TA 202A

Lecture 7

Non-Conventional Machining Processes

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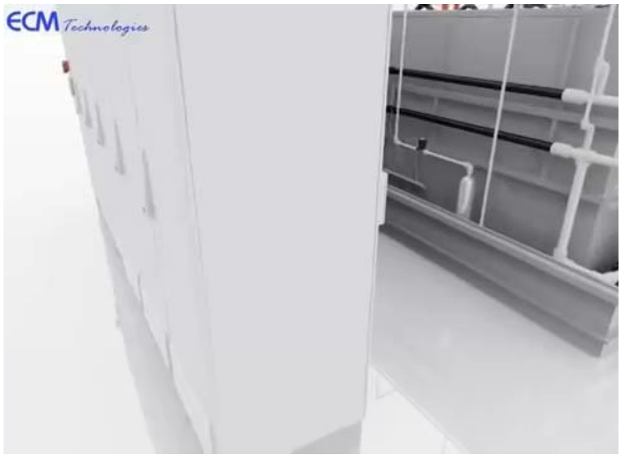
Electrical Energy Processes

- Electrical energy used in combination with chemical reactions to remove material
- Work material must be a conductor of electricuty

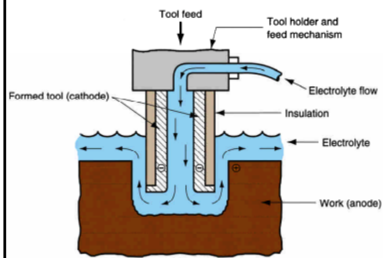
Processes

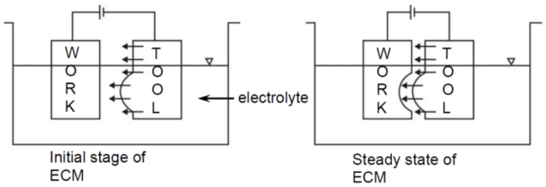
- Electrochemical Machining (ECM)
- Electrochemical Grinding (ECG)
- Electrochemical Deburring (ECD)

Electrochemical Machining (ECM)



Electrochemical Machining (ECM)

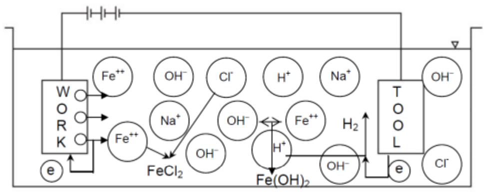




Schematic principle of Electro Chemical Machining (ECM)

- ECM is opposite of galvanic coating or deposition
- ECM is a controlled anodic dissolution at atomic level of conducting workpiece
- A flow of high current at relatively low potential through an electrolyte which is quite often water based neutral salt solution

ECM Process



Schematic representation of electro-chemical reactions

- Reactions occur at electrodes
- Neutral solution – NaCl with water
- Electrolyte and water undergoes ionic dissociation as potential difference is applied

$NaCl \leftrightarrow Na^+ + Cl^-$

$H_2O \leftrightarrow H^+ + (OH)^-$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece.

Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$$2H^+ + 2e^- = H_2\uparrow \text{ at cathode}$$

Similarly, the iron atoms will come out of the anode (work piece) as:

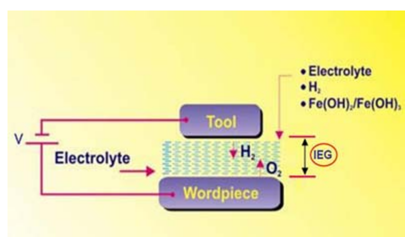
$$Fe = Fe^{++} + 2e^-$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$$Na^+ + OH^- = NaOH$$

In practice $FeCl_2$ and $Fe(OH)_2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode.

