ME338 – Manufacturing Process II

Lecture 9 : Nonconventional Machining & Electrical discharge machining

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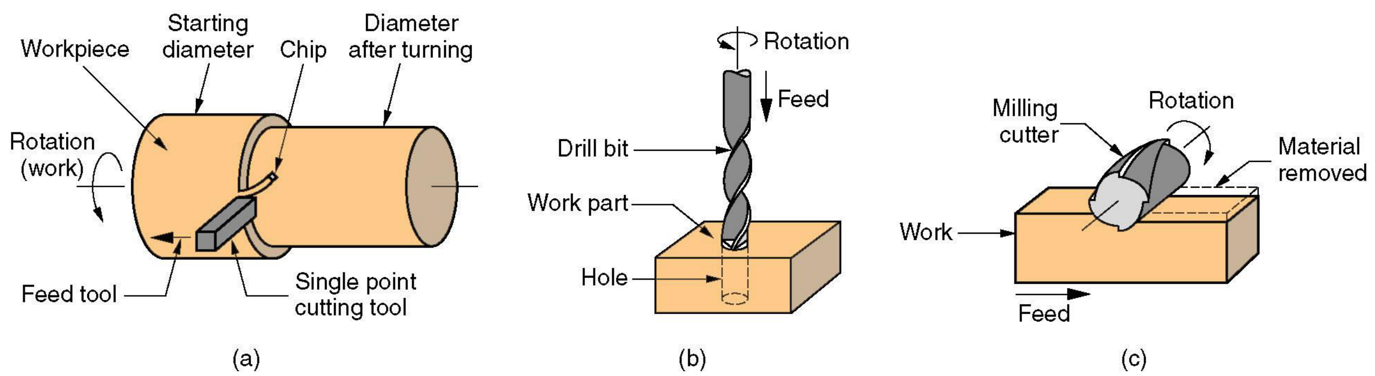
Outline

- Non-Traditional Machining (NTM) methods ?
  - What are these? Why do we need them ?
- Classification of various NTM methods
- Detailed understanding of NTM Processes
  - Electrical discharge machining (EDM)
  - Electrochemical machining (ECM)
  - Abrasive Jet Machining
  - Ultrasonic Machining
- Summary

Traditional Machining Processes

- Machining : Removing of excess material from the starting workpiece to make a desired part
  - Traditional machining: milling, drilling, grinding process
  - Non-traditional machining: electro-discharge, electro-chemical, abrasive jet machining, ultrasonic machining etc
- Traditional machining processes are quite good, popular and economical for commonly used materials
  - direct contact with workpiece, tool hardness > work-piece hardness



Metal removal processes

Non Traditional Machining

- Traditional machining Processes removes materials using tools that are harder than the materials themselves.
- Traditional machining process may be ineffective (both technical as well as cost point of view)
  - machining hard materials like ceramics and composites
  - machining under very tight tolerance requirement as in micromachined components.
- New and novel materials because of their greatly improved chemical, mechanical and thermal properties are sometimes very difficult to machine using traditional machining processes.
  - Titanium is now used in aerospace industry, however it has low thermal conductivity >> low heat dissipation >> high tool wear
  - Ceramics/Composit/nickel alloys ….
- New processes and methods play a considerable role in machining for aircraft manufacture, automobile industry, tool and die industry mold making etc.
- They are classified under the domain of non traditional processes.

Need for Non-Traditional Machining

- New materials are coming in manufacturing
  - Can operate in very high temperature environments
  - making through-holes in Gas turbine blades in aerospace applications
  - Examples: Ni-Cr super alloys (Inconel 718 – BHN >400)
- Machining of these super alloys (NiCr alloys, Ti, WC) ?
  - Very difficult to machine by traditional machining – high tool wear, low material removal rate
- Machining of non-conductive, brittle materials (fused silica, quartz, glass)
  - Applications: semiconductors, MEMS, Microfluidics
- New material removal processes have been developed
  - Material removal is independent of work-piece hardness
  - No direct contact between tool and work-piece

NTM is useful

- Situations where traditional machining processes are unsatisfactory or uneconomical:
- Workpiece material is too hard, strong, or tough.
- Workpiece is too flexible to resist cutting forces or too difficult to clamp.
- Part shape is very complex with internal or external profiles or small holes.
- Requirements for surface finish and tolerances are very high.
- Temperature rise or residual stresses are undesirable or unacceptable.

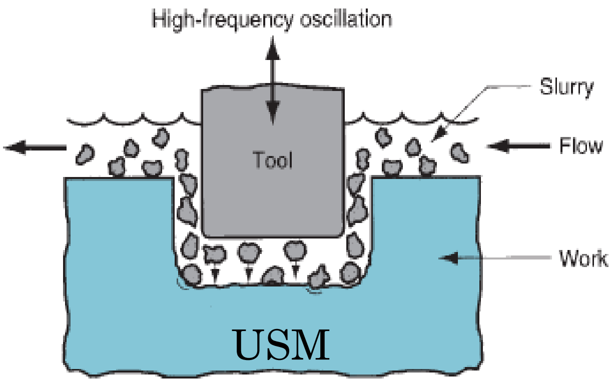
How are NTM methods different ?

Traditional Machining	Non-Traditional Machining (NTM)
• Primary source of energy – Mechanical/friction • Material removal mechanism – shearing • Tool and work piece are in direct contact • Material removal rate depends a lot on the hardness of workpiece	• Primary source of energy – Electrical, Chemical, Thermal, Optical • Material removal mechanism – Chemical, erosion, • Tool and work piece are often not in direct contact • Material removal rate is independent on the hardness • NTM are used when a workpiece is too hard to machine or part shape geometry is too complex

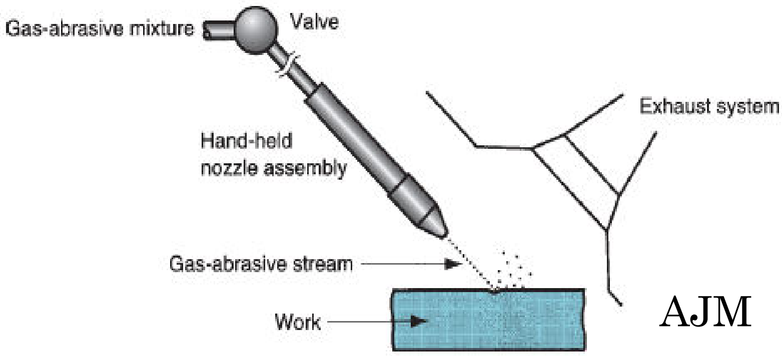
Classification of NTM methods

Removal Mechanisms			
Mechanical Failure	Plastic shear	Conventional machining	
	Brittle fracture	Abrasive powder impingement	AJM/WJM
		Hammering of abrasive grain	Ultrasonic machining
Thermal	Melting, evacuation		EDM, ECDM
	vaporization		EBM, LBM, PAM
Electrochemical dissolution	Electrochemical machining		
Selective chemical etching	Chemical wet machining		
	Chemical dry machining		

