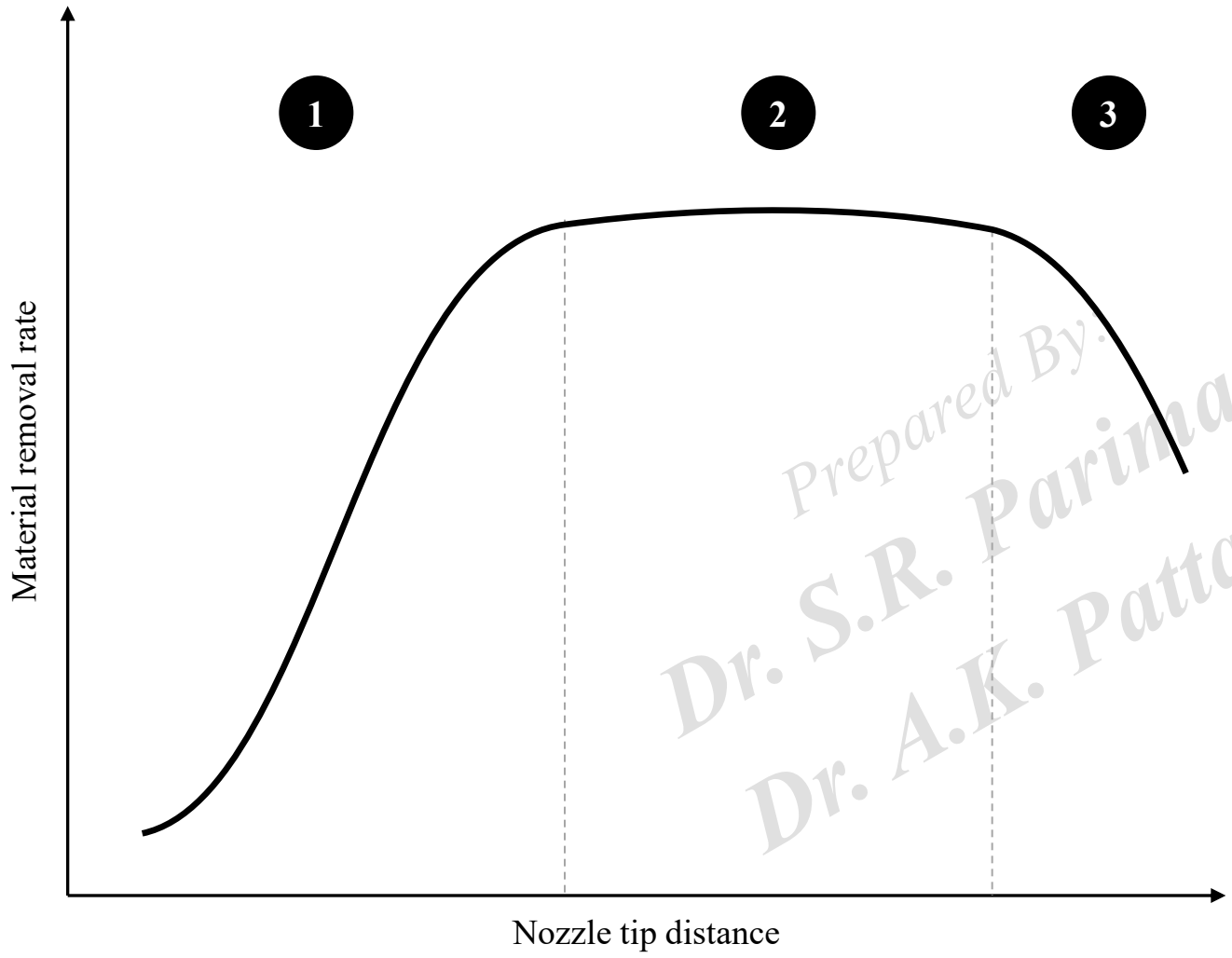
Effect of NTD on shape and size of cut (not to scale)



- Cut diameter grows **4 times** (0.5 to 2.0 mm) as NTD rises from 0.75 to 15 mm.
- The cavity changes from a **flat-bottom hole** to a **wide, shallow, rounded** crater.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Parimanik

Nozzle Tip Distance (NTD): Effect on MRR



Effect of nozzle tip distance on MRR (qualitative)

1. **MRR rises:** particles keep accelerating after leaving the nozzle, so impact velocity grows with NTD.

2. **MRR levels off:** atmospheric drag starts to check the velocity gain.

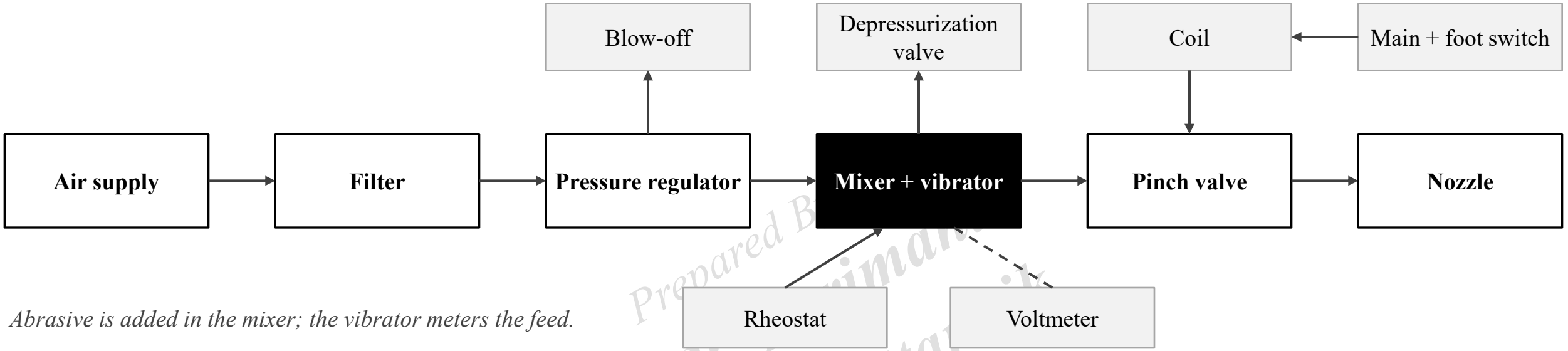
3. **MRR falls:** at larger NTD, drag reduces particle velocity and MRR drops.