Material removal by anodic dissolution, using electrode (tool) in close proximity to the work but separated by a rapidly flowing electrolyte

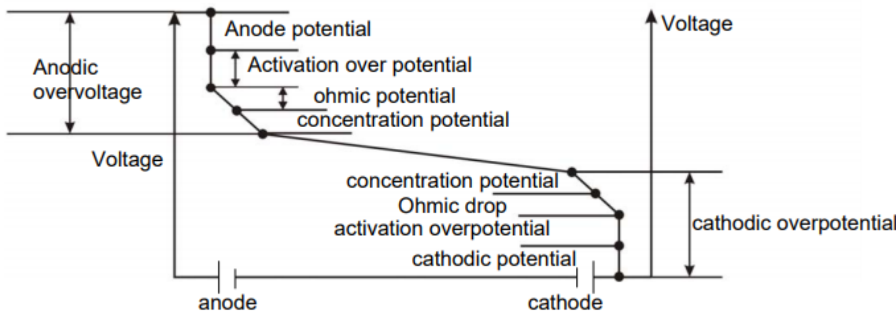


- Material is deplated from anode workpiece (positive pole) and transported to a cathode tool (negative pole) in an electrolyte bath
- Electrolyte flows rapidly between the two poles to carry off depleted material, so it does not plate onto tool
- Electrode materials: Cu, brass, or stainless steel
- Tool has inverse shape of part
- Tool size and shape must allow for the gap

ECM process is also known as a contactless electrochemical forming process

Electrochemical energy detaches metal from anode atom by atom

ECM: Potential drop



Total potential drop in ECM cell

Process Parameters

Power Supply	
Type	direct current
Voltage	2 to 35 V
Current	50 to 40,000 A
Current density	0.1 A/mm^2 to 5 A/mm^2
Electrolyte	
Material	NaCl and $NaNO_3$
Temperature	20^{o}C – 50^{o}C
Flow rate	20 lpm per 100 A current
Pressure	0.5 to 20 bar
Dilution	100 g/l to 500 g/l
Working gap	0.1 mm to 2 mm
Overcut	0.2 mm to 3 mm
Feed rate	0.5 mm/min to 15 mm/min
Electrode material	Copper, brass, bronze
Surface roughness, R_a	0.2 to 1.5 μm

NO ELECTROLYTE IS BEING CONSUMED IN THE PROCESS

Material Removal Rate for Pure Metals

The electrolysis process is governed by the following two laws proposed by Faraday:

1. The amount of any material dissolved or deposited, is proportional to the quantity of electricity passed.
2. The amounts of different substances dissolved or deposited by the quantity of electricity are proportional to their chemical equivalent weights

$$m \propto It\varepsilon$$

where m = weights (in grams) of a material dissolved are deposited

I = current (in amperes)

t = time (in seconds)

ε = gram equivalent weight of the material ($\varepsilon = A/Z$)

where A is the atomic weight and Z is the valancy of the ions produced

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

F = Constant of proportionality (Faraday = 96,500 coulombs)

Rate of mass removal: $\dot{m} = \dfrac{AI}{ZF}$

Volumertic material remval rate: $MRR\ (Q) = \dfrac{AI}{\rho ZF}\ \text{cm}^3/\text{s}$

ρ = density of the anode (g/cm^3)

The tool feed rate (thickness): $MRR_f\ (Q_f) = \dfrac{MRR\ (Q)}{Area} = \dfrac{AI}{\rho ZF \times Area}\ \text{cm}$

Material Removal Rate for Alloys

When the anode is made of an alloy instead of a pure metal, the removal rate can be found out by considering the charge required to remove a unit volume of each element. Let us assume there are *'n'* elements in an alloy. If the atomic weights and the valencies (of the corresponding lost entering the electrolyte) are A_1, A_2, A_3....... A_n and Z_1, Z_2, Z_3....... Z_n respectively, and the composition (by weight) of the alloy is x_1% of element 1, x_2% of element 2,........... x_n% of element n.

Then a volume v cm^3 of the alloy contains $v\rho x_i/100$ gram of the i-th element, where ρ is the overall density of the alloy in g/cm^3. The charge required to remove all the i-th element of volume v is given by:

$$\frac{v\rho x_i}{100} \bullet \frac{Z_i F}{A_i}$$

Thus, the volume of the alloy removed per unit charge is = $\dfrac{100}{\rho F} \bullet \left(\dfrac{1}{\sum_i x_i Z_i / A_i} \right) \text{cm}^3/\text{amp-sec}$

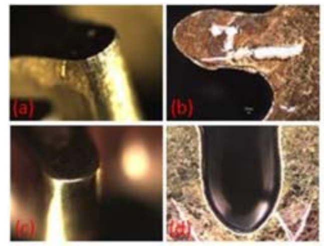
The volumetric material remval rate (MRR) of the alloy : $MRR\,(Q) = \dfrac{100I}{\rho F} \bullet \left(\dfrac{1}{\sum_i x_i Z_i / A_i} \right) \text{cm}^3/\text{sec}$

The overall density (ρ) of the alloy can be expressed as: $\rho = \dfrac{100}{\sum_i x_i / \rho_i}\ \text{g/cm}^3$

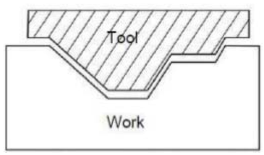
ρ_i is the density of the i-th element.