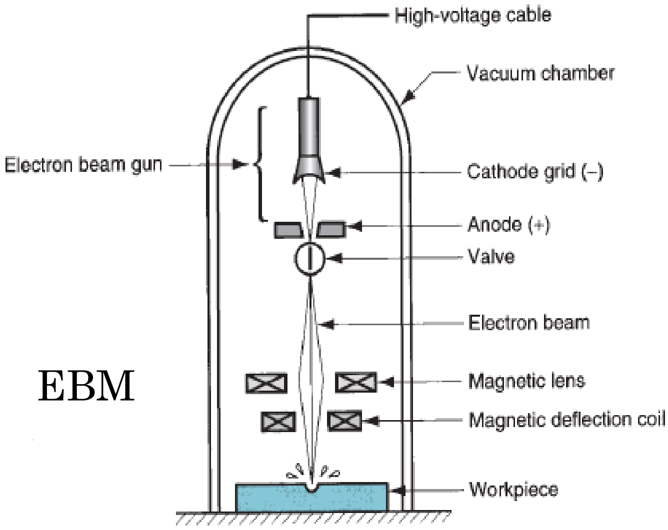
Various NTM processes



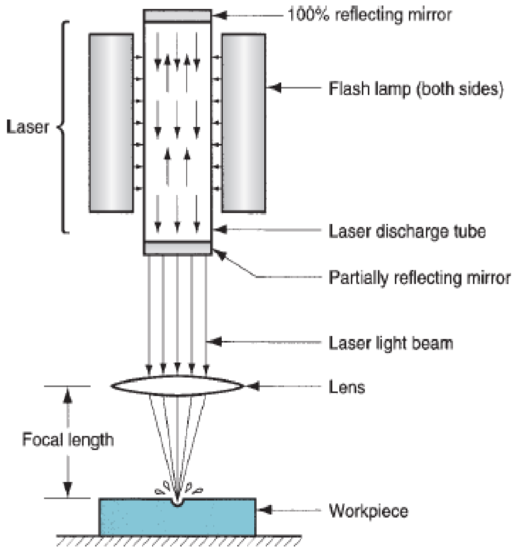
USM



AJM



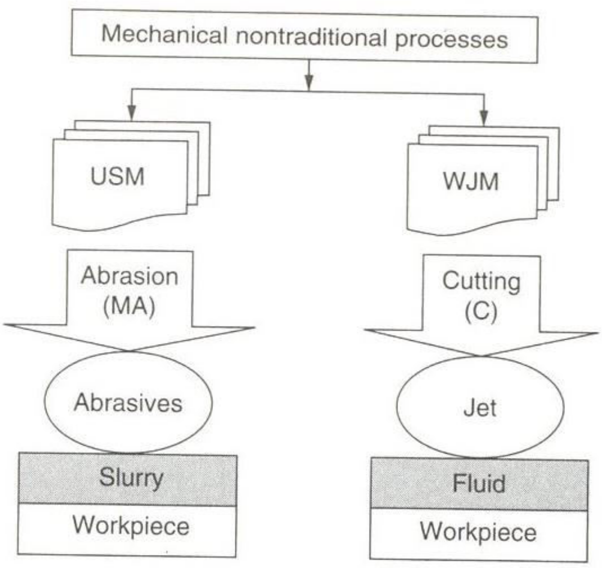
EBM



LBM

Mechanical Machining

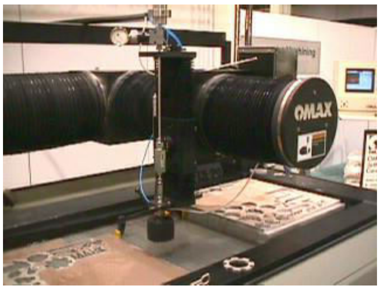
- Ultrasonic Machining (USM) and Waterjet Machining (WJM)
  - single action, mechanical non traditional machining processes.
  - Machining medium is solid grains suspended in an abrasive slurry in the former, while a fluid is employed in the WJM process.
- The introduction of abrasives to the fluid jet enhances the machining efficiency and is known as abrasive water jet machining.
- Similar case happens when ice particles are introduced as in Ice Jet Machining.