Practical NTD: 0.25–75 mm; typically ≈ 0.8 mm.

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

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Abrasive Jet Machine



Abrasive is added in the mixer; the vibrator meters the feed.

Schematic of abrasive jet machining equipment (simplified)

- **Supplier:** made and marketed by a single manufacturer, S.S. White Co., New York, under the name "Airbrasive".
- **Air path:** supply air is filtered and pressure-regulated before it picks up abrasive in the mixing chamber.
- **Abrasive feed:** the vibrator on the mixer meters abrasive into the stream; the rheostat sets the vibration.
- **Jet on/off:** the pinch valve, worked by a coil from the main and foot switches, starts and stops the jet.

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Summary of AJM Characteristics

Characteristic	Value
Mechanics of material removal	Brittle fracture by impinging abrasive grains at high speed
Media	Air, CO_2
Abrasives	Al_2O_3, SiC; 0.025 mm diameter; 2–20 g/min; nonrecirculating
Velocity	150–300 m/s
Pressure	2–10 atm
Nozzle	WC or sapphire; orifice area 0.05–0.2 mm^2; life 12–300 hr
Nozzle tip distance	0.25–75 mm
Critical parameters	Abrasive flow rate and velocity, nozzle tip distance, abrasive grain size, jet inclination

Prepared By :
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

AJM: Applications and Limitations

Applications

- **Materials:** hard and brittle metals, alloys and nonmetallic materials (germanium, silicon, glass, ceramics, mica).
- **Thin sections:** AJM is specially suited to them.
- **Jobs:** drilling, cutting, deburring, etching and cleaning.

Limitations

- **Low MRR:** about 40 mg/min (15 mm^3/min).
- **Embedding:** abrasive grains embed in the workpiece.
- **Tapering:** drilled holes come out tapered.
- **Stray cutting:** the abrasive can strike areas that should not be cut.

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Laser Beam Machining (LBM)