ECM Applications

- Die sinking - irregular shapes and contours for forging dies, plastic molds
- Multiple hole drilling - many holes can be drilled simultaneously with ECM
- Holes that are not round, since rotating drill is not used in ECM
- Deburring



(a) and (b) before deburring; (c) and (d) after deburring



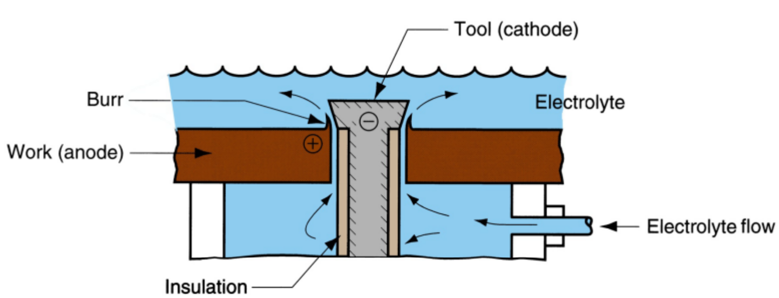
Die sinking


Drilling


Complex part

Electrochemical Deburring (ECD)

Adaptation of ECM to remove burrs or round sharp corners on holes in metal parts produced by conventional through-hole drilling

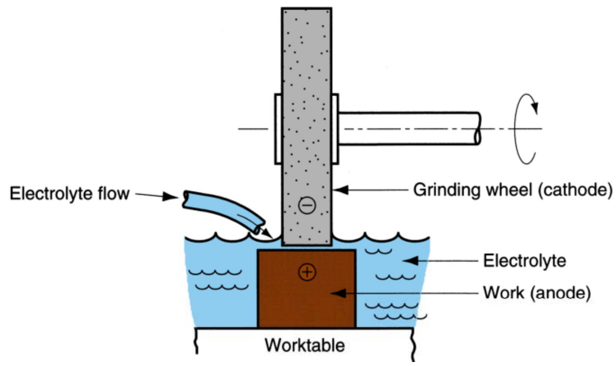


What is a burr?

Loosely adhered machine material on the edges or intersecting surfaces of the workpiecce

Electrochemical Grinding (ECG)

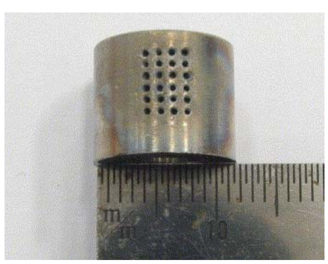
Special form of ECM in which a grinding wheel with conductive bond material is used to augment anodic dissolution of metal part surface



Applications

- Sharpening of cemented carbide tools
- Grinding of surgical needles, other thin wall tubes, and fragile parts

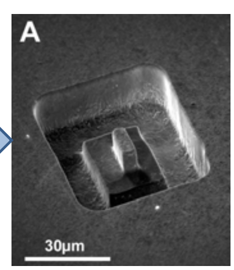
Examples of Electrochemical Micro Machining (ECMM)



MICRO-HOLES PRODUCED ON A Ti_6Al_4V CYLINDER USING JET-ECM

PRODUCTION OF HIGH ACCURACY HOLES

Cu STRUCTURE (SMALL PRISM, 5 µm BY 10 µm BY 12 µm) MACHINED INTO THE Cu SHEET OF AN ELECTRONIC CIRCUIT BOARD



3D MICROMACHINING

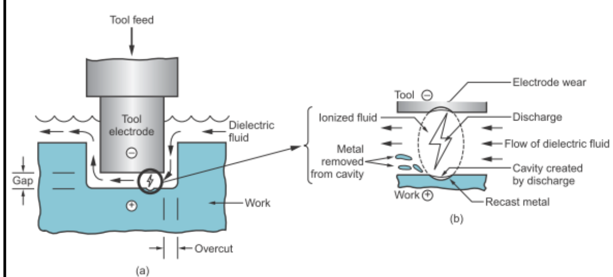
Electro-Thermal Energy based Material Removal Processes