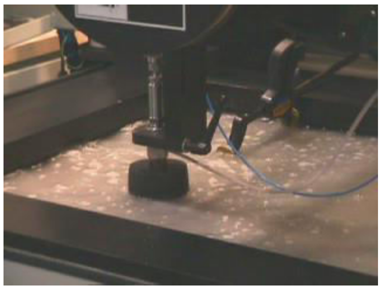


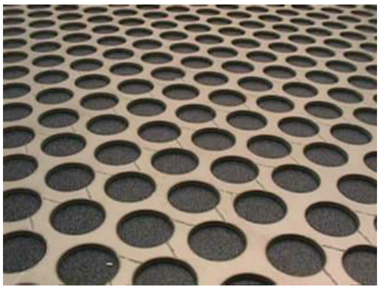
Abrasive jet machining

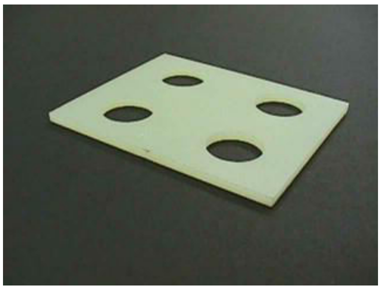
Water jet machining

Examples: Abrasive Water-jet & Water-jet machining

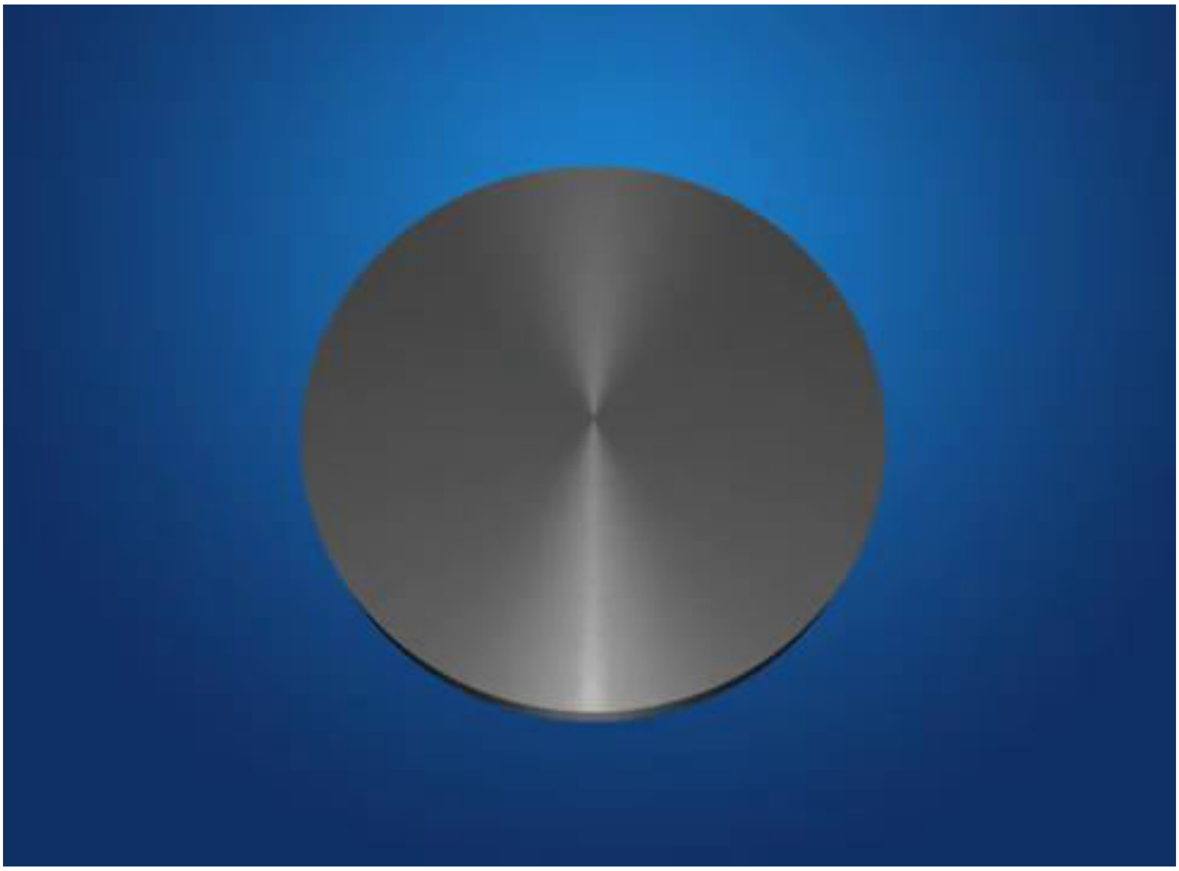






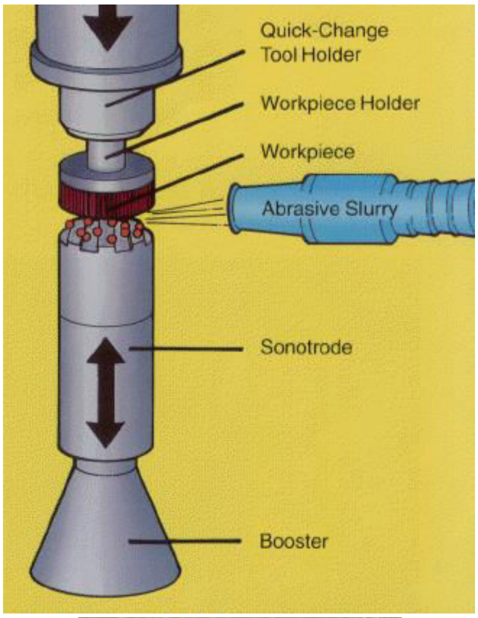


Ultrasonic machining



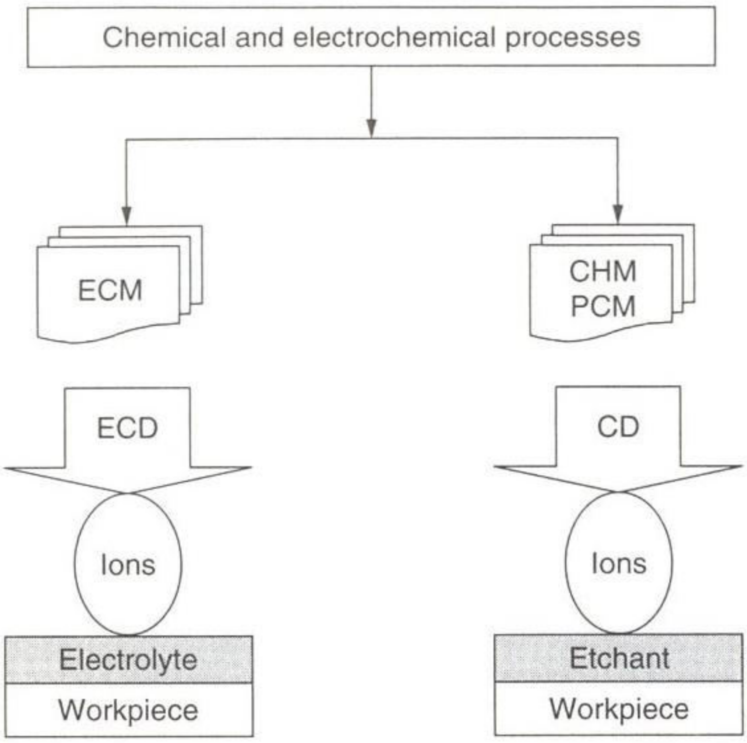
Ultrasonic Machining

- Ultrasonic vibration (20 KHz) of very small amplitudes (0.04-0.08 mm) drive the form tool (sonotrode) of ductile material (usually soft steel)
- An abrasive slurry is flowed through the work area
- The workpiece is brittle in nature (i.e. glass)
- The workpiece is gradually eroded away.



Chemical and Electrochemical Machining

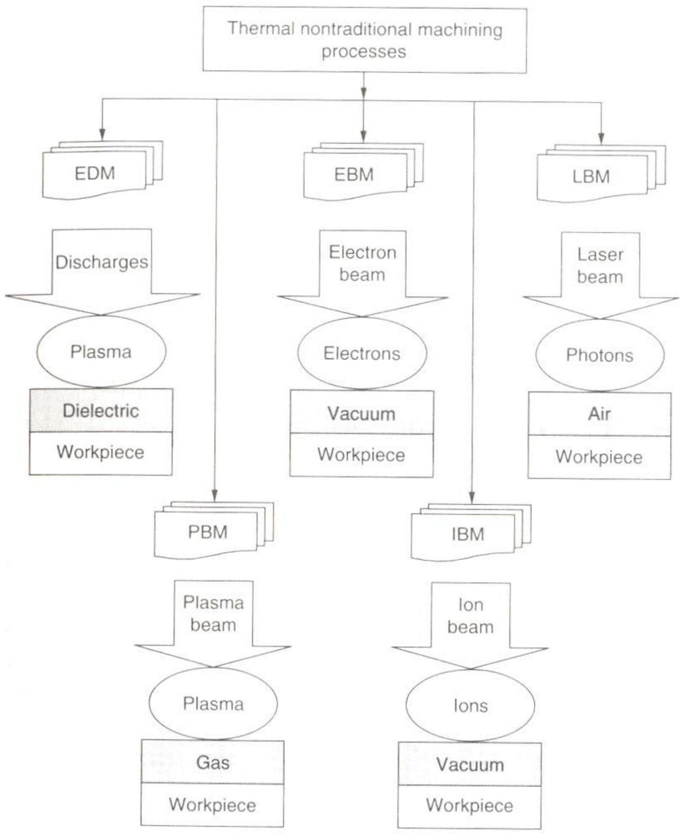
- Chemical milling and photochemical machining or photochemical blanking all use a chemical dissolution action to remove the machining allowance through ions in an etchant.
- Electrochemical machining uses the electrochemical dissolution phase to remove the machining allowance using ion transfer in an electrolytic cell.



Electrochemical machining

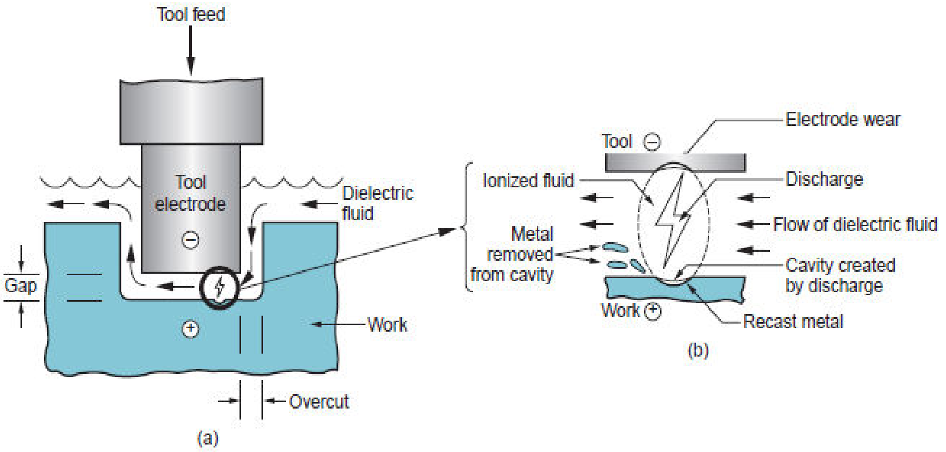
Thermal machining

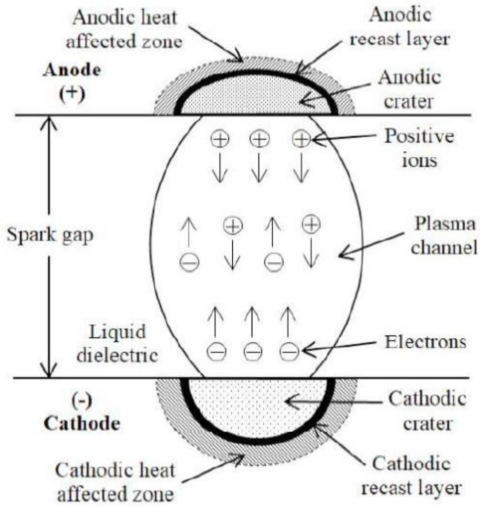
- Thermal machining removes the machining allowance by melting or vaporizing the work piece material.
- Many secondary phenomena occur during machining such as microcracking, formation of heat affected zones, striations etc.
- The source of heat could be plasma as during EDM and PBM or photons as during LBM, electrons in EBM, ions in IBM etc.



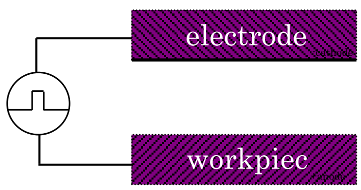
Electrical Discharge Machining (EDM)

- One of the most popular NTM method used in manufacturing industry
- Based on thermal erosion method
  - Workpiece and tool electrode are immersed in a dielectric medium
  - Electrical spark is generated between the electrodes
  - Workpiece Material is melted at localized spots and washed away through the incoming fluid flow

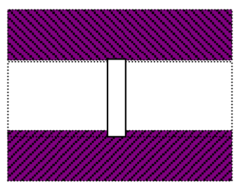




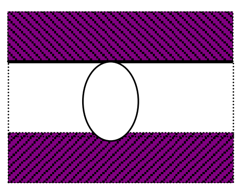
Basics of EDM



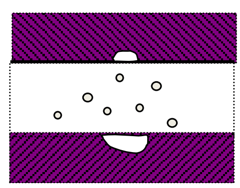
(a) Tool and workpiece immersed in dielectric liquid.



(b) A spark is generated between tool and workpiece.



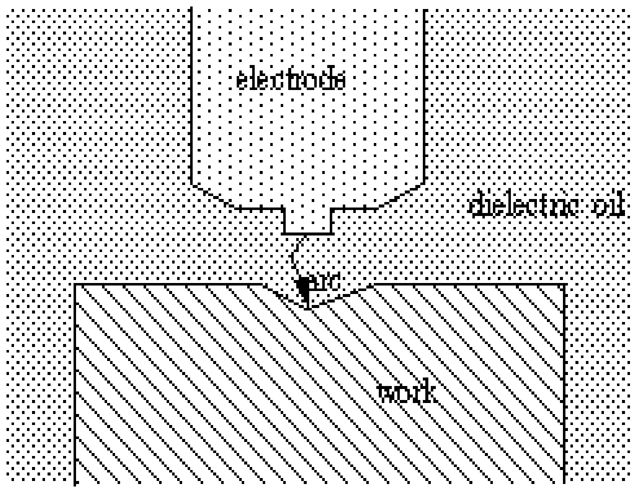
(c) The high temperature causes the melting and vaporization of electrodes.