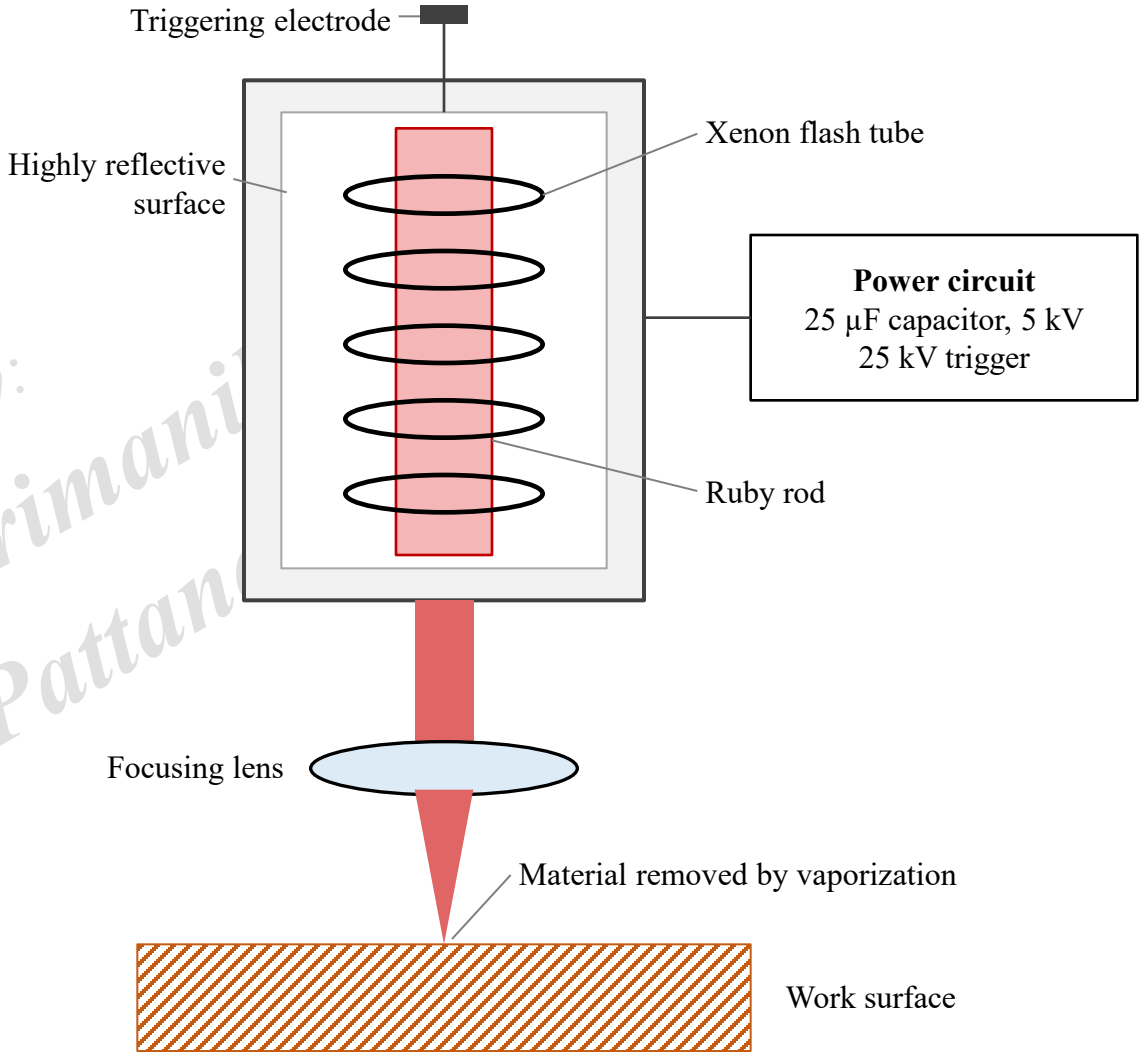
Contents

1. Principle of LBM
2. Working of a pulsed ruby laser
3. Mechanics of LBM: interaction with work
4. Temperature rise: one-dimensional model
5. Circular spot model and critical intensity
6. Hole penetration: melting and vaporization
7. Summary of LBM characteristics

Prepared By:
Dr. S.R. Panimanik
Dr. A.K. Pattanaik

Principle of LBM

- **Laser:** a highly coherent beam (in space and time) of electromagnetic radiation that, like an electron beam, gives a very high power density.
- **Wavelength:** 0.1–70 μm; the power requirement restricts the usable range to 0.4–0.6 μm.
- **Focusing:** the rays are parallel and monochromatic, so they focus to a very small spot with power density up to 10^7 W/mm^2.
- **Sources:** a pulsed ruby laser for high power; the continuous CO_2–N_2 laser is also used.
- **Removal:** the focused beam melts and vaporizes a small portion of the work; the molten metal is thrown out by high-speed ablation.



Schematic diagram of laser beam machining

Prepared By: Dr. S. R. Parimani Dr. A.K. Pattanaik

Working of a Pulsed Ruby Laser

Operation

1. A coiled **xenon flash tube** surrounds the ruby rod; the container walls are highly reflecting, so most of the light falls on the rod for pumping.
2. The **capacitor** is charged, and a very high voltage on the triggering electrode starts the flash.
3. The emitted laser beam is **focused by a lens** onto the work surface.
4. Material is removed by **vaporization and high-speed ablation**: a small fraction of the molten metal vaporizes so fast that the impulse throws out much of the liquid metal.
5. The flash tube releases far more energy than the laser beam carries, so the laser head must be **cooled**.

Typical values

0.3–0.5%	efficiency of the LBM process
20 J, 1 ms	typical output energy and pulse duration
20,000 W	peak power
2×10^{-3} rad	beam divergence
≈ 50 μm	spot diameter (lens focal length 25 mm)
≤ 250 μm	hole diameter drilled easily
± 0.025 mm	dimensional accuracy
0.05 mm/mm	taper when work is over 0.25 mm thick

Prepared By: Dr. S.R. Parimanik, Dr. A.K. Pattanaik

Mechanics of LBM: Interaction with the Work

(i) Interaction of the beam with the work → **(ii) Heat conduction and temperature rise** → **(iii) Melting, vaporization and ablation**

Interaction of laser beam with work

- Machining depends on the **thermo-optic interaction** between the beam and the work, so the work should not reflect much of the beam.
- Absorbed light energy passes to the lattice atoms as heat. Absorption follows **Lambert's law**:

$$I(z) = I(0)\, e^{-\mu z}$$

- $I(z)$ = intensity at depth z; μ = absorption coefficient.
- Most energy is absorbed in a very thin surface layer (≈ 0.01 μm), so the beam is treated as a **heat flux at the surface**.

Heat conduction and temperature rise

- Reradiation at 3000 K is only ≈ 600 W/cm^2, negligible against the input flux of 10^5–10^7 W/cm^2.
- Spot diameter ≫ depth of penetration, so the problem is **one-dimensional**; k and specific heat stay constant.
- Model: semi-infinite body with uniform surface flux $H(t)$. For $z > 0$:

$$\partial^2\theta/\partial z^2 - (1/\alpha)\,\partial\theta/\partial t = 0$$

- At the surface ($z = 0$): $\partial\theta/\partial z = -H(t)/k$, with $\theta = 0$ at $t = 0$.
- α = thermal diffusivity, k = thermal conductivity, θ = temperature rise.

Prepared By: Dr. S.R. Parimanik, Dr. A.K. Pattanaik

Temperature Rise: One-Dimensional Model

Solution for a constant heat flux

If the flux H stays constant (a step pulse), the heat equation gives:

$$\theta(z,t) = (2H/k)\,[\sqrt{(\alpha t/\pi)}\exp(-z^2/4\alpha t) - (z/2)\,\mathrm{erfc}(z/2\sqrt{(\alpha t)})\,]$$

Surface temperature ($z = 0$):

$$\theta(0,t) = (2H/k)\,(\alpha t/\pi)^{1/2}$$

Time to reach the melting point θ_m:

$$t_m = (\pi/\alpha)\,(\theta_m k / 2H)^2$$

- Higher beam intensity H cuts t_m as $1/H^2$.

Example: tungsten surface reaching melting point

Given: beam 10^5 W/mm^2 on tungsten; 10% absorbed; θ_m = 3400 °C; k = 2.15 W/cm-°C; volume specific heat = $2.71\ \mathrm{J/cm^3 - °C}$.