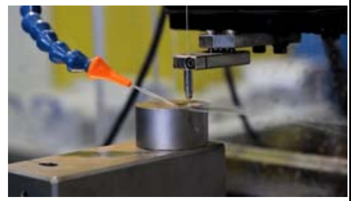
Processes
- Electric discharge machining (EDM)
- Laser beam machining (LBM)

Electric Discharge Machining (EDM)

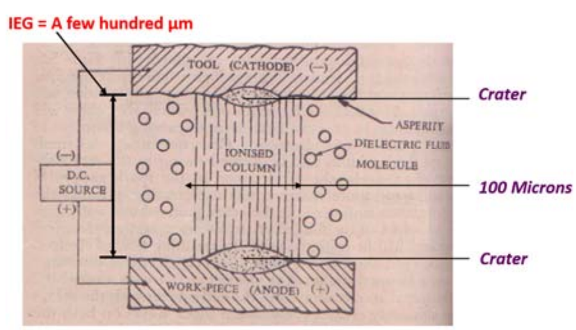
Electric Discharge Machining (EDM)

- In EDM, electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark.
- The sparks occur across a small gap between tool and work surface.
- The EDM process takes place in the presence of a dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The discharges are generated by a pulsating direct current power supply connected to the work and the tool.
- The shape of the finished work surface is produced by a formed electrode too.l
- Work material to be machined by EDM has to be electrically conductive.
- EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis.





Plasma Formation and Spark Generation in EDM



- ***Sparks*** **created deliberately**
- **Heat in a localized area**

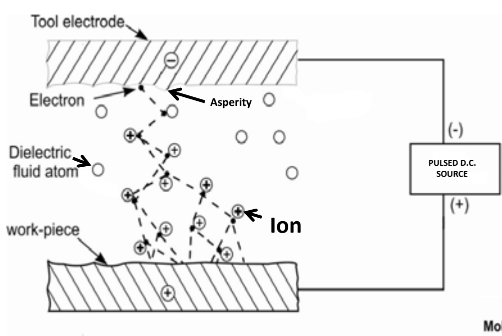
Melting and /or vaporization

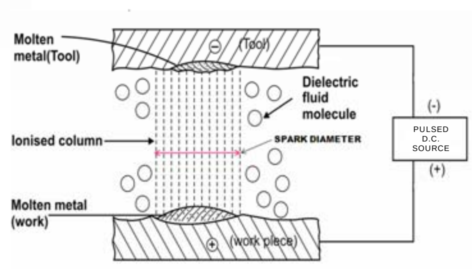
- Voltage across the electrodes reaches the breakdown Voltage
- Dielectric Breakdown: **Formation of plasma**
- Spark Generation at the point of lowest inter electrode gap (IEG)
- Melting and Vaporization of workpiece material
- Bubble generation and their Expansion
- Plasma Channel Explodes

Mechanics of Material Removal in EDM

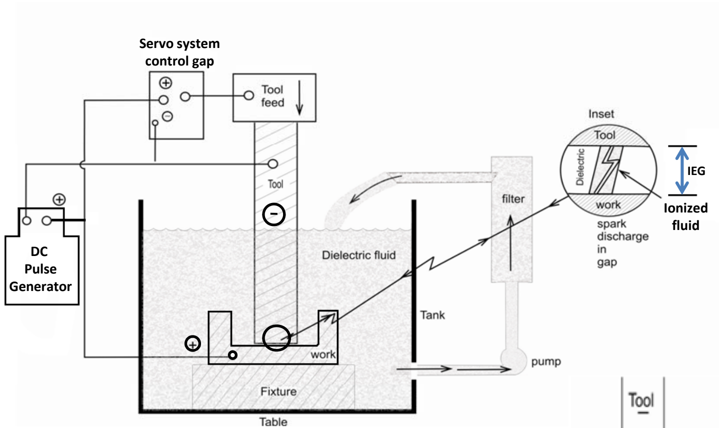
- The discharge occurs at the location where the two surfaces are closest.
- The dielectric fluid ionizes at this location to create a path for the discharge.
- The region in which discharge occurs is heated to extremely high temperatures, so that a small portion of the work surface is suddenly melted and removed.
- The flowing dielectric then flushes away the small particle (call it a 'chip').
- Because the surface of the work at the location of the previous discharge is now separated from the tool by a greater distance, this location is less likely to be the site of another spark until the surrounding regions have been reduced to the same level or below.
- Although the individual discharges remove metal at very localized points, they occur hundreds or thousands of times per second so that a gradual erosion of the entire surface occurs in the area of the gap.