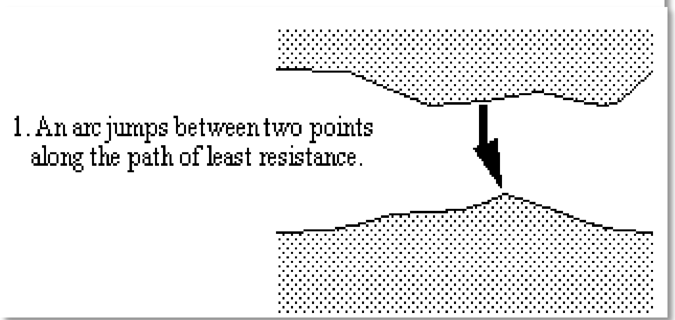


(d) At the end of the pulse, the molten material is ejected from surface, leaving a shallow crater.

Mechanism of metal removal in EDM (1/3)

- Voltage is applied to the electrodes, which results in the ionization of dielectric fluid
- The interelectrode gap becomes conductive, allowing current to flow from one electrode to the other in the form of a <u>spark discharge .</u>

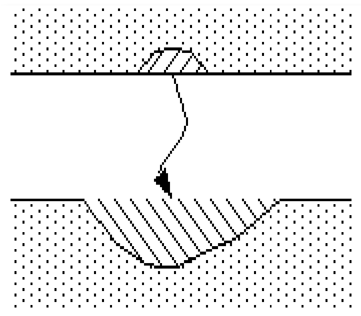


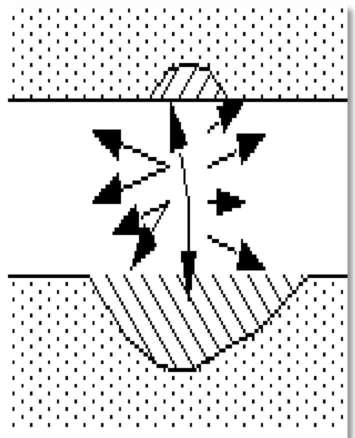


- The *spark channel* in the first few microseconds has a very *small cross-sectional* area <u>resulting in</u> a correspondingly <u>high current density</u>
- It can be as high as 10^4~10^6 A /cm^2.

Mechanism of metal removal in EDM (2/3)

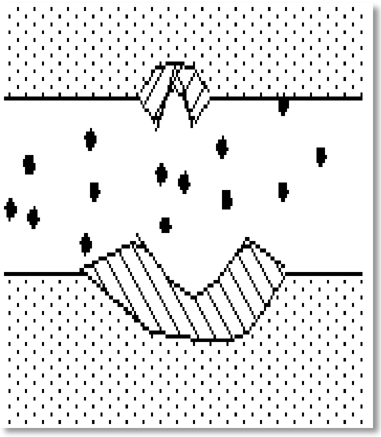
- Due to such high current density, temperature in the spark channel can be very high (>5000°C)
- It <u>resulting in</u> the *melting* and *vaporization* of a small amount of material from the surfaces of both the electrode and the workpiece at the points of spark contact
- A rapidly expanding bubble is created in the dielectric fluid around the spark channel.



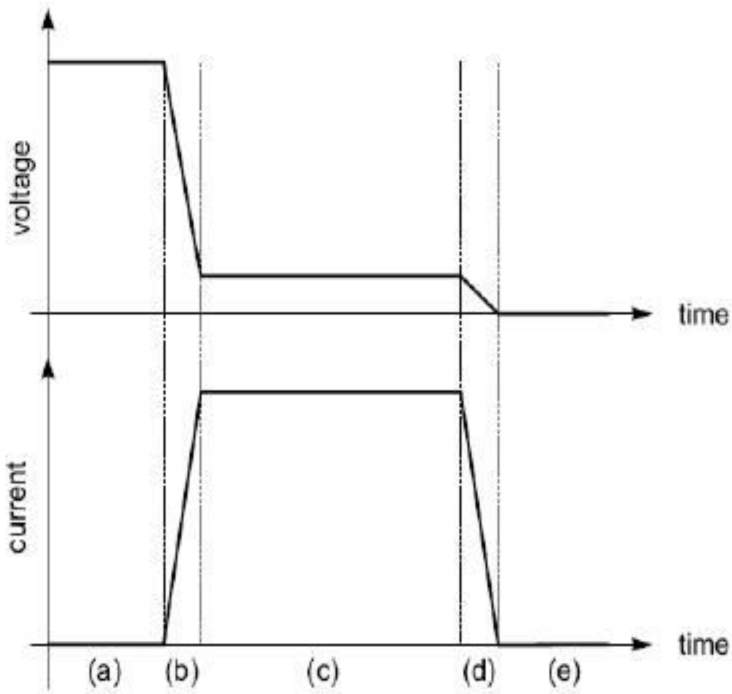


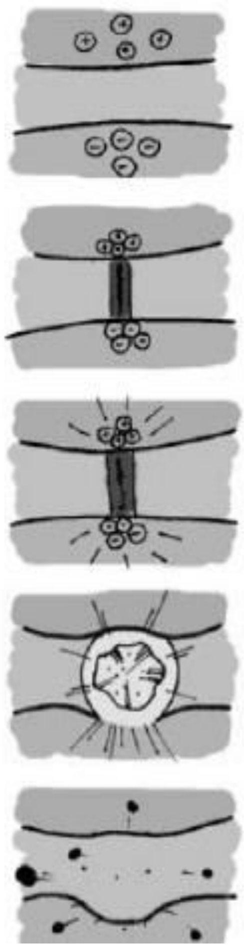
Mechanism of metal removal in EDM (3/3)

- When the electrical pulse is terminated, both the *spark channel* and the *vapor bubble* collapse
- The violent inrush of cool dielectric fluid results in an explosive expulsion of molten metal from both the electrode and workpiece surfaces
- It resulting in the formation of a small crater in the surfaces of the two conductors, solidifying hollow balls of material, which are removed from the gap by the fluid.
- The erosion of metal from the cathode can be as high as *99.5%*
- The wear of the anode being kept as low as *0.5%.*



Summary of metal removal mechanism in EDM





(a) Pre-breakdown : voltage applied between the electrode and the workpiece

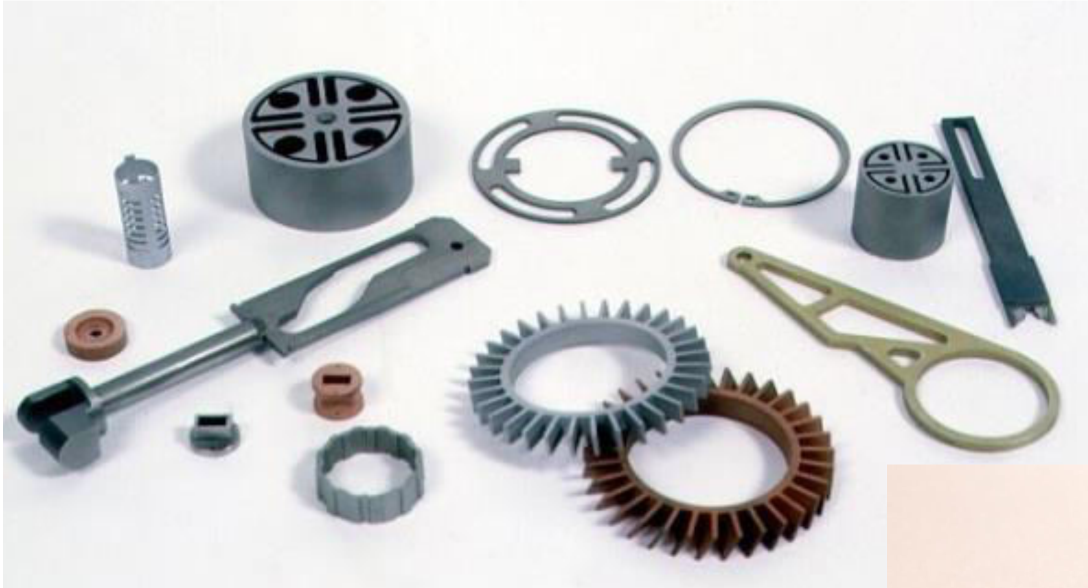
(b) Breakdown : dielectric breakdown, creation of the plasma channel