1. Thermal diffusivity

$\alpha = k$ / (volume specific heat) = $2.15/2.71 = 0.79\ \mathrm{cm^2/s}$

2. Absorbed heat flux

$H = 0.1 \times 10^5 \times 100\ \mathrm{W/cm^2} = 10^6\ \mathrm{W/cm^2}$

3. Time to melt

$t_m = (\pi/0.79)\,[3400 \times 2.15 / (2 \times 10^6)]^2$

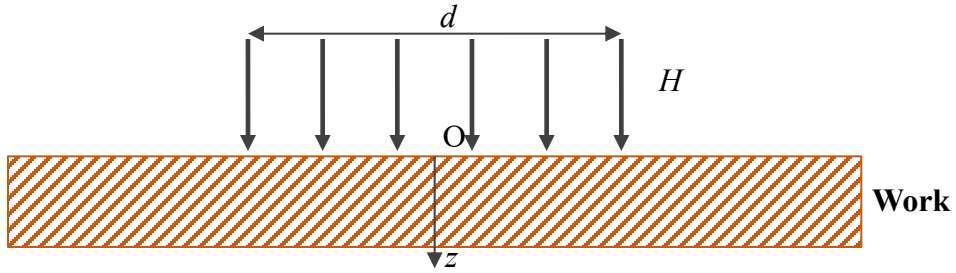
$= 3.98 \times (3.655 \times 10^{-3})^2$

Answer: $\boldsymbol{t_m \approx 0.000053\ \mathrm{s}}$ **(53 μs)**

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Circular Spot Model and Critical Beam Intensity

Uniform flux on a spot of diameter d



Temperature along the z-axis:

$$\theta(z,t) = (2H\sqrt{(\alpha t)}/k)\,[\text{ierfc}(z/2\sqrt{(\alpha t)}) - \text{ierfc}(\sqrt{(z^2 + d^2/4)}\,/\,2\sqrt{(\alpha t)})]$$

At the centre O of the spot:

$$\theta(0,t) = (2H\sqrt{(\alpha t)}/k)\,[1/\sqrt{\pi} - \text{ierfc}(d/4\sqrt{(\alpha t)})]$$

For a large time, erf → 0 gives the **critical intensity**:

$$H_{cr} \approx 2k\theta_m\,/\,d$$

- Below H_{cr}, the melting temperature is **never reached**; the 1-D model cannot show this.

Examples: tungsten, d = 200 µm, 10% absorbed

(a) Time for the spot centre to melt (beam 10^5 W/mm^2)

1. Substitute in the centre equation ($d = 0.02$ cm):

$$3400 = (2 \times 10^6 \times \sqrt{(0.79t_m)}\,/\,2.15)\,[1/\sqrt{\pi} - \text{ierfc}(0.02\,/\,4\sqrt{(0.79t_m)})]$$

2. Put $\beta = \sqrt{(0.79t_m)}$; solve numerically with erf tables: $\beta \approx 0.01$
3. $t_m = \beta^2/0.79 \approx$ **0.00013 s**, about 2.5 times the 1-D estimate (0.000053 s).

(b) Minimum beam intensity to melt

1. $H_{cr} = 2 \times 2.15 \times 3400\,/\,0.02 = 7.31 \times 10^5$ W/cm^2 (absorbed)
2. Only 10% is absorbed, so the beam needs 10 times this:

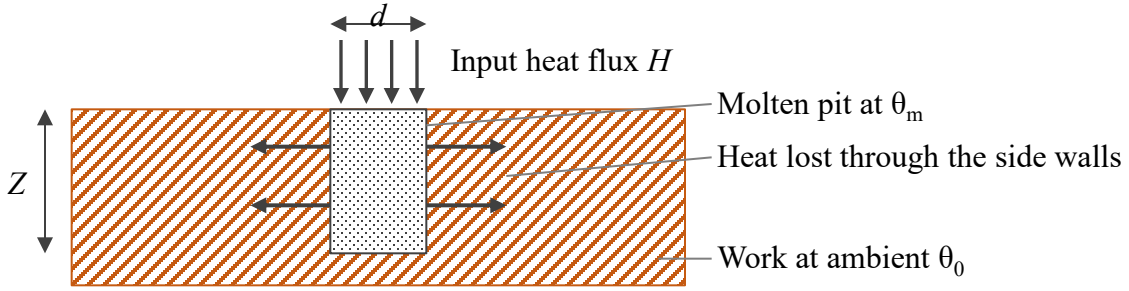
Answer: $H_{cr} \approx 7.31 \times 10^6$ W/cm^2

Lesson: the 1-D relation underestimates t_m; it holds only when H is very high, as the ierfc term then becomes small against $1/\sqrt{\pi}$.

Prepared by Dr. S.R. Paul, Dr. A.K.

Hole Penetration: Melting and Vaporization

Medium intensity: steady-state molten pit



Deep, narrow pit: heat leaves mainly through the **side walls**. Heat loss rate:

$$2\pi Zk\,(\theta_m - \theta_0) / \ln(D/d)$$

Experience: $D \approx 55d$, so $\ln(D/d) \approx 4$. Heat input = heat loss:

$$H \cdot \pi d^2/4 \;\approx\; \pi Zk(\theta_m - \theta_0) / 2$$

Depth of the molten pit (≈ hole depth):

$$Z \;\approx\; Hd^2 / [2k(\theta_m - \theta_0)]$$

High intensity (> 10^7 W/cm²): vaporization

Heating is so rapid that the surface **vaporizes and recedes** with velocity v. Heat input rate = heat to vaporize:

$$H \;\approx\; vL$$

L = energy to vaporize a unit volume of the material.

Example: drilling time in tungsten

Given: 10^5 W/mm² beam; 200 μm hole in 0.5 mm tungsten; $L = 3 \times 10^4$ J/cm³; efficiency 10%.