How Sparking Takes Place?

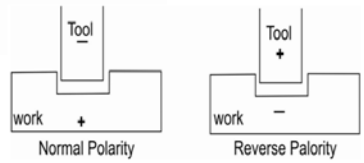




EDM: Machine Elements



Replica of the tool ➔ Workpiece



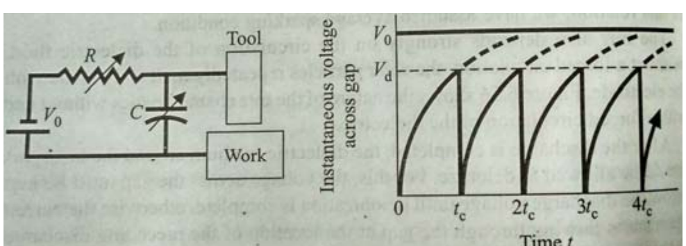
Polarity in EDM

EDM Circuits and Operating Principles

The different electric circuits are available to provide the pulsating DC across the work-tool gap. In all such circuits a capacitor is used for storing the electric charge before the discharge takes place across the gap. The commonly-used principles for supplying the pulsating DC can be classified into the following three groups:

1. Resistance-capacitance relaxation circuit with a constant DC source
2. Rotary impulse generator
3. Controlled pulse circuit

Resistance-Capacitance (RC) Relaxation Circuit:



(a) Relaxation circuit (b) Variation of gap voltage

The capacitor *C* (which can be varied) is charge through a variable resistance *R* by the DC source of voltage V_o.

Voltage Across the Gap

The voltage across the gap (which is almost the same as that across the capacitor) V varies with time according to the relation:

$$\frac{V_0 - V}{R} = C\frac{dV}{dt}$$

at time when V_o is applied

$$\int_0^V \frac{dV}{V_0 - V} = \int_0^t \frac{dt}{RC}$$

At $t=0$, $V=0$, and at any instant t, the voltage across the gap is V

$$\ln\left(\frac{V_o}{V_o - V}\right) = \frac{t}{RC}$$

$$\frac{V_o}{V_o - V} = e^{t/(RC)} \Rightarrow \frac{V_o - V}{V_o} = e^{-t/(RC)}$$

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

Average Power Delivered by the Capacitor

The frequency of sparking (ν) is approximately given by the following equation:

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

The energy released per spark is given by:

$$E = \frac{1}{2}CV_d^{\,2}$$

If $t_c(=1/\nu)$ is the cycle time, then the average value of the power delivered is given by:

$$W_{av} = \frac{E}{t_c + t_s}$$

$$V_d = V_0(1 - e^{-t_c/(RC)})$$

$$W_{av} = \frac{1}{2}\frac{C}{t_c}V_0^{\,2}(1 - e^{-t_c/(RC)})^2 \qquad t_c \gg t_s$$

$$Let\ \xi = t_c/RC \Rightarrow W_{av} = \frac{V_0^{\,2}}{2R}\frac{1}{\xi}(1 - e^{-\xi})^2$$

$$\text{For maximum power delivery:} \left.\frac{\partial W_{av}}{\partial \xi}\right|_{\xi=\xi_{opt}} = 0$$

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

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

Assumption:

- The discharge time (t_s) is much smaller (about 10%) than the charging time (t_c)
- The time required for deionization is also very small under normal circumstances

V_d = discharge voltage (the voltage across the gap at which spark takes place)
t_c = the charging time which is equal to the time required for the gap voltage to reach a value V_d.

Thus for maximum power delivery, the discharge voltage should be 72% of the supply voltage V_o.

Material Removal Rate (MRR) in EDM

If we assume the material removed per spark to be proportional to the energy released per spark, then the MRR can be expressed as:

$$MRR(Q) \approx K \times E \times \nu$$

$$MRR(Q) \approx K\left(\frac{1}{2}CV_d^{\,2}\right)\nu$$

where K is the constant of proportionality denoting the fraction of power effectively used in material removal.

$$MRR(Q) \approx K\left(\frac{1}{2}CV_d^{\,2}\right)\frac{1}{RC\log_e\left(\frac{V_o}{V_o - V_d}\right)}$$

$$MRR(Q) \approx K\frac{V_d^{\,2}}{2R\log_e\left(\frac{V_o}{V_o - V_d}\right)}$$

So, it is evident from the equation that, for a given circuit, the *MRR* increases as *R* is decreased. However, *R* can not be decreased below a critical value as, otherwise, arcing, instead of sparking, will take place.