(c) Discharge : heating, melting and vaporizing of the workpiece material

(d) End of the discharge plasma implosion, removing of the molten metal pool

(e) Post-discharge : solidifying and flushing of the eroded particles by the dielectric

Example of mechanical parts made by EDM



Main features of EDM

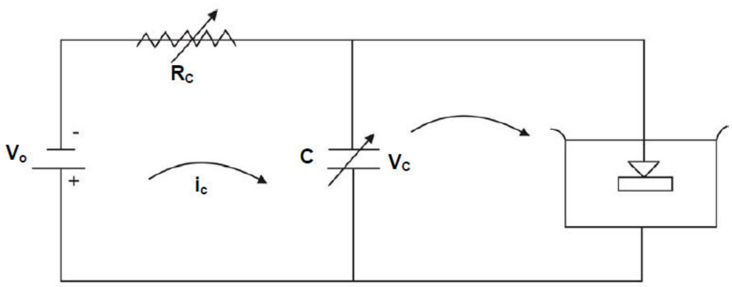
- Main features in EDM process:
  - Pulsed power supply
  - Tool electrode – Cathode
  - Workpiece – Anode WHY ??
  - Medium: Dielectric (DI water, mineral oil)
- Electrodes: Conductive, high melting point
  - Easy machinability, allowing easy manufacture of complex shapes.
  - Low wear rate, high electrical and thermal conductivity, readily available
  - Copper, Graphite, Brass
- Dielectric:
  - Cheap, low viscosity, Oxygen free environment
  - DI water, Kerosene-based oil
- Inter-electrode gap: 10-100 μm.
  - Constant gap is maintained by the servo-motor
- Applied voltage: 30-300V
  - Frequency: 100 Hz – 1 MHz, Duty cycle : 20 – 80%
  - Electrical spark last about 1μs to 8 ms.
- Resulted Temperature during electric spark: > 5000°C
- Size Removed material :
  - > 2 μm

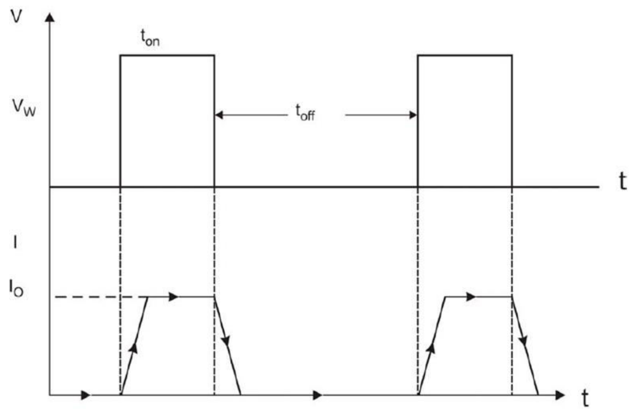
Macro Vs. Micro EDM

	Macro	Micro
Principle	Thermal Material Removal	Similar (?)
Equipment		
Pulse Generator	Mechanical Switch/RC circuit	Advanced RC circuit
Dielectric	Mineral oil, Deionized water	Mineral oil
Flushing	External and Internal	No flushing
Electrode Material	Copper / Graphite	Tungsten
Process Parameters		
Current	0.5 – 400A	0.1 – 10mA
Voltage	40 – 400V	60 – 120V
Pulse Duration	0.5µs – 8ms	ns – µs
Electrode Wear Ratio	1 – 5%	5 – 50%
Surface Roughness	0.8 – 3.1µm	0.07 – 1µm

*Prof. Rajurkar presentation

RC relaxation circuit in EDM machines





- RC circuit – popular for providing DC pulse in EDM
- Charging and discharging cycles in EDM
- Charging takes places until dielectric medium breaks down, after that discharging starts
- Spark formation and material removal takes place during the discharging of capacitor

- V_o Open circuit voltage,
- V_c charging voltage,
- V_d discharging voltage,
- R_m – machine resistance,
- I_d- discharge current
- $V_c = V_o\left(1 - e^{-\frac{t}{RC}}\right)$, $I_c = I_o e^{-t/RC}$
- $V_d = V_c e^{-t_d/R_m C}$, $I_d = \frac{V_c}{R_m} e^{-t_d/R_m C}$

RC type generator : EDM during charging

- During charging cycle

or $$\frac{dV}{V_o - V_c} = \frac{1}{CR_c}dt$$

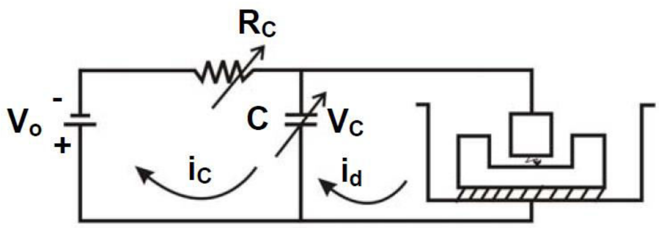
At t=0, V_c=0 and $t = t_c$, V_c=V_c*

$$\therefore \int_0^{V_c^*} \frac{dV_c}{V_o - V_c} = \frac{1}{CR_c}\int_0^{t_c} dt$$

$$\Rightarrow -\frac{t_c}{R_c} = \left|\ln(V_o - V_c)\right|_0^{V_c^*}$$

$$\therefore V_c^* = V_o\left\{1 - e^{-\frac{t_c}{R_cC}}\right\}$$

$$\text{or} \quad V_c = V_o\left\{1 - e^{-\frac{t}{R_cC}}\right\}$$



I_c = charging current
V_o= open circuit voltage
R_c= charging resistance
C = capacitance
V_c= instantaneous capacitor voltage during charging

$$i_c = \frac{V_o - V_c}{R_c} = \frac{V_o - V_o\left(1 - e^{-\frac{t}{R_cC}}\right)}{R_c}$$

$$i_c = \frac{V_o e^{-\frac{t}{R_cC}}}{R_c} = i_o.e^{-\frac{t}{R_cC}}$$

EDM – mechanism during discharging

- During discharging, electrical load from EDM may be assumed a totally resistive (Rm : machine resistance)
- Current passing through EDM machine :

$$i_d = \frac{V_c}{R_m} = -C\frac{dV_c}{dt}$$

  - I_d = discharge current or current flowing through the machine
  - V_c = instantaneous capacitor voltage during discharging
  - R_m= machine resistance
  - Negative sign in front of the derivative of the voltage represents that the V_c is gradually decreasing during discharging.
- At t = 0 (at start of discharge/initiation of spark), $V_c = V_c^*$, at $t = t_d$, $V_c = V_d^*$
- Discharging or the machining current I_d

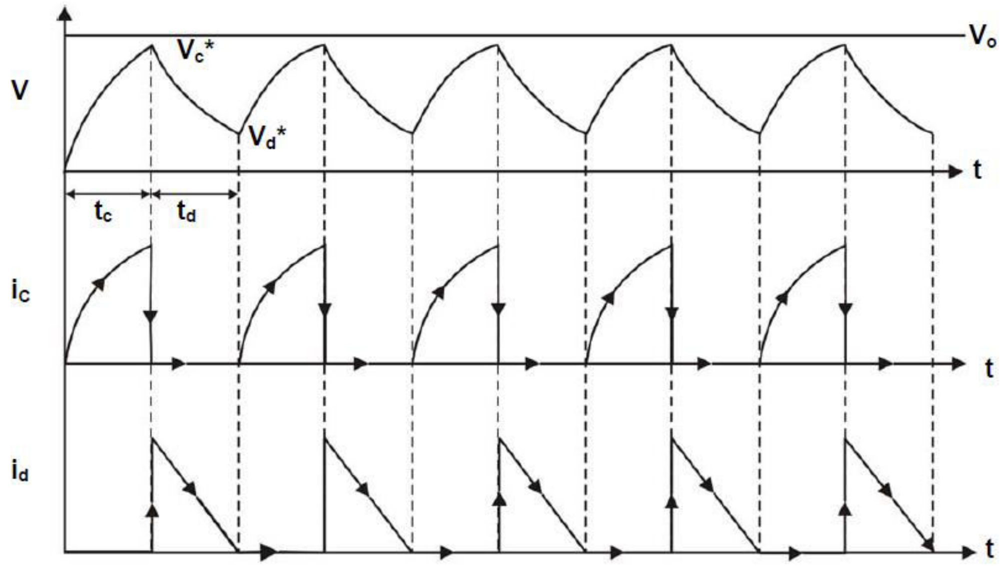
$$\int_{V_c^*}^{V_d^*} \frac{dV_c}{V_c} = -\frac{1}{CR_m}\int_0^{t_d} dt$$