1. Effective flux: $H = 0.1 \times 10^5 \times 100 = 10^6$ W/cm²
2. Recession velocity: $v = H/L = 10^6 / (3 \times 10^4) = 33.3$ cm/s $= 333$ mm/s
3. Time: t = thickness / v = 0.5 / 333 s

Answer: $\boldsymbol{t \;\approx\; 0.0015}$ **s (1.5 ms)**

Prepared By: Dr. S.R. P... Dr. A.K. ...nik

Summary of LBM Characteristics

Characteristic	Value
Mechanics of material removal	Melting, vaporization
Medium	Normal atmosphere
Tool	High power laser beam
Maximum material removal rate	5 mm^3/min
Specific power consumption (typical)	1000 W/mm^3/min
Critical parameters	Beam power intensity, beam diameter, melting temperature
Materials application	All materials
Shape application	Drilling fine holes
Limitations	Very large power consumption; cannot cut materials with high heat conductivity and high reflectivity

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Plasma Arc Machining (PAM)

Contents

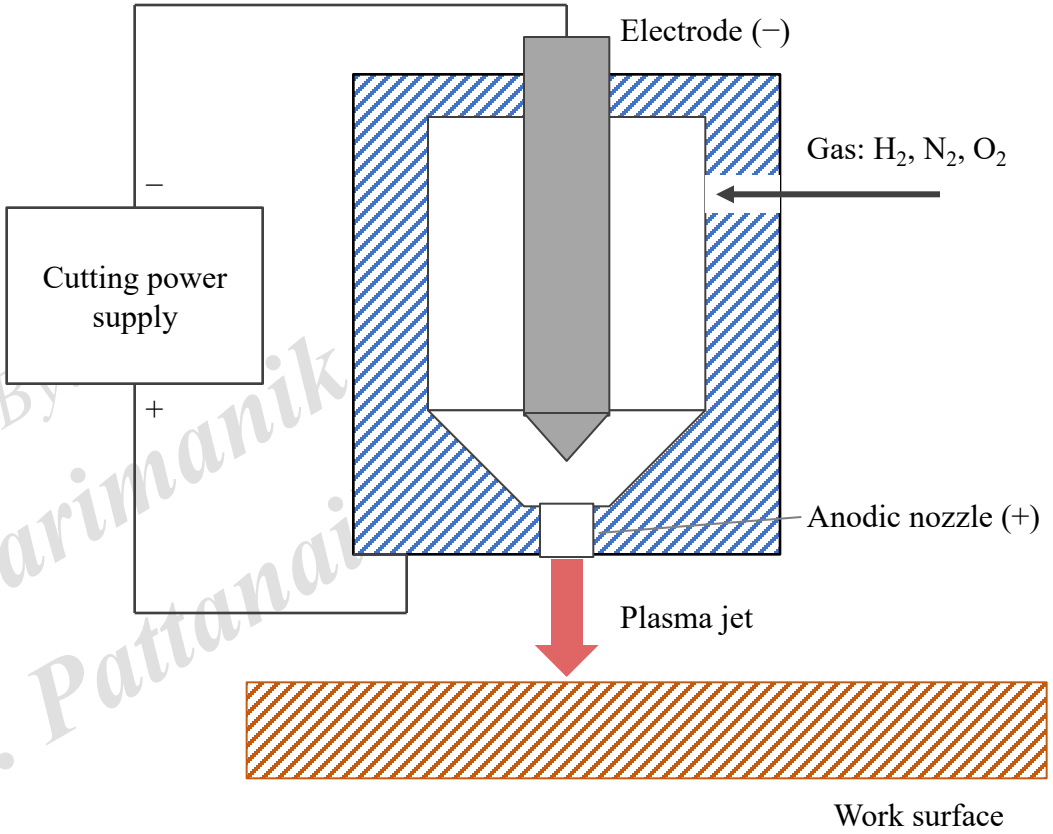
1. Principle of PAM
2. Plasma generation and material removal
3. Summary of PAM characteristics

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

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Principle of PAM

- **Plasma:** a high-temperature ionized gas. PAM cuts with a high-speed jet of this plasma.
- **Action:** the jet heats the work where it strikes, causing quick melting; the jet then blasts the molten metal away.
- **Set-up:** an arc is struck between the **electrode (−)** and the **anodic nozzle (+)**; the gas (H_2, N_2, O_2) is forced to flow through the arc.
- **Materials:** all electrically conducting materials, including those that resist oxy-fuel gas cutting.
- **Use:** profile cutting of stainless steel, monel and superalloy plates.



Schematic diagram of plasma arc machining

Prepared by Dr. S.R. Parimanik Dr. A.K. Pattanai

Plasma Generation and Material Removal

How the plasma is generated

1 Collision
High-velocity electrons of the arc collide with the gas molecules.

→

2 Ionization
Diatomic molecules or atoms split into ions and electrons; gas conductivity rises sharply (plasma state).

→

3 More heating
Free electrons accelerate and cause more ionization and heating.

→

4 Recombination
Ions and electrons recombine into atoms, and atoms into molecules; these exothermic reactions raise the temperature further.

→

5 Plasma jet
The high-temperature plasma is forced through the nozzle as a jet.

Mechanism of material removal

- **(i) Heating and melting:** the jet heats the work where it strikes and melts it quickly.
- **(ii) Blasting:** the high-velocity jet blows the molten metal out of the cut.