The critical value of the resistance depends on the inductance *L* of the discharging circuit. It can be shown that, for a purely inductive discharging circuit, the critical value is

$$R_{\min} = \sqrt{\frac{L}{C}}$$

However, the discharging circuit is seldom purely inductive and *R* should not be lowered below a value $30\sqrt{L/C}$.

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- Tool: Usually graphite, Brass, Cu, Cu - W
- Diameter can be as low as 0.1 mm
- Dielectric fluid (mineral oil, kerosene, distilled and de - ionized water) between tool and work piece
- Voltage: 50 – 380 V; Current: 0.1 – 500 A
- Discharge is repeated at rates between 50-500 kHz

Applications

- Tooling for many mechanical processes: molds for plastic injection molding, extrusion dies, wire drawing dies, forging and heading dies, and sheetmetal stamping dies
- Production parts: delicate parts not rigid enough to withstand conventional cutting forces, hole drilling where hole axis is at an acute angle to surface, and machining of hard and exotic metals

Speaker die for car stereo system

Hole drilling

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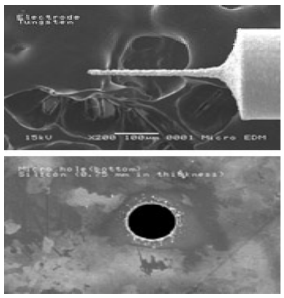
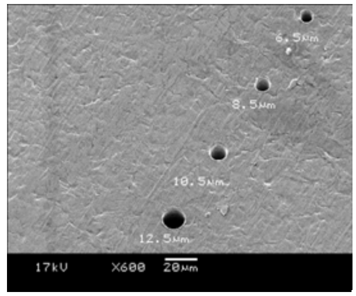
Examples of Electric Discharge Micro Machining (EDMM)

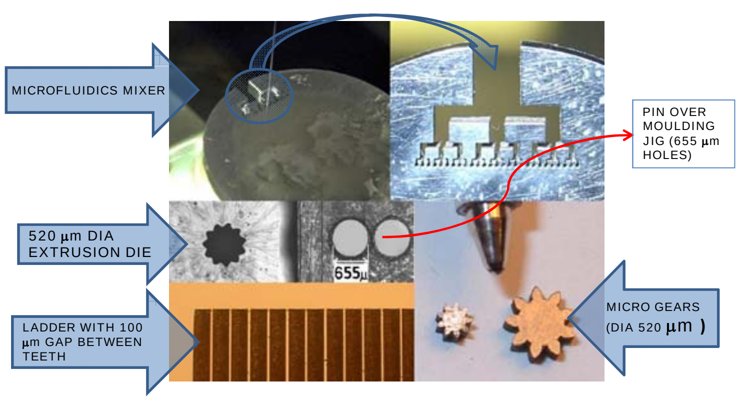


30-micron shafts and 50-micron holes produced by micro-EDM



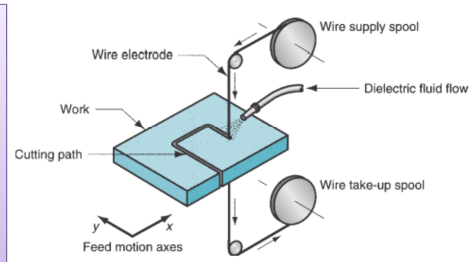
Holes as small as 6.5 microns in diameter and an aspect ratio of 7.5

Examples of Electric Discharge Micro Machining (EDMM)



Wire EDM

- Work is fed slowly past wire along desired cutting path, like a bandsaw operation
- CNC used for motion control
- While cutting, wire is continuously advanced between supply spool and take-up spool to maintain a constant diameter
- Dielectric required, using nozzles directed at tool-work interface or submerging workpart



Applications
- Production of die cavities for large automotive–body components
- Deep small diameter holes
- Narrow slots in turbine blades

Recap of This Lecture

- Introduction to ECM process
- Material removal rate in ECM process
- Application of ECM process
- Introduction to EDM process
- Material removal rate in EDM process
- Application of EDM process

Next Lecture

Laser Beam Machining (LBM)