$$-\frac{t_d}{CR_m} = \ln\frac{V_d^*}{V_c^*}$$

$$\therefore \quad V_d^* = \frac{V_c^*}{R_m}.e^{-\frac{t_d}{R_mC}}$$

$$i_d = \frac{V_d}{R_m} = \frac{V_c^*}{R_m}.e^{-\frac{t}{R_mC}}$$

Current pulses in charging/discharging in EDM

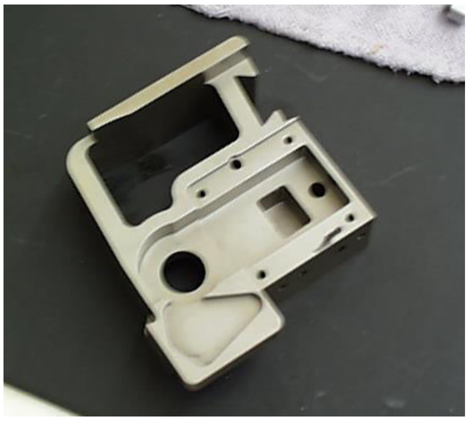


Schematic representation of the current pulses during charging and discharging in EDM process

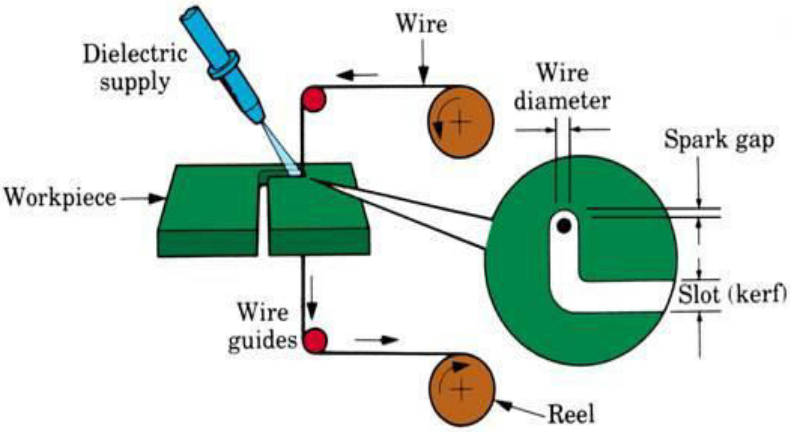
Important consideration in EDM

- Amount of material removed depends upon the supplied voltage and thus current
- Melting point of the material affects the material removal rate, however hardness of material does not matter
- If supplied current is I (in amp), Melting points of workpiece and electrode are is T_m (in°C) and T_e (in°C), then
  - Material Removal rate MRR(mm^3/min) = $(4 \times 10^4).I / T_m^{1.23}$
  - Wear rate of electrode W(mm^3/min) = $(11 \times 10^3).I / T_e^{2.38}$
  - Wear ratio of workpiece to electrode $R = (2.25).(T_e/T_m)^{2.3}$
- Graphite electrodes are therefore prefered due to their low wear rate, high melting points

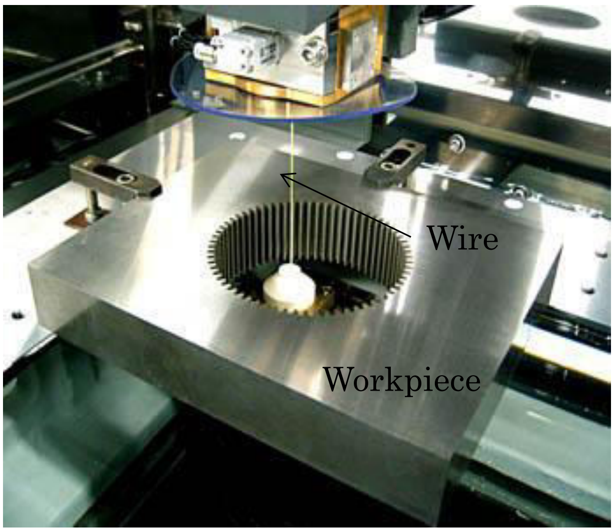
Die-sinking EDM Vs Wire-EDM

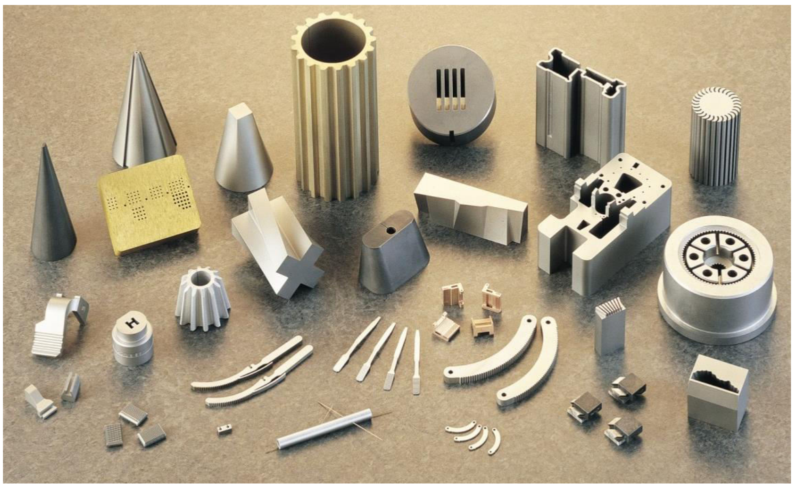


- Mirror image of tool is transferred into the workpiece in die-sink EDM
- In Wire EDM, the electrode is a wire that traverses through the part



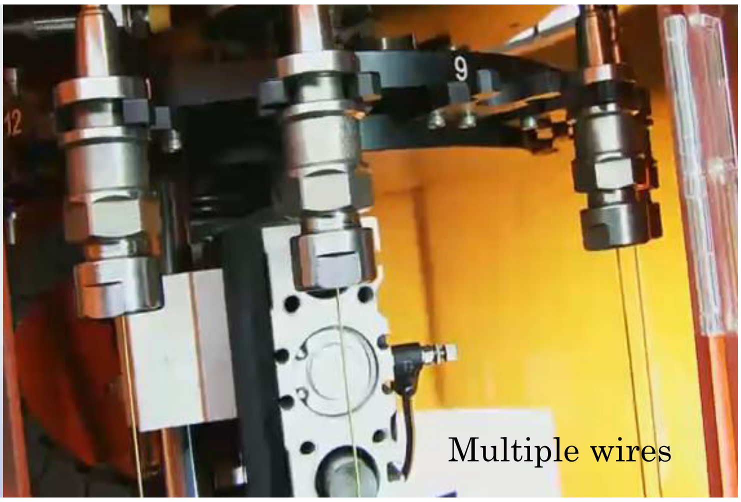
Wire Electrical discharge Machining (W-EDM)

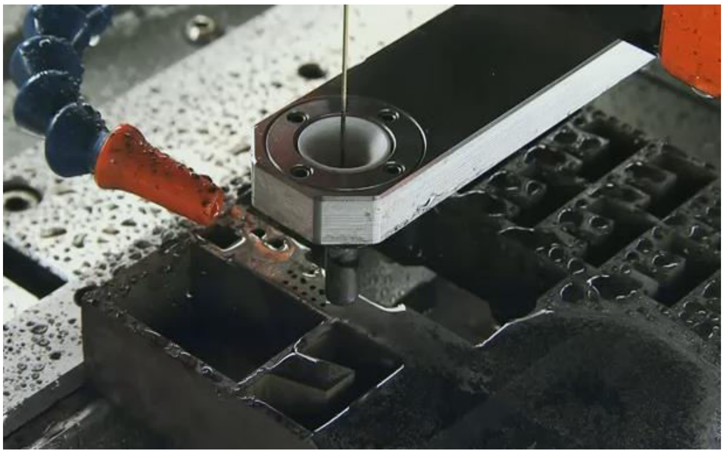




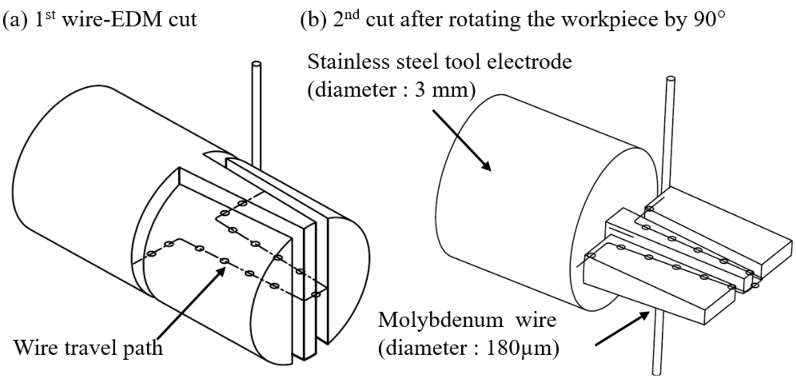
- A thin wire of brass, tungsten, or copper is used as an electrode.
- Wire diameter > 100 μm
- Deionized water is used as the dielectric.
- A wire travels along a prescribed path, cutting the workpiece, with the discharge sparks acting like cutting teeth