Jet conditions

16,000 °C	maximum temperature
500 m/s	maximum jet velocity

Dr. S. R. [illegible]
Dr. A.K. Sattar

Summary of PAM Characteristics

Characteristic	Value	Characteristic	Value
Mechanics of material removal	Melting	**Maximum plate thickness**	Up to 200 mm (depends on material)
Medium	Plasma	**Cutting speed**	0.1–7.5 m/min
Tool	Plasma jet	**Voltage**	30–250 V
Maximum temperature	16,000 °C	**Current**	Up to 600 A
Maximum velocity of jet	500 m/s	**Critical parameters**	Voltage, current, electrode gap, gas flow rate, nozzle dimensions, melting temperature
Maximum MRR	150 cm^3/min	**Materials application**	All conducting materials
Specific energy	1000 W/cm^3-min	**Shape application**	Cutting plates
Power range	2–200 kW	**Limitation**	Low accuracy

Prepared By:
Dr. S.R. Parimanik
Dr. A.K. Pattanaik

Solved Questions (Q&A)

Prepared By:
Dr. S.R. Panimanik
Dr. A.K. Pattanaik

Contents

QNS 1. ECM: removal rate of a Nimonic alloy
QNS 2. ECM: removal rate from the equilibrium gap
QNS 3. EDM: time to drill a square hole
QNS 4. EDM: optimum discharge voltage and finish
QNS 5. USM: effect of changed process settings
QNS 6. AJM: effect of grain size and velocity
QNS 7. LBM: time to reach the melting point
QNS 8. PAM: removal rate and cutting speed

QNS 1 (ECM)

Question: A Nimonic alloy turbine blade is 18% cobalt, 62% nickel and 20% chromium. It is machined electrochemically with a current of 1500 A. Find the volume removal rate. Dissolution valency: chromium 6; nickel and cobalt 2.

Solution (step by step)

Step 1. Data for each element

Co: $A = 58.93, Z = 2, \rho = 8.85\ \text{g/cm}^3$
Ni: $A = 58.71, Z = 2, \rho = 8.90\ \text{g/cm}^3$
Cr: $A = 52.00, Z = 6, \rho = 7.19\ \text{g/cm}^3$

Step 2. Charge to dissolve 1 g of alloy

Each element of mass fraction x needs xZF/A coulombs, so find $\Sigma\, xZ/A$:

$0.18\times2/58.93 + 0.62\times2/58.71 + 0.20\times6/52.00$
$= 0.00611 + 0.02112 + 0.02308 = 0.05031\ \text{g}^{-1}$

Step 3. Mass removal rate

$\dot{m} = I / (F\, \Sigma\, xZ/A) = 1500 / (96{,}500 \times 0.05031)$
$\dot{m} = 0.309\ \text{g/s}$

Step 4. Density of the alloy

$1/\rho = \Sigma\, x_i/\rho_i = 0.18/8.85 + 0.62/8.90 + 0.20/7.19$
$= 0.02034 + 0.06966 + 0.02782 = 0.11782\ \text{cm}^3/\text{g}$
$\rho = 1/0.11782 = 8.49\ \text{g/cm}^3$

Step 5. Volume removal rate

$Q = \dot{m} / \rho = 0.309 / 8.49 = 0.0364\ \text{cm}^3/\text{s}$
$Q = 0.0364 \times 60 = 2.18\ \text{cm}^3/\text{min}$

Check

Chromium is only 20% of the mass but takes 46% of the charge, because its valency is 6.

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Answer: volume removal rate $Q \approx 0.0364\ \text{cm}^3/\text{s} \approx \mathbf{2.18\ cm^3/min}$

QNS 2 (ECM)

Question: The equilibrium gap when machining iron electrochemically in NaCl solution is 0.2 mm at an operating voltage of 12 V. Iron dissolves at valency 2, its density is 7.8 g/cm^3, and the specific resistance of the electrolyte is 2.8 Ω-cm. Taking the overvoltage as 1.5 V, find the metal removal rate per unit work surface area.

Solution (step by step)

Step 1. Data

$V = 12\ \text{V}, \quad \Delta V = 1.5\ \text{V}, \quad y_e = 0.2\ \text{mm} = 0.02\ \text{cm}$

Iron: $A = 55.85,\ Z = 2,\ \rho = 7.8\ \text{g/cm}^3;\ F = 96{,}500\ \text{C}$

Conductivity $\kappa = 1/2.8 = 0.357\ \Omega^{-1}\text{cm}^{-1}$

Step 2. Idea

At equilibrium the gap stays constant, so the work surface recedes at the feed rate f. Volume removed per unit area per second $= f$.

Step 3. Current density in the gap

$J = \kappa(V - \Delta V) / y_e = 0.357 \times 10.5 / 0.02$

$J = 187.5\ \text{A/cm}^2$

Step 4. Equilibrium-gap relation

$y_e = \kappa A(V - \Delta V) / (\rho Z F\, f)$

$\Rightarrow\ f = \kappa A(V - \Delta V) / (\rho Z F\, y_e) = JA / (\rho Z F)$

Step 5. Substitute

$f = 187.5 \times 55.85 / (7.8 \times 2 \times 96{,}500)$

$f = 10{,}472 / 1{,}505{,}400 = 0.00696\ \text{cm/s}$

Step 6. Convert units

$0.00696\ \text{cm}^3/\text{s per cm}^2 \times 60 = 0.417\ \text{cm}^3/\text{min per cm}^2$

(the surface recedes at about 4.2 mm/min)

Answer: removal rate per unit area $\approx$ $0.00696\ \text{cm}^3/\text{s per cm}^2$ $\approx$ $\mathbf{0.42\ cm^3/min\ per\ cm^2}$

Prepared By Dr. S.R. Panimahi Dr. A.K. Pattanaik

QNS 3 (EDM)

Question: A 5 mm × 5 mm square through hole is spark machined in a 5 mm thick low carbon steel plate with a brass tool and kerosene dielectric. The relaxation circuit has R = 100 Ω and C = 15 μF; the supply is 220 V dc and the gap is set so that discharge takes place at 120 V. Estimate the time to complete the job.

Solution (step by step)

Step 1. Data

$V_0 = 220\ \text{V}, \quad V_\text{d} = 120\ \text{V}, \quad R = 100\ \Omega,$
$C = 15 \times 10^{-6}\ \text{F}$

Work is steel, so use $Q \approx 27.4\, W^{1.54}$ (Q in mm^3/min, W in kW)

Step 2. Energy per spark

$E = \tfrac{1}{2}\, C V_\text{d}^2 = \tfrac{1}{2} \times 15 \times 10^{-6} \times 120^2$
$E = 0.108\ \text{J}$

Step 3. Charging (cycle) time

$t_\text{c} = RC \ln[V_0 / (V_0 - V_\text{d})] = 100 \times 15 \times 10^{-6} \times \ln(220/100)$
$t_\text{c} = 1.5 \times 10^{-3} \times 0.788 = 1.18 \times 10^{-3}\ \text{s}$ (≈ 846 sparks/s)

Step 4. Average power

$W = E / t_\text{c} = 0.108 / (1.18 \times 10^{-3}) = 91.3\ \text{W} = 0.0913\ \text{kW}$

Step 5. Material removal rate

$Q = 27.4 \times (0.0913)^{1.54} = 27.4 \times 0.0251$
$Q = 0.687\ \text{mm}^3/\text{min}$

Step 6. Volume to remove

$V = 5 \times 5 \times 5 = 125\ \text{mm}^3$

Step 7. Machining time

$t = 125 / 0.687 = 182\ \text{min}$

Answer: time to complete the job ≈ **182 min (about 3 hours)**

Prepared By Dr. S.R. Paramanik Dr. A.K. Paramanik

QNS 4 (EDM)

Question: A steel workpiece is machined by EDM with an RC relaxation circuit: supply 200 V dc, $R = 40\ \Omega$, $C = 20\ \mu F$. Find (a) the discharge voltage for maximum power, (b) the sparking frequency, (c) the energy per spark, (d) the average power, (e) the MRR and (f) the expected surface roughness H_{rms}.

Solution (step by step)

Step 1. Optimum discharge voltage (a)

Maximum power at $\zeta_{opt} = 1.26$, so $V_d/V_0 = 1 - e^{-1.26} = 0.72$

$V_d = 0.72 \times 200 = 144\ V$

Step 2. Sparking frequency (b)

$t_c = RC \ln[V_0 / (V_0 - V_d)] = 40 \times 20 \times 10^{-6} \times \ln(200/56)$

$t_c = 8 \times 10^{-4} \times 1.273 = 1.02 \times 10^{-3}\ s$

$\nu = 1/t_c \approx 982\ Hz$

Step 3. Energy per spark (c)

$E = \frac{1}{2} C V_d^2 = \frac{1}{2} \times 20 \times 10^{-6} \times 144^2 = 0.207\ J$

Step 4. Average power (d)

$W = E / t_c = 0.207 / (1.02 \times 10^{-3}) = 204\ W = 0.204\ kW$

Check: $W = (V_0^2/2R)(1 - e^{-\zeta})^2/\zeta = 500 \times 0.518/1.273 \approx 204\ W$

Step 5. Material removal rate (e)

$Q = 27.4\, W^{1.54} = 27.4 \times (0.204)^{1.54}$

$Q = 2.36\ mm^3/min$

Step 6. Surface roughness (f)

$H_{rms} \approx 1.11\, Q^{0.384} = 1.11 \times (2.36)^{0.384}$

$H_{rms} \approx 1.54\ \mu m$

Answer: $V_d = 144\ V$; $\nu \approx 982\ Hz$; $E = 0.207\ J$; $W \approx 0.20\ kW$; $Q \approx \mathbf{2.36\ mm^3/min}$; $H_{rms} \approx \mathbf{1.54\ \mu m}$

Prepared By Dr. S.R. Parmanik Dr. A.K. Pattanaik

QNS 5 (USM)

Question: An ultrasonic machining set-up removes a 100 mm^3 cavity in 10 min with a tool amplitude of 20 µm at 20 kHz. The amplitude is raised to 30 µm, the frequency to 25 kHz, and a finer abrasive of half the grain size is used; all else is unchanged. Using Shaw's MRR relation, estimate the new machining time.

Solution (step by step)

Step 1. Shaw's MRR relation

$Q \propto d\, F^{3/4}\, A^{3/4}\, C^{1/4}\, \nu / [H_w^{3/4}\, (1 + \lambda)^{3/4}]$

F, C, H_w and λ are unchanged, so $Q \propto d\, A^{3/4}\, \nu$

Step 2. Present MRR

$Q_1 = 100 / 10 = 10\ mm^3/min$

Step 3. Ratio of new to old MRR

$Q_2 / Q_1 = (d_2/d_1)\, (A_2/A_1)^{3/4}\, (\nu_2/\nu_1)$

Step 4. Each factor

Grain size: $d_2/d_1 = 0.5$

Amplitude: $(30/20)^{3/4} = 1.5^{0.75} = 1.355$

Frequency: $25/20 = 1.25$

Step 5. New MRR

$Q_2 / Q_1 = 0.5 \times 1.355 \times 1.25 = 0.847$

$Q_2 = 0.847 \times 10 = 8.47\ mm^3/min$

Step 6. New machining time

$t_2 = 100 / 8.47 = 11.8$ min

Comment

Higher amplitude and frequency do not offset the finer grit, but the finer grit gives a better surface finish.

Answer: new MRR ≈ 8.47 mm^3/min, so the time rises from 10 min to ≈ **11.8 min**

Prepared By Dr. S.R. Parimanik Dr. A.K. Patranik

QNS 6 (AJM)

Question: An AJM job cuts glass at 15 mm^3/min using 15 µm abrasive grains at a jet velocity of 200 m/s. The grain size is changed to 20 µm and the velocity to 250 m/s. Estimate the new MRR (a) if the number of grains striking per unit time stays the same, and (b) if the abrasive mass flow rate stays the same.

Solution (step by step)

Step 1. MRR model

$Q \propto Z\, d^3\, v^{3/2}$ (abrasive density and work hardness unchanged)

Z = grains striking per unit time, d = grain diameter, v = grain velocity

Step 2. Each factor

Grain size: $(20/15)^3 = 2.370$

Velocity: $(250/200)^{3/2} = 1.25^{1.5} = 1.398$

Step 3. Case (a): *Z* constant

$Q_2/Q_1 = 2.370 \times 1.398 = 3.31$

$Q_2 = 3.31 \times 15 = 49.7\ mm^3/min$

Step 4. Case (b): mass flow constant

Mass flow $= Z \times (\pi d^3/6) \times \rho$, so $Z \propto 1/d^3$

$Z\, d^3$ stays constant and the grain-size effect cancels: $Q \propto v^{3/2}$

Step 5. Case (b) result

$Q_2/Q_1 = 1.398$

$Q_2 = 1.398 \times 15 = 21.0\ mm^3/min$

Comment

MRR rises with grain size only when more abrasive mass is supplied; at a fixed mass flow, velocity is what raises MRR.

Prepared By
Dr. S.R. Panigrahi
Dr. A.K. Pattanaik

Answer: (a) $Q \approx$ **49.7 mm^3/min** (3.3 times); (b) $Q \approx$ **21.0 mm^3/min** (1.4 times)

QNS 7 (LBM)

Question: A laser beam with a power intensity of 2×10^5 W/mm^2 falls on a stainless steel sheet. Find the time for the surface to reach the melting temperature if only 8% of the beam power is absorbed. Take $\alpha = 0.071$ cm^2/s, $k = 0.27$ W/cm-°C and $\theta_m = 1455$ °C.

Solution (step by step)

Step 1. Absorbed heat flux

Beam: $2 \times 10^5\ \text{W/mm}^2 \times 100 = 2 \times 10^7\ \text{W/cm}^2$

Absorbed: $H = 0.08 \times 2 \times 10^7 = 1.6 \times 10^6\ \text{W/cm}^2$

Step 2. Model

One-dimensional heating of a semi-infinite body by a uniform surface flux. Surface temperature: $\theta(0,t) = (2H/k)(\alpha t/\pi)^{1/2}$

Setting $\theta = \theta_m$: $t_m = (\pi/\alpha)(\theta_m k / 2H)^2$

Step 3. Bracket term

$\theta_m k = 1455 \times 0.27 = 392.9\ \text{W/cm}$

$\theta_m k / 2H = 392.9 / (3.2 \times 10^6) = 1.228 \times 10^{-4}$

Step 4. Square it

$(1.228 \times 10^{-4})^2 = 1.507 \times 10^{-8}$

Step 5. Multiply by π/α

$\pi/\alpha = 3.1416 / 0.071 = 44.25$

$t_m = 44.25 \times 1.507 \times 10^{-8} = 6.67 \times 10^{-7}\ \text{s}$

Comment

About 80 times faster than tungsten under 10^5 W/mm^2 (53 μs): the absorbed flux is higher and stainless steel has a lower conductivity and melting point.

The 1-D model underestimates the time; the circular spot model gives a longer value.

Prepared By: Dr. S.R. Parimanik Dr. A.K. Parimanik

Answer: time to reach the melting temperature $t_m \approx \mathbf{6.7 \times 10^{-7}\ s}$ **(0.67 μs)**

QNS 8 (PAM)

Question: A plasma arc torch running at 200 V and 400 A cuts a 20 mm thick stainless steel plate, leaving a kerf 4 mm wide. Taking the specific energy of PAM as 1000 W per cm^3/min, estimate (a) the material removal rate and (b) the cutting speed. Check the results against the usual PAM operating range.

Solution (step by step)

Step 1. Arc power

$P = VI = 200 \times 400 = 80{,}000\ \text{W} = 80\ \text{kW}$

Step 2. Material removal rate (a)

Specific energy $u = 1000\ \text{W per cm}^3/\text{min}$

$\text{MRR} = P / u = 80{,}000 / 1000 = 80\ \text{cm}^3/\text{min}$

Step 3. Kerf cross-section

Area = kerf width × plate thickness $= 0.4\ \text{cm} \times 2.0\ \text{cm} = 0.8\ \text{cm}^2$

Step 4. Cutting speed (b)

Speed = MRR / area $= 80 / 0.8 = 100\ \text{cm/min}$

Speed $= 1.0\ \text{m/min}$

Step 5. Check with typical PAM values

Voltage 200 V (range 30–250 V) and current 400 A (up to 600 A): OK

Power 80 kW (range 2–200 kW): OK

MRR 80 cm^3/min (maximum 150 cm^3/min): OK

Speed 1.0 m/min (range 0.1–7.5 m/min): OK

Prepared By Dr. S.R. Panmand Dr. A.K. Pattanaik

Answer: (a) MRR ≈ **80 cm^3/min**; (b) cutting speed ≈ **1.0 m/min**, both within the normal PAM range