Wire Electrical discharge Machining (W-EDM)





EDM research @IIT B: Tool electrode by wire EDM



- Roughness of the tool electrode surface is affected by machining current and pulse-on period in wire-EDM process.
- Medium - deionized water
- Tool materials – Molybdenum wire
- Workpiece: Stainless steel

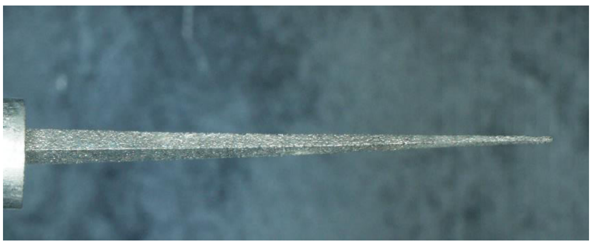
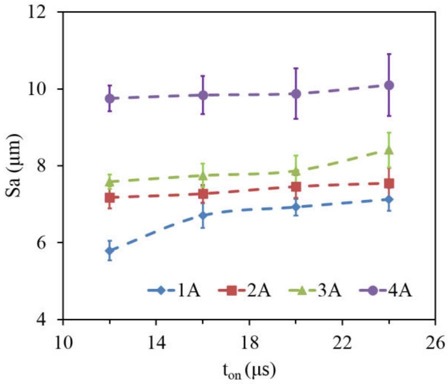


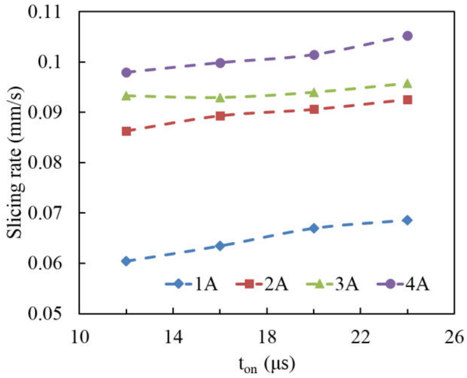
Table 1. Wire-EDM process parameters used in fabricating tool electrodes

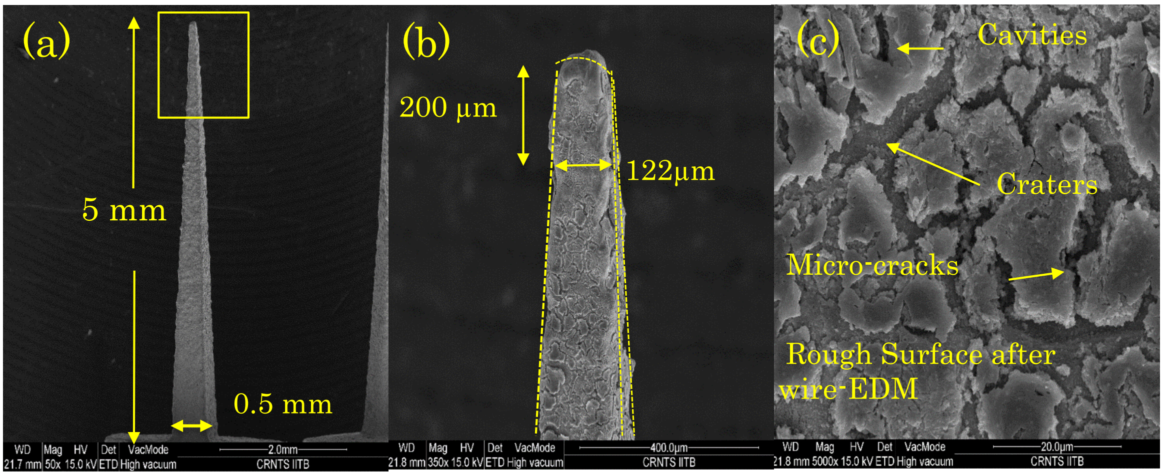
Tool No.	Process parameters: Machining current (A)	Process parameters: Pulse-on duration (μs)	Tool No.	Process parameters: Machining current (A)	Process parameters: Pulse-on duration (μs)
#1	1	12	#9	3	12
#2	1	16	#10	3	16
#3	1	20	#11	3	20
#4	1	24	#12	3	24
#5	2	12	#13	4	12
#6	2	16	#14	4	16
#7	2	20	#15	4	20
#8	2	24	#16	4	24

PDixit et al, "Effect of tool electrode roughness on the geometric characteristics of through-holes formed by ECDM", Precision Engineering, 60 (2019) 437–447

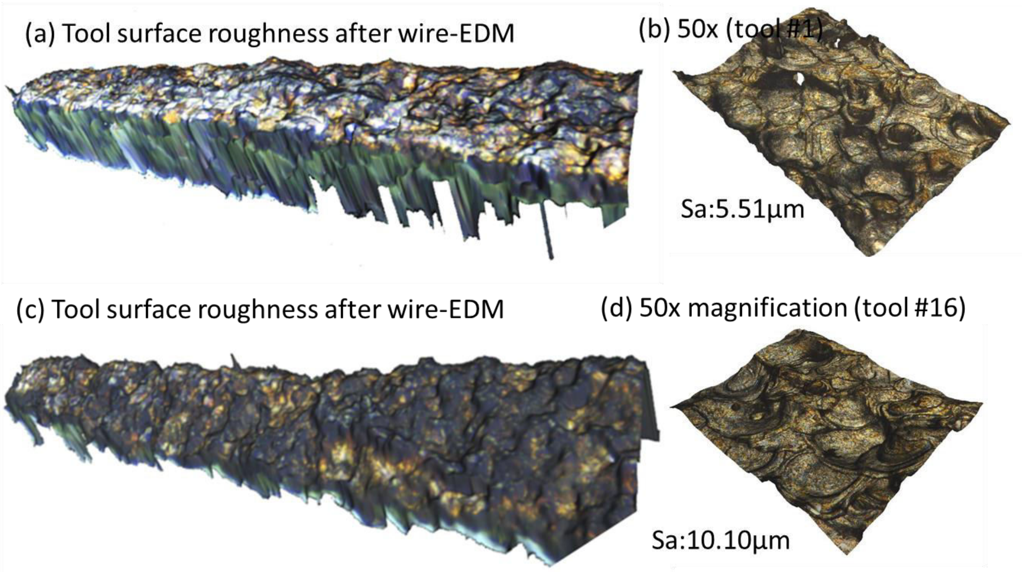
EDM research @IIT B: Single tool electrode by wire EDM



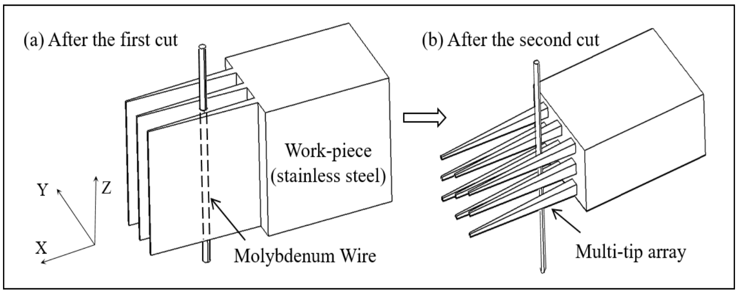


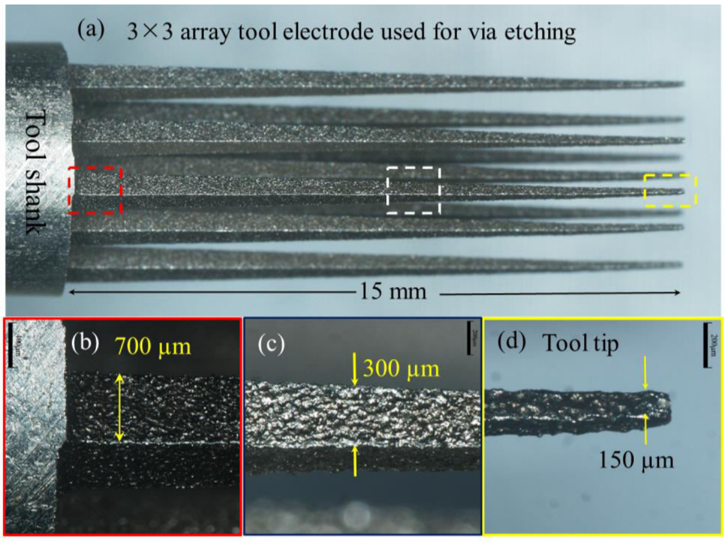


EDM research @IIT B: Single tool electrode by wire EDM



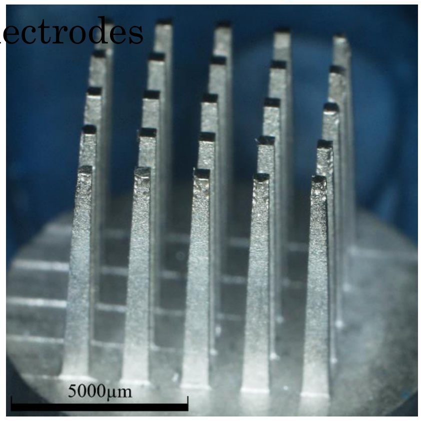
Tool array prepared by wire EDM@IIT Bombay

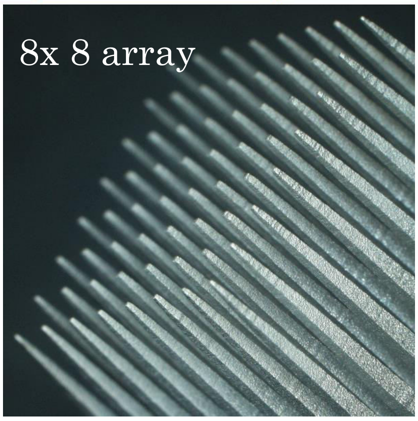




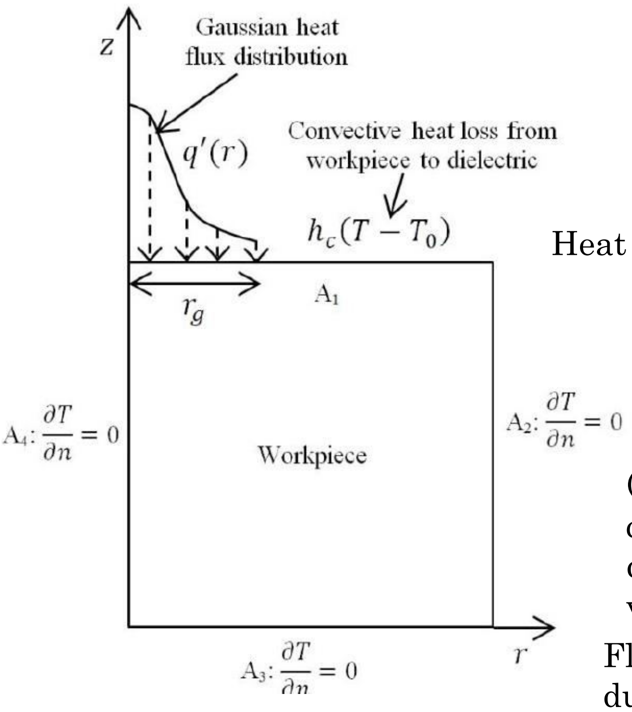
J Arab et al "Journal of Materials Processing Tech. 271 (2019) 542–553"

Multi tip tool electrodes





Single spark modelling*



Fourier heat conduction equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K_t r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(K_t\frac{\partial T}{\partial z}\right)=\rho C_p\frac{\partial T}{\partial t}$$

Heat source radius r_g (in μm) and heat flux distribution *q(r)*

$$r_g = 2040 * I^{0.43} * t_{on}^{0.44}$$

$$q(r) = q_0 \exp\left\{-4.5\left(\frac{r}{r_g}\right)^2\right\} \qquad q_0 = \frac{4.45 F_C U I}{\pi r_g^2}$$

(*Fc*) is the fraction of energy which goes to cathode from the total energy generated during individual spark discharge. Typical value: 0.10-0.25

Flushing efficiency – material removed by dielectric during pulse off period is assumed to be 100%.
It is difficult to measure. Researchers try to match the experimental results with the simulated results

Boundary conditions:
On boundary A_1

$$-K_t\frac{\partial T}{\partial z} = \begin{cases} q'(r), r \le r_g \\ h_c(T - T_0), r > r_g \\ 0, t > t_{on} \end{cases}$$

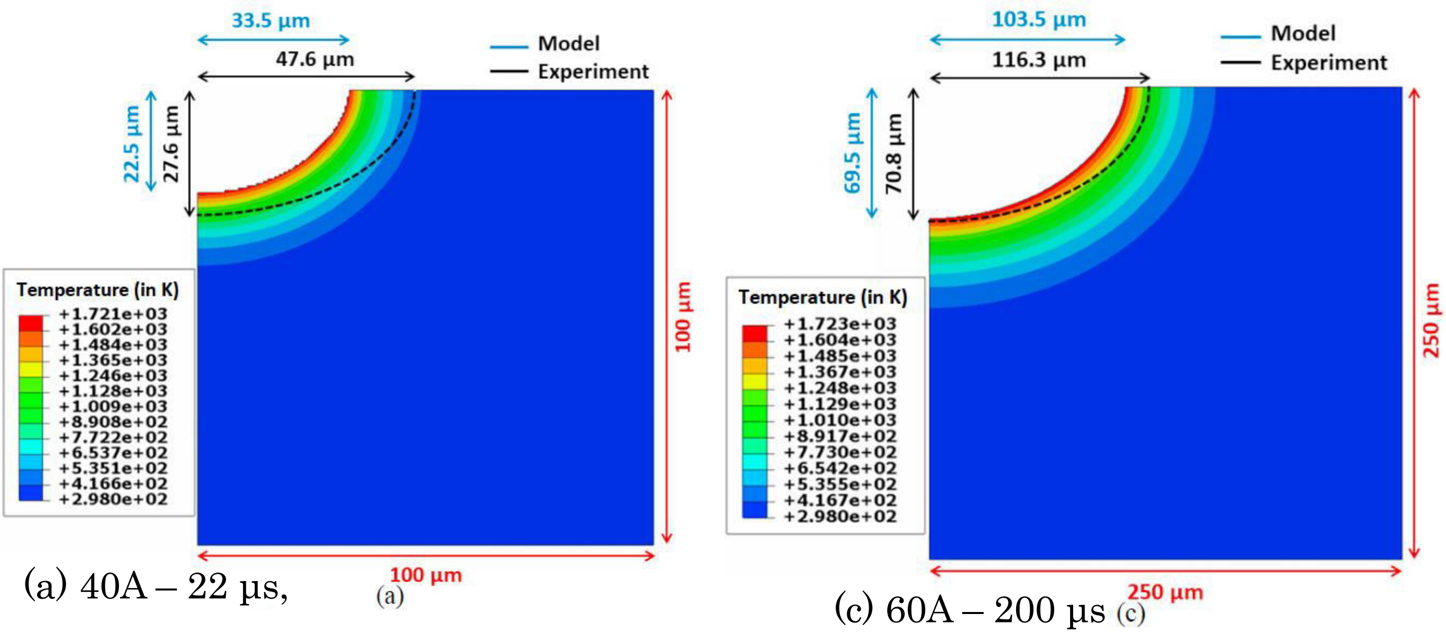
And, on boundaries A_2, A_3 and A_4

$$\frac{\partial T}{\partial n} = 0$$

SS Joshi, "FEM for single spark in EDM", 46th NAMRC Conference, USA (2018).

Experimental validation of Single spark EDM model

Material: SS 304



(a) 40A – 22 µs, (c) 60A – 200 µs

SS Joshi, "FEM for single spark in EDM", 46th NAMRC Conference, USA (2018).

Summary of EDM

- Mechanism of material removal - melting and evaporation
- Medium - dielectric fluid, deionized water
- Tool materials – Graphite, Cu, Brass,
- Inter-electrode gap = 100 to 125 µm
- Maximum MRR = $5*10^3$ mm^3/min
- Critical parameters - voltage, spark gap, melting, dielectric circulation
- Materials application - all conducting metals and alloys
- Shape application - blind complex cavities, micro-holes for nozzles, through cutting of non-circular holes, narrow slots
- Cons: surface hardening, only conductive